Matlab Wi-Fi simulations considering interferences in dense urban environments

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Abstract

In recent years, there has been a high growth in the number of mobile devices and the transit of global data, with a forecast of exponential growth.
It has also been observed that this growth takes place in urban environments such as offices or apartment buildings where the deployment of WLAN networks and the IEEE 802.11 standard prevails.
Those facts have consolidated the standard as a widely used technology and have generated the need for companies to understand and optimize the performance of WLANs.

This thesis is part of a larger project, which consists in the creation of a measurement software tool for WLANs in urban environments (TUWIPA©) as a graphical user interface developed in MATLAB.
The dense urban environments constitute a hostile environment for the operation of Wi-Fi networks in which, among several drawback, stands out the broad spectrum of interference sources that operates on the same frequency band and can highly condition the service provided.
The thesis is mainly focused on complementing the tool with the characterization and implementation of different interference sources with diverse properties, such as microwaves or neighboring Wi-Fi networks. It is also proposed the implementation of additional free-choice features that can complement the program.

The obtained results show that the sources of interference have been successfully characterized, making TUWIPA© a more complete and robust tool that can provide more precise and reliable numerical results.

Key words: WLAN, Simulations, MATLAB, Graphical user interface (GUI), Interference, Markov Chains.
Resum

En els últims anys, s’ha observat un alt creixement en el número de dispositius mòbil i el transit de dades globals, amb una previsió de creixement exponencial. També s’ha observat que aquest creixement té lloc en entorns urbans com oficines o blocs de pisos on predomina el desplegament de xarxes WLAN i el estàndard IEEE 802.11. Aquests fets han consolidat el estàndard com una tecnologia àmpliament utilitzada i han generat la necessitat per a les empreses de l’àmbit d’entendre i optimitzar el rendiment de les WLAN.

Aquesta tesi s’engloba en un projecte més gran, que consisteix en la creació d’una eina software de mesura per a WLANs en entorns urbans (TUWIPA©), desenvolupada en MATLAB com una interfície gràfica d’usuari. Els entorns urbans densos constitueixen un entorn hostil per al funcionament de les xarxes Wi-Fi en el qual, entre diversos inconvenients, destaca l’ampli espectre de fonts d’interferència que operen en la mateixa banda de freqüència i que poden condicionar altament el servei ofert. La tesi està principalment enfocada a complementar la eina a través de la caracterització i implementació de diferents fonts d’interferència amb propietats diverses, com per exemple els microones o les xarxes Wi-Fi properes. També es proposa la implementació de funcionalitats addicionals de lliure elecció que puguin complementar el programa.

Els resultats obtinguts mostren que les fonts d’interferència han sigut caracteritzades amb èxit, convertint TUWIPA© en una eina més completa i robusta que pot proporcionar resultats numèrics més precisos i fiables.

Paraules clau: WLAN, Simulacions, MATLAB, interfície gràfica d’usuari (GUI), interferència, Cadenes de Markov.
Resumen

En los últimos años, se ha observado un alto crecimiento en el número de dispositivos móviles y el tráfico de datos globales, con una previsión de crecimiento exponencial. También se ha observado que este crecimiento tiene lugar en entornos urbanos como oficinas o bloques de pisos, donde predomina el despliegue de redes WLAN y el estándar IEEE 802.11. Estos hechos han consolidado el estándar como una tecnología ampliamente utilizada y han generado la necesidad para las empresas del ámbito de entender y optimizar el rendimiento de las WLAN.

Esta tesis se engloba en un proyecto más grande, que consiste en la creación de una herramienta software de medida para WLANs (TUWIPA ©) desarrollada en MATLAB, como una interfaz gráfica de usuario. Los entornos urbanos densos constituyen un entorno hostil para el funcionamiento de las redes Wi-Fi en el cual, entre varios inconvenientes, destaca el amplio espectro de fuentes de interferencia que operan en la misma banda de frecuencia y que pueden condicionar altamente el servicio ofrecido.

La tesis está principalmente enfocada a complementar la herramienta a través de la caracterización e implementación de diferentes fuentes de interferencia con características diversas, como por ejemplo los microondas o las redes Wi-Fi cercanas. También se propone la implementación de funcionalidades adicionales de libre elección que puedan complementar el programa.

Los resultados obtenidos muestran que las fuentes de interferencia han sido caracterizadas con éxito, convirtiendo TUWIPA © en una herramienta más completa y robusta que puede proporcionar resultados numéricos más precisos y fiables.

Palabras clave: WLAN, Simulaciones, MATLAB, interfaz gráfica de usuario (GUI), interferencia, Cadenas de Markov.
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# Table of contents

1 Introduction .......................................................... 1  
  1.1 Motivation ................................................................ 1  
  1.2 Statement of purpose ............................................... 2  
  1.3 Requirements and specifications ................................. 3  
  1.4 Project Background and Structure ............................. 4  
    1.4.1 Project Background ........................................... 4  
    1.4.2 Work Packages and Milestones ......................... 4  
    1.4.3 Gantt Diagram ............................................... 6  
    1.4.4 Scenarios Definition ....................................... 6  
  1.5 Deviations and incidences ........................................ 7  

2 State of the art .......................................................... 8  
  2.1 IEEE 802.11 Standard and WLAN basis .................... 8  
  2.2 Devices Coexistence in ISM Band ............................ 12  
  2.3 Data Link Layer in WLANs .................................... 13  
  2.4 Urban environments characterization ....................... 16  
    2.4.1 Microwave Oven ........................................... 16  
    2.4.2 High density WLANs ...................................... 17  

3 Project development ................................................... 18  
  3.1 TUWIPA© Overview .............................................. 18  
  3.2 TUWIPA© Settings General Operation and Settings ........ 22  
    3.2.1 General Settings ......................................... 22  
    3.2.2 General operation ....................................... 24  
  3.3 Developed Analytical Models .................................. 28  
    3.3.1 Microwave Oven signal modeling .................... 28  
    3.3.2 High Density WLANs ................................... 31  
  3.4 Scenarios implementation ........................................ 39
# TABLE OF CONTENTS

3.4.1 Microwave Oven Scenario .................................................. 39  
3.4.2 Neighboring Interferer Hotspots Scenario ............................... 41  
3.5 TUWIPA® Version 4.5 other new features .................................. 46  

4 Results ....................................................................................... 47  
4.1 Micro Wave Oven scenario ....................................................... 47  
4.2 Neighboring Interferer Hotspots Scenario ................................. 51  

5 Conclusions and future development .......................................... 56  

Bibliography .................................................................................. 57  

Glossary ....................................................................................... 60  

Appendices .................................................................................. 61  

A Work Packages .......................................................................... 62  

B TUWIPA® General Operation details ......................................... 65  
  B.1 Propagation Model tables ....................................................... 65  
  B.2 Wall Materials table ............................................................ 66  
  B.3 SNR to MCS Conversion Table ............................................. 66  
  B.4 MCS to Data Rate Conversion table ..................................... 67  

C TUWIPA® Version 4.5 other new features .................................. 68  

D Code ......................................................................................... 70  

E Budget ....................................................................................... 78  

F Miscellaneous ........................................................................... 79  
  F.1 OSI model ........................................................................... 79
# List of Figures

1.1 Data Traffic expectancy growth until 2021 [1] ........................................ 1  
1.2 Number of Devices expectancy growth until 2021[1] ................................. 1  
1.3 Thesis Work Packages structure ............................................................. 5  
1.4 Project Gantt diagram ............................................................................. 6  

2.1 Wi-Fi alliance Logo .................................................................................. 9  
2.2 IEEE 802.11 standards versions ................................................................ 10  
2.3 Existing ISM Bands .................................................................................. 12  
2.4 Data Link and Physical Layers .................................................................. 14  

3.1 TUWIPA© welcome window ................................................................. 18  
3.2 Current Settings Window ....................................................................... 19  
3.3 Signal Strength Simulation ..................................................................... 20  
3.4 TUWIPA© structure outline ................................................................... 21  
3.5 Device settings windows .......................................................................... 22  
3.6 Dipole radiation diagram ......................................................................... 23  
3.7 AP FB6840 data rate table ....................................................................... 27  
3.8 Experimental MWO Spectrogram ............................................................ 29  
3.9 MWO signal analytical model in time domain ....................................... 30  
3.10 Markov Chain [29] ................................................................................ 33  
3.11 Markov Modeling of a 3 WLANs system [22] ......................................... 37  
3.12 Flat model 7 with multiple interferer neighbors .................................... 42  
3.13 Interference strength simulation with 2 interferer neighbors ............... 43  
3.14 Markov analysis with three interferer neighbors ................................... 45  

4.1 Data Rate without interference case 1 ..................................................... 48  
4.2 Data Rate with interference case 1 .......................................................... 48  
4.3 Channel Air Time case 1 .......................................................................... 49  
4.4 Average and decrease data rate maps case 1 ......................................... 49
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
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<tbody>
<tr>
<td>4.5</td>
<td>Channel Air Time case 2</td>
<td>50</td>
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<tr>
<td>4.6</td>
<td>Average and decrease data rate maps case 2</td>
<td>50</td>
</tr>
<tr>
<td>4.7</td>
<td>Markov analysis with WLANS A and B not overlapped</td>
<td>52</td>
</tr>
<tr>
<td>4.8</td>
<td>Channel Air Time in Markov case 1</td>
<td>52</td>
</tr>
<tr>
<td>4.9</td>
<td>Data rate decrease in Markov case 1</td>
<td>53</td>
</tr>
<tr>
<td>4.10</td>
<td>Markov analysis with WLANs A,B and C overlapped</td>
<td>54</td>
</tr>
<tr>
<td>4.11</td>
<td>Markov analysis with WLANs B-C not overlapped</td>
<td>54</td>
</tr>
<tr>
<td>4.12</td>
<td>Markov analysis with 7 neighboring WLANs</td>
<td>55</td>
</tr>
<tr>
<td>B.1</td>
<td>SNR to MCS conversion table for different protocols and channel widths</td>
<td>66</td>
</tr>
<tr>
<td>B.2</td>
<td>MCS to Data Rate conversion table</td>
<td>67</td>
</tr>
<tr>
<td>C.1</td>
<td>QoS measurement with a normal interference source</td>
<td>68</td>
</tr>
<tr>
<td>C.2</td>
<td>Incorrect position value exception</td>
<td>69</td>
</tr>
</tbody>
</table>
List of Tables

2.1 Wi-Fi 2.4GHz band channels ............................................................... 11
2.2 MWO emission patterns [20] ............................................................... 17
3.1 SNR to Data rate conversion table ......................................................... 27
B.1 Power Loss coefficient $N$ ................................................................. 65
B.2 Floor penetration factor $Pf(n)$ ......................................................... 65
B.3 Penetration losses of different materials ............................................. 66
1 | Introduction

1.1 Motivation
In the last years the standard for wireless systems IEEE 802.11 has became one of the most relevant standards in communication.
The main reasons of it is the growth of Wireless Local Area Network deployments in different kinds of environments, the low complexity of operation in the Industrial, Scientific and Medical (ISM) band and the ever increasing number of wireless devices such as smart phones, tablets or laptops.
Directly related with that, there has been an exponential growth of the data traffic with an expectancy of even more increase. Figures 1.1 and 1.2 provided by Cisco makes easier to understand the scale of this phenomenon.

Figure 1.1: Data Traffic expectancy growth until 2021 [1]

Figure 1.2: Number of Devices expectancy growth until 2021[1]
CHAPTER 1. INTRODUCTION

Moreover, as an interesting fact, different studies have shown that most of this data traffic and use of mobile devices increase, takes places in indoor environments such as apartment buildings and offices \[2\].

Those types of environment constitutes a specially challenging ambient in which constants drawback can be found, including dealing with high building attenuation, provide service to diverse user profiles and numbers and face interferences sources of different nature.

The interference topic is a specially complex drawback to deal with, mainly because of the overwhelming quantity of devices that operates in the ISM band, interfering with the Wi-Fi performance but also because of the difficult characterization of all the interactions between all of this interferences and the network.

All of those drawbacks have created a need for better understanding, modeling and optimize WLAN performance.

In addition, The WLAN performance comprehension is of special relevance since the path of development to 5G and the next generation to come of telecommunication technologies points to the coexistence between IEEE 802.11 and the mobile communication standards as a key element \[3\].

1.2 Statement of purpose

This thesis is part of a bigger project which its main purpose is to create a measurement software tool of WLANs deployed in urban dense environments, that will be focused in performing and analyze different types of measures in the framework of a residential apartment. The tool, TUWIPA© (Technische Universität Wireless Indoor Performance Analyzer) consists in a Graphical User Interface (GUI) that has been developed in MATLAB using GUIDE. The thesis will be focused of improve this software in order to provide the Institute of Telecommunications from the Technische Universität Wien (TU Wien) with a more complete tool capable to be used in other projects or for a personal use as well.

The thesis main goals are:

- Improve the software tool to perform and analyze simulations of KPI’s like SNR, Data Rates and so on, in a more complete way by adding new functionalities as the air time fairness (channel occupation time).

- It is needed to focus the work on the topic of interferences. Different scenarios have to be defined by considering different interference sources types and locations in order to study how they affect the service performance.
1.3 Requirements and specifications

The requirements that should be filled during this thesis development are:

- Build a flexible and robust software tool capable to perform reliable Wi-Fi measures and analysis considering a dense urban environment.
- Study, characterize and implement different types of interferer sources such as microwaves or neighbor WLANS and analyze how they affect the user service.
- Considerate other ways of improving the software such as enhancing the performance in terms of efficiency, improve the interface visually or adding new measurement options.
- The GUI has to maintain the ease of use for the non-familiar users.

There are no particular project specifications in terms of numerical values. All the new functionalities have to be implemented, using different information sources in order to implement them using the most thorough parameters settings and in consequence obtain coherent results.
1.4  Project Background and Structure

1.4.1  Project Background

As it has been said before, this thesis is part of a bigger project, which consist in creating a WIFI measurement tool in MATLAB and is based in an already existing work (GUI) in which has intervened other students form different universities as well as PhD and teachers. It is performed in the framework of the Institute of telecommunications of TU Wien. The main idea of the project is provided by the supervisor and the department. Despite this, the thesis is focused on improving the tool departing from a problem statement and the way of doing it is not defined and free of choice by the student.

1.4.2  Work Packages and Milestones

Work Packages

This thesis has been structured in different Work Packages (WP). Each one includes different tasks that had to be fulfilled to complete successfully this thesis. Figure 1.3 shows the overview of the structure of the thesis. As it can be seen the structure is divided in five different WP:

- Definition of Scenarios.
- Software Implementation.
- Simulation Performance.
- Results analysis and Conclusions.
- Dissemination.

Each of them includes a set of subtask that specifies different work areas of the WP where they belong.
1.4. PROJECT BACKGROUND AND STRUCTURE

Figure 1.3: Thesis Work Packages structure

For a more detailed look of each WP and its subtasks see Appendix A.

Milestones

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1.4.3 Gantt Diagram

The Gantt Diagram shows the temporal structure of the defined WP. As it can bee seen, the duration of the project has been around 6 months from March to October 2017.

![Gantt Diagram]

Dissemination WP (number 5) includes subtask and deliverables like the mid-term one Project Critical Review or the final code and thesis memory as well as the Documentation process. Therefore, this WP has been transversal and its duration is the entire thesis development.

1.4.4 Scenarios Definition

Considering the needs that have to be filled and having in mind the main objective that is the interference characterization, a set of scenarios have been derived. These scenarios encompass different urban environment common interference sources which have pretty distinct properties. After a research process (later detailed on next chapters) two scenarios were derived:

- The microwave oven as a non-continuous and non-data transmitter interference source that can be found in almost every apartment environment.

- The High Density WLANs defined as an environment with different interferer nearby wi-Fi networks which its main characteristic is the random probability of transmission.

Different scenario cases will be considered combining the sources with diverse possible deployments and settings.
1.5 Deviations and incidences

Incidences

After a few setbacks and general delay in the work packages the decision of extend the degree thesis had been taken.
Apart from that fact, there haven’t been major important incidences during the realization of the different tasks.
As minor incidence, it should be remark that the performance offered by the equipment used for the simulations (laptop) has not been the optimal, since during the running of simulations problems of memory and leading sometimes to the shutdown of the system.
For that, UPC has offered the possibility to access a laboratory and use its equipment such as a special computer used for simulations.

Deviations

As a consequence of the extension of the thesis there are a few modifications on the Work Plan.
The main change that has implied the extension, is that the final report and final oral presentation deadlines were modified to October 2017. In addition, since some of the subtask included in the WP number 2 and number 3 had taken more time than the stipulated, the planned ending dates for both WP had been modified.
Apart from that, it was planned to start some of the WP one after the previous one but since the Internal Task number 3 of WP2 (code implementation) had been taking much more time than the expected, some of the tasks of the WP number 4 had been already started by that time. Those changes have been reflected in the Gantt Diagram and notified during the Project Critical Review delivery.

In the last months, WP number 4 was modified after considering the project main objective, omitting the optimization part. Hence, the WP 4 was renamed to Results.
That being said, the major structure of the whole thesis hasn’t been modified during its development.
State of the art

This chapter includes an overview look at the basic concepts and technologies that takes parts in the Wireless Local Area Networks (WLANs), going through the Wi-Fi standard creation and evolution until today, putting special emphasis in the currently panorama. The main idea is to settle the basis that will provide a better idea and comprehension of the all the related concepts and the further mathematical models that developed.

2.1 IEEE 802.11 Standard and WLAN basis

The origin of the Wireless Communications as known today dates back to the finals of the 20th century [4]-[5].

Around 1980 several communications technologies such as first cellular networks (1G) or the Ethernet Local Area Network\(^1\) standard, were emerging with a prevision of an incredible fast change and growth.

With the main aim of integrating different technologies and work together with them, the standard IEEE 802 was created in 1980 by the Institute Institute of Electrical and Electronics Engineers (IEEE). In parallel the International Organization for Standardization (ISO) was developing the Open System Interconnection (OSI)\(^2\).

IEEE 802 comprises a family of networking standards for LAN that specifies both lower levels of the OSI model (Data link and physical layer) of technologies from Ethernet to wireless. Nowadays, IEEE 802 specifications include 802.3 Ethernet, 802.11 Wi-Fi, 802.15 Bluetooth/ZigBee and 802.16 Wireless Metropolitan Area Networks (WMAN) among others [7]. The currently 802 standard also includes standards for Wide Area Networks (WAN)

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\(^1\)Local Area Networks are networks that connect together computers that are relatively close to each other generally, within the same room or building. The majority of regular LANs usually imply wired connections [6].

\(^2\)OSI model is a conceptual model that defines the networks communications between systems. Is divided in 7 layers, each of them characterize the behavior and represents different collections of services that can be provided to the communication. For more information, see Appendix F.1.
2.1. IEEE 802.11 STANDARD AND WLAN BASIS

With the explosion in the expansion of computers, Internet and the recent creation of the promising IEEE 802 standard, by 1985 the LAN was already a consolidate technology. Although the first wireless computer communications dates from 1971 with the ALOHAnet developed in Hawaii University, by 1980 the wireless networks were not a wide used technology, mainly because the high cost in front the LAN [8].

It was not until 1997, after few years of an enormous expansion of wired LAN, that the IEEE created the IEEE 802.11 standard. The main objective was to make the wireless technology a reliable and robust solution in front the wired ones and convert it in a widespread technology using the 2.4GHz ISM band. IEEE was anticipating also the arrival of wireless-using devices such as Laptops and smart phones.

Wireless Local Area Networks (WLAN) became one of the most important communication technologies, offering a better mobility, flexible deployment and cost compared to the LAN.

In 2000, with the growing of the wireless devices, different companies of the telecommunications community, created the Wireless Ethernet Compatibility Alliance (WECA) in order to ensure the interoperability between such devices under the 802.11 standard (by that time the standard had already evolved to 802.11b). This alliance became later the Wi-Fi Alliance, the main organization to commercialize and regulate the so-called Wi-Fi devices as we know them today. All of the Wi-Fi devices operates within the ISM band [9].

The standard 802.11 establishes the lower levels of the OSI model for wireless connections:

- The Physical Layer (PHY)
- The Data Link Layer divided into two sub-layers, the Medium Acces Layer (MAC) and Logical Link Control Layer (LLC)
CHAPTER 2. STATE OF THE ART

From its birth until today, the 802.11 standard had received constant revisions and modifications. Those modifications seek to keep up with the continuous and increasingly fast changes and covers different aspects of the wireless communications such as quality of service or security. The main aspect that those standards deal with, is the trade off between delivering a higher throughput together with other features and the interference mitigation and network robustness.

![IEEE 802.11 standards versions](image)

Figure 2.2: IEEE 802.11 standards versions

As it can be seen Figure 2.2 each version of the standard enhance enormously the achievable throughput the and introduce different new technologies.

The introduction of the 5GHz as a operation frequency band and the Multiple Input Multiple Output (MIMO) technology in the version IEEE 802.11n are one of the most important introduced features.

Nowadays, Wi-Fi is able to compete well with wired systems and the IEEE 802.11 standard is widely used to provide WLAN solutions both for temporary connections in Hotspots\(^3\) placed in cafes, airports or hotels or permanent installations such as offices or apartments [10].

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\(^3\)A Hotspot is a telecommunications concept that makes references to areas with high traffic demand in which is provided wireless Internet access
Wi-Fi Channels

The 2.4 GHz bands it’s currently divided into 14 channels with a 22 MHz of bandwidth. Each has its own laws that stipulates which channels are available or not for the use. Depending the regulation, there are different channels considered the ideal ones and hence the ones that are used by the systems. Those channels are considered ideal because they can be used in parallel without overlapping (interference). In Europe those channels are the numbers 1, 7 and 13.

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<td>2437 MHz</td>
<td>13</td>
<td>2472 MHz</td>
</tr>
<tr>
<td>7</td>
<td>2442 MHz</td>
<td>14</td>
<td>2484 MHz</td>
</tr>
</tbody>
</table>

Table 2.1: Wi-Fi 2.4GHz band channels
2.2 Devices Coexistence in ISM Band

The Industrial, Scientific and Medical (ISM) Band is a group of radio-frequency bands that comprises different segments of the electromagnetic spectrum. Some of the segments included are 900 MHz, 2.4 GHz and 5GHz, being those last two bands the most important ones [11]-[12].

Those bands are also called unlicensed bands. Unlicensed bands can be understood as bands in which the operation of devices is allowed without individual authorization and centralized management by the Communications Authorities of each country. In other words, is a non-commercial and open-use band intended to be used by private companies, all type of public infrastructures (hospitals, schools, etc.) or particular uses as well. Moreover, there are no major restrictions of use for this band apart from the basic requirements of coexistence such as power limits, limited power spectral densities bandwidth and so on.

The ISM band, established at the International Telecommunications Conference of the International Telecommunication Union (ITU) in 1947, it was initially created with the idea of be used for machines such as industrial heaters, Micro Wave Ovens or RF Welders. Although the main approach was not conceived for the radio communications soon afterwards, the ISM Band opened up for wireless LANs and mobile communications. From that moment on, all types of short-ranged and low-powered devices have been appearing and using that band.
2.3 DATA LINK LAYER IN WLANS

Nowadays the list of devices that use this band is quite long, even if we reduce the list to the domestic ones. All type of Blue-tooth devices (headphones, speakers, computer peripherals), Microwaves, Cordless phones, toys and even amateur radio. In addition, with the proliferation of technologies such as NFC (Near Field Communications) the list just increases with an expectancy of exponential growth in the nearest future.

As it can be seen, as an important drawback for the ISM Band is that any device operating there will encounter several number of interferences coming from different types of source, hence it becomes and hostile environment for accomplishing a proper performance. Therefore, the coexistence for all of those devices had became a quite challenging and important issue for the companies and the ISM Band had became object of exhaustive studies and investigation.

2.3 Data Link Layer in WLANs

The Data Link Layer is the second layer of the OSI model and is responsible for the reliable transfer of information through any network (or data transfer circuits).

One of the most important functions of this layer is the provision of resources to detect and correct possible errors occurred during data transmissions and the encapsulation of data into frames

The data Link Layer is divided into two sub-layers; the Logical Link Control (LLC) Layer and the Medium Access Control (MAC) Layer.

The LLC sub-layer is defined in the standard IEE 802.2 and its shared among the other types of networks. However, MAC sub-layer is differently defined on each network type (as well as the lowest layer). Figure 2.4 illustrates this idea.

When the transmission medium is shared between two or more network devices, it is needed the moderation of the access to this medium. The MAC layer defines the set of mechanisms and protocols to ensure a proper management of the access to this medium and avoid collisions.

---

4 In networking a frame is a transmission unit that contains bits of data along header and trailer that indicate the start and end of it.
5 A collision is defined as two network devices attempting to transmit at the same time in a shared medium.
IEEE 802.11 defines a distributed coordination function (DCF) for sharing the access to the medium based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [13]-[14]. Nowadays inter and intra-wlan interactions are governed by the CSMA/CA. But first to understand the CSMA/CA, it is needed to take a look into one of the basic MAC protocol used in networks, the Carrier Sense Multiple Access (CSMA).

In this protocol, a node\(^6\) can verify before transmitting if the channel (TX medium) is being used or not by any other network devices. This process is also called listening mechanism. CSMA/CA works based on the same listening principle. The main difference here is that this protocol is capable to avoid the collisions. Compared with other CSMA variants (specially CSMA/CD), it presents two main benefits [15]:

1. Collision detection usually becomes an issue, since for a node, transmitting and receiving data at the same time implies extra cost.

2. Solves the hidden node problem. A transmitting node can be able to listen the medium but not others nodes that are not within its coverage range. This invisible node might want to access the same medium, in this case, the channel would be detected free by the transmitting node, when in fact it is busy (or about to be).

---

\(^6\)A node in networking, is an electronic device attached to a network, capable of creating, receiving or transmitting information over a communication channel.
In CSMA/CA, the access process is basically divided in 3 stages:

1. The node that wants to transmit listens the medium in order to see if its free
2. Data Transmission if the medium it is free or wait a random time to retransmit the data determined by the back off algorithm.
3. Wait the confirmation by the Receiver Side.

The backoff is an algorithm that multiplicatively decrease the collision probability of the network. When a collision is detected, the transmitter will stop from retransmitting for a random number of slots time\(^7\) derived from the number of attempts to retransmit [15]. The back off as is usually defined in the CSMA/CA is called exponential because the equation that defines the waiting time, decreases exponentially the collision probability.

\[
0 \leq r \leq 2^k
\]

Where:
\(r\) = Number of slots time to wait.
\(k = \min(\text{Number of collisions, Contention Window})\).

The contention window (CW) is a parameter that determines the upper limit of the backoff timer. The contention has also a range of values between CWmin and CWmax.

The dimensioning of the CW size is an important aspect for the network optimal performance. If the size of the window is small and the number of stations\(^8\) high, the collision probability increases. Otherwise if the size is too large, the station might wait too long to transmit. Both cases results in a degradation of the network performance.

To solve the hidden node problem, the CSMA/CA implements the Request-to-send (RTS) and Clear-to-send (CTS) frames (RTS/CTS technique) [16]. The RTS is a frame that is sent to the AP by a node every time it wants to access the medium. When the frame is received by the AP if the channel is free it notifies all the other nodes that the channel is busy and sends the CTS frame to the transmitter to allow the use of the channel. If two or more RTS frames are received at same time, the AP does not send any CTS frame, the collision is assumed by the nodes and waiting time is derived by the backoff algorithm.

---

\(^7\)Slot time in networking is a kind of measurement unit for the time. Instead of seconds, the timings are calculated as slots time. Its value is usually taken as the double of the time that takes for a transmitted pulse to reach the maximum distance within a network.

\(^8\)In IEEE 802.11 terminology, a station (abbreviated as STA) is a device that has the capability to use the 802.11 standard. For example, a station may be a laptop, a desktop PC, a smartphone or an access point.
2.4 Urban environments characterization

Regarding at the last sections, the urban environments can be see as the environments in which the exponential data traffic and device increasing is taking place. There, the high attenuation, the diverse user devices that requires a certain quality of service and the wide spectrum of interference source makes that environment specially problematic and hard to study.

The interference problem in that environment is subject mainly to the wide use of ISM Band devices together with the deployment of what is called High Density WLANs (HDW).

The coexistence of different network in the HDW has resulted in the apparition of even more difficulties for a proper service performance, such as the near-far\(^9\) problem or the hidden node issue.

The Wi-Fi, as standard based on a collision sensing and avoidance technology, has offered quite optimal solutions for some of those problems such as the hidden node.

2.4.1 Microwave Oven

The Microwave oven (MWO) is a pretty common device used in urban environments such as offices, flats and universities. Is a non-data transmitters device that operates in the ISM Band. It uses the 2.4 GHz band and emits unintentional radio-frequency power that can interfere with the Wi-Fi and highly affect the service causing data loss and even disconnection of service [17]-[18].

In addition, MWO is what is called a pulsed interference source, that can be understood as a signal which has periods of activity and inactivity [19].

The MWO is an interesting device to study taking into account the environment in which the thesis has been developed and its characteristics. The emission pattern of the leakage can change depending on a lot of factors such as the type of oven, load, orientation, age or temperature.

There are mainly three types of microwaves: the transformers, the switchers and the inverters. Each one with different properties that obviously condition completely the signal characterization.

Table 2.2 shows the emission pattern characterization and how drastically it can change depending MWO types.

\(^9\)The near–far problem is a condition in which a receiver captures a strong signal and thereby makes it impossible for the receiver to detect a weaker signal.
2.4. **URBAN ENVIRONMENTS CHARACTERIZATION**

<table>
<thead>
<tr>
<th>Microwave type</th>
<th>Microwave Emission Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer type</td>
<td>emit once per AC power cycle (16.7-20 ms)</td>
</tr>
<tr>
<td>Switching type</td>
<td>emit twice per AC power cycle (16.7-20 ms)</td>
</tr>
<tr>
<td>Inverter type I</td>
<td>emit once per inverter switching cycle (20-35 $\mu$s)</td>
</tr>
<tr>
<td>Inverter type II</td>
<td>emit twice per inverter switching cycle (20-35 $\mu$s)</td>
</tr>
</tbody>
</table>

Table 2.2: MWO emission patterns [20]

Since the most popular MWO used in urban environments is in general the transformer type, the later model developed and simulations will attend to that guideline [20].

Nowadays, several studies can be found that have dig into the MWO properties and signal characterization, obtained feasible experimental results and developed pretty accurate analytical models.

### 2.4.2 High density WLANs

The definition of HDW is not clear, different information sources defines the concept including numerical values such as the number of devices or different networks but the environments in which the studies are defined doest not seem to match the framework in which the thesis is developed [21].

The concept Hight density WLANS (HDW), as its defined in our environment, makes reference to those environments in where different various nearby WLANs coexist. A WLAN, seen from the point of an interference, constitutes a source that transmit data randomly and occupies the channel for a certain time. The random data transmission and the channel occupation highly conditions the service that our networks provides. Characterize the random nature of this source is not trivial. Different studies have proposed a feasible model of conceiving this interference in the HDW environment, based on the Markov Chain and its analysis [22]-[23].

The conception of this models goes through a fully comprehension of the interactions between multiple WLANs operating in the same channel. Although those studies are quite recent, they have wide acceptation in the investigation community. Therefore, this model will be used to develop the mathematical models of this thesis in which the simulations will be based.
3 | Project development

This chapter includes the step by step the process carried out during the thesis development, starting from the basic understanding of the already existing software and how it works, going through the analytical models used and eventually, the implementation of the stated scenarios and some of the other important new features.

3.1 TUWIPA© Overview

This section aims to make a short outline of the TUWIPA software in order to understand its characteristics and basic functionality. As is explained in the welcome window, TUWIPA is a graphical interface (GUI) developed in MATLAB. This interface constitutes a software tool to simulate and analyze WLAN performance in indoor urban environment through the measures of different KPI’s such as the Signal Strength, SNR and so on.

![TUWIPA welcome window](image)

Figure 3.1: TUWIPA© welcome window

The GUI allows to the user to modify several parameters of the WLAN and its environment
with the main purpose to be as faithfully to reality as possible. The first window accessed after the welcome one, shows to the user the set of characteristics that can be configured. The parameters that can be modified are:

- **Device (AP):** Some of the parameters of the device that can be modified, are the transmission antenna power and its radiation pattern, receiver gain, transmitter and receiver diversity and the AP position, frequency or the protocol.

- **Interference:** The modifiable settings here are almost the same similar to the device one. As it's been explained before, one of the main goals of the project is to work on the topic of interference, so here is where most of the new features will be focused.

- **Flat layout:** All of this elements are deployed into an indoor urban scenario, in other words, a flat. The flat is formed by a set of different walls type such as concrete, wood or glass, each one with a specific attenuation level. The software allows the drawing of new flat layout as well. The flat layout includes also the configuration of the noise floor level and granularity.

- **Subscriber List:** A set of users can be specified and create a list with them, characterizing parameters such as the service profile, the TCP/IP throughput and so on.

![Figure 3.2: Current Settings Window](image)
CHAPTER 3. PROJECT DEVELOPMENT

Once all the settings are configured, the user can access the next window which shows the different measures that the software allows to do. Some of the simulation includes measures of Signal and Interference Strength, Signal-to-Noise ratio (SNR), Data Rate or the Modulation and Codification Scheme (MCS)\(^1\).

In each simulation a different set of the parameters configured previously, are used to deliver an exhaustive and realistic measure result. The results are presented in form of matrices maps. Once the simulation is executed, in those maps the user can place pointers to see the exact value of the measure in an specific coordinate point. Apart from that, the results are also presented in a ECDF (Empirical Cumulative distribution Function)\(^2\) graphic. The software allows also to export those result as MATLAB figures.

![Signal Strength Simulation](image)

**Figure 3.3: Signal Strength Simulation**

---

\(^1\)The MCS Values can be used in conjunction with the bandwidth channel, modulation, coding rate and other parameters values to provide instantly the available data rate of a wireless hardware.

\(^2\)In statistics, an empirical cumulative distribution function (ECDF) is the distribution function associated with the empirical measure of a sample. Basically the function shows the % of sample values that are smaller or equal to an specific measure value.)
Figure 3.4 shows the structure of the program and the stages that the user can go through with the different functionalities in each of them.

In the functions stage there are some options missing such as Subscriber or Video evaluation, since they are not fully implemented and working or they are just in first stage of development.
3.2 TUWIPA© Settings General Operation and Settings

After taking a look at the main measurement options and functions that the software offers, it is important for the project development to understand the basics of how the already implemented simulations work and how the set parameters are used. The settings values exposed here will be the ones used by default in the simulations. If they are not changed, it will be assumed that the default value is being used.

3.2.1 General Settings

Device Settings

Figure 3.5 shows an example of the GUI parameter settings windows with them default values.

![Device Settings windows](image)

Figure 3.5: Device settings windows

Although some parameters like Tx and Rx Diversity (MIMO) or Spatial Stream are modifiable they are not currently implemented into the program so changing them values will not change the simulations results. Some of the simulations parameters are worth comment:

- The Antenna pattern set \( \text{abs}(\cos(pi/2. \times \cos(theta)))./(\sin(theta)) \) is equivalent to the \( \lambda/2 \) dipole radiation pattern. This pattern is used as TX gain when it comes to simulate the signal strength but it will be explained in a later section.
• The frequency, with the 5GHz as a selectable as well, will basically mark the propagation losses.

• The standard can be chosen between 802.11n and 802.11ac. The standard dictates mainly conversion factor from SNR to Data Rate. At the moment there are no difference between choosing one standard or another.

• The propagation model ITU-R recommendations p.1238-1 and COST-231 Multi-Wall Model is the only selectable and it will be explained later.

• In the device settings box, real devices characteristics can be exported or keep the theoretical values. This parameter will be used as well for the conversion of SNR to data rate.

Interferer settings

The set of parameters and them values for the interference source are almost the same. The length of the Packets can be modified but this parameter is not currently being used in the simulations.

The other parameters has exactly the same default value as the device ones.

Flat and Noise Floor Settings

The flat layout is currently selectable between 6 different models. Each model has different dimensions and walls structures. The default flat model is the number 1 (the layout of this model can be seen in 3.5).

In the same windows the noise floor modification is available with a default value of -80dBm. The noise floor is a value that represents the sum of all the noise sources of the environment and hence it will be the used value to simulate the noise source power in the the SNR or SINR measures.
3.2.2 General operation

The comprehension of the general operation went through mainly the run of simulations and code observation and also the use as information source of two thesis which worked on previous versions of the software and developed some of the features such as the propagation model [24]-[25].

Parameter initialization

All of the parameters of the GUI are created and initialized at the start of the program execution. The parameters are set with the default values and saved on the base workspace in order to allow the access of those variables from any of the GUI windows of the program.

Map Building

The obtained measurements maps the different measures, are created with the same principle and Matlab functions. The Map creation and result depends in almost all the configurable parameters of the program.

Consider the Signal Strength map building case. To explain it briefly; the map is generated through a function that analyzes all the possible points within a specific flat model. The strength on each point is calculated as placing a hypothetical receiver device in relation the transmitter position (in this case the AP) an calculating the strength of signal that this device would receive. Equation 3.1 illustrates how the signal strength is calculated.

\[
\text{signalStrength} = \text{tx}_p + \text{tx}_g + \text{rx}_g - \text{totalLoss}
\]  

(3.1)

Where:

- \(\text{tx}_p\): transmitter power.
- \(\text{tx}_g\): transmitter gain.
- \(\text{rx}_g\): receiver gain.
- \(\text{totalLoss}\): total calculated propagation losses.

On this equation the transmitter gain is obtained from the analysis of the radiation pattern given the polar coordinates of the relative position. The value of this gain can be between 0 and 1.

The receiver gain is the gain of the hypothetical receiver. The total propagation losses are given by the propagation model set. Later on this section it will be explained.
The obtained result, signal strength is a matrix with the size according the flat model dimensions an contains the measured values on each point.

For all measures, the first step is always to calculate the signal strength. For example, if the interference is being analyzed, the process is the same but the input parameters of the function have to be changed for the interference ones. In the case of the SNR calculation, the procedure is the same but taking into account the noise floor value to calculate the ratio.

**Propagation Model**

It’s specially interesting to dig into the ITU-R propagation model for indoor environments used in the program. The model comprehension will help to better understand how the environment parameters are used in order to create the propagation losses [2].

The model considers the main propagation path between transmitter and receiver (direct distance) and is actually formed by combination of ITU-R Recommendation model as a base and the Multi-Wall model, thus the total amount of propagation losses will be calculated using combined equations. This model does not take into account the possible multi path losses.

The ITU-R model calculates the path losses considering the distance between Tx-Rx, the type of urban environment and others factors described in equation (3.3)

\[
L_p = 20 \log(f) + N \log_{10}(d) + P_f(n) - 28 \tag{3.2}
\]

Where

- \( f \) = Frequency of transmission in megahertz.
- \( d \) = Distance in meters
- \( N \) = distance power loss coefficient.
- \( n \) = Number of floors between the transmitter and receiver.
- \( P_f(n) \) = the floor loss penetration factor.

\( N \) and \( P_f(n) \) are modeled according the used frequency band and the environment. Both are empirical obtained results.

See Appendix B.1 for the detailed specific tables of both parameters. The complete tables (different frequency and environments) can be found in [26].
The Multi-Wall model, completes the ITU-model by computing losses generated by the wall penetration. It takes into account the number of penetrated walls and its material during the direct path.

\[ L_w = \sum_{i=1}^{kw} k_{wi} L_{wi} \]  

(3.3)

Where

- \( kw \) = Number of penetrated walls
- \( L_w \) = Attenuation of each wall (depends on the type)

In Appendix B.2, the table of the material list and its attenuation depending on the frequency of operation, can be found.

**SNR to Data Rate conversion**

The software calculates the data rate with different methods. There are mainly two ways of obtain the translation from SNR to Data Rate depending if the device settings are selected as Theoretical maximum (default option) or a Real Device.

The translation usually has an in between stage that consist in computing the MCS.

**Theoretical maximum case**

In this case, the translation is created based on the values provided by the IEEE 802.11 standard tables, that provides a MCS Index according the selected protocol, the channel bandwidth and the SNR level.

Once the SNR is converted to MCS index, the next step is to analyze the index value and convert it into data rate through the MCS table.

Both complete tables are provided in Appendices B.3 and B.4 (SNR to MCS and MCS to data rate correspondingly).

Analyzing the code, the translation Map (as is called in the code) it’s always the same, as the implemented protocol at this moment is only IEEE 801.11n and the bandwidth channel is considerer to be 20 MHz with no option to modify it.
Table 3.1 shows the current used conversion table for this case.

<table>
<thead>
<tr>
<th>SNR (dB)</th>
<th>0</th>
<th>11</th>
<th>14</th>
<th>16</th>
<th>19</th>
<th>23</th>
<th>27</th>
<th>28</th>
<th>29</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate (Mbps)</td>
<td>0</td>
<td>14.4</td>
<td>28.9</td>
<td>43.3</td>
<td>57.8</td>
<td>86.7</td>
<td>115.6</td>
<td>130</td>
<td>144.4</td>
</tr>
</tbody>
</table>

Table 3.1: SNR to Data rate conversion table

**Real device case**

In the case of selecting the real device option, the software uses files (already included along with the code) that contains translation tables based on real measurements of different AP models.

Figure 3.7 shows an example of a data rate table file for an imported device.

Figure 3.7: AP FB6840 data rate table
CHAPTER 3. PROJECT DEVELOPMENT

3.3 Developed Analytical Models

3.3.1 Microwave Oven signal modeling

Develop the analytical model for the MWO is required to understand the interference process and aims to characterize the MWO in three mains aspects: power, frequency and time. To be able to derive this analytical model, some experimental emulations are required as a previous step.

The model development and understanding will be the key for the later implementation of the MWO into the software [17]-[18].

Experimental emulation

Different experimental emulations have been carried out with results that allows to make a first approach to the MWO signal characterization. As a reminder, the referenced papers includes emulations that had been performed with different models of transformer type Microwaves.

The MWO is a periodic interference source. It contains a single magnetron that turns ON-OFF periodically with a 60 Hz frequency to synchronize with the AC supply line changes. Therefore, the signal is repeated with a period 16.67 ms.

In the ON mode the signal of the MWO is pretty similar to a Frequency Modulated signal (sinusoidal waveform) centered in the operation frequency.

The observed peak-power operation frequency in different tested models is around 2.45 - 2.485 GHz, although it can slightly vary depending on different factors. During the ON cycle the signal can be characterized as a FM waveform with varying power levels (amplitude variance). Hence, a AM-FM waveform model will work to characterize this part.

The emulations shows as well the transients\(^3\) signals in the beginning and end of the ON cycle.

The transient signals together with the frequency sweeping part form the total radiated MWO signal.

The spectrogram obtained during the emulations becomes specially useful for the analytical model derivation since it shows the MWO signal sweeping part as a combination of an AM-FM waveform and the transients of the signal.

\(^3\)A transient event is a short-lived burst of energy in a system caused by a sudden change of state.
3.3. DEVELOPED ANALYTICAL MODELS

As it has been said previously the MWO signal has a period of 16.67 ms but the frequency sweeping part presents a duration of 6 ms approximately, that means that the duty cycle\textsuperscript{4} of the signal will be less than 50%.

The observed Effective Isotropic Radiated Power (EIRP)\textsuperscript{5} microwave ranges values from 16 dBm to 33 dBm of maximum and average level of 5 dBm. The radiation pattern of this MWO types is approximated as an isotropic one, although usually the strongest leakage is detected in positions in front of the MWO [20].

**Analytical model**

Starting from the previous obtained experimental results an analytical microwave signal can be developed.

The signal can be expressed as the sum of two transient and a AM-FM signal during the ON cycle and zero during the OFF.

The AM-FM signal $s(t)$ consist in a sinusoidal modulated FM signal with an amplitude sinusoidally-shaped $x(t)$. The carrier frequency of this signal varies in each cycle but normally is around 2.4 GHz with 50±50 MHz of deviation. The two transient signals are modeled as two sinc pulses modulated at two different frequencies. The approximate duration of each transient is about 1 ms.

The final signal $v(t)$ is expressed as the sum of the ON cycle signals $c(t)$ repeated every period time $T = 1/f_{ac}$ where $f_{ac} = 60\, \text{Hz}$.

\[
v(t) = \sum_{-\infty}^{\infty} c(t - nT)
\]

\textsuperscript{4}The Duty cycle of a signal is the fraction of time in which it is active.

\textsuperscript{5}The EIRP corresponds to a theoretical power level that is equivalent to a power level transmitted by an isotropic transmitter. This value is calculated taking into account the transmitted power, the direction of maximum gain of the antenna, and the circuit losses.
CHAPTER 3. PROJECT DEVELOPMENT

The next figure shows a qualitative representation of described signal in a single ON cycle.

![Figure 3.9: MWO signal analytical model in time domain](image)

From here on, the developing of this model gets quite complex and when it comes to implementation dig more into this model is no longer necessary.

We can summarize the key aspects of the MWO that will be needed for the implementation into a short list:

- It is a non-continuous interference source that is repeated periodically with frequency of 60 KHz.
- During the ON cycle the signal is formed by two transients and a frequency sweeping part characterized as a AM-FM Waveform. The duration of those cycles is around 6 ms.
- The higher power pikes are concentrated around 2.45 GHz.
- The radiation pattern can be approximated as an Isotropic one with an average EIRP of 5dBm.
3.3. DEVELOPED ANALYTICAL MODELS

3.3.2 High Density WLANs

The analytical model proposed will be a simple but accurate approach for both inter-WLANs interaction and the collisions impact on the network performance in a High Density environment as it was described in previous Chapters [22].

To characterize the interaction between WLANs a continuous time Markov Chain (CTMC) is proposed and developed. Basically this model provides equations to obtain:

1. The fraction of time that the channel is occupied by each different WLAN, taking into account the probability of each WLAN to become active for data transmission.

2. The achievable throughput (TH) of each WLAN (with particulate interest on our WLAN) subject to the probability distribution of the system

Before developing the CTMC modeling it important to take a short look to a few probability theory basic concepts and the Markov Chain.

Stochastic processes and Markov chain basis

In probability theory a stochastic process is a mathematical concept that makes reference to a set of random variables and provides the description of the evolution of a specific event through time [27].

A Markov process is a stochastic process that satisfies the Markov property, called also Memoryless property. The Memoryless property implies that the probability distribution of the future random variable values depends only on the present values and not of the sequence of event that precedes it.

\[ \{X(t), t \in T\} \]

The stochastic processes can be classified analyzing two aspects, the index set \( T \) and the State-space of \( X(t) \) [27].

Interpreting the time, if the index \( T \) of the stochastic process \( X(t) \) has a finite or countable number of elements, the process is called to be discrete in time.

\[ \{X_n, n = 0, 1, 2...\} \]
Otherwise if the index is an interval on the real line, the process is a continuous-time process

\[ \{X(t), t \geq 0\} \]

The state-space of a stochastic process is the set of possible values that the variable can take.

Following the index set classification, if space-state can be observed in integers or natural indexes, then the stochastic process is called process with continuous space-state. If the state-space is the real line then the process is referred as process with continuous space-state.

Combining both aspect results in a total of 4 type of stochastic processes:

- discrete-time process with discrete state space
- discrete-time process with continuous state space
- continuous-time process with discrete state space
- continuous-time process with continuous state space

From the previous definitions derives the Markov Chain concept. A Markov Chain is type of Markov process that, satisfies the Markov property and has a discrete state space. The index set can be either discrete or continuous in time, depending the case.

The proper analysis of the Markov Chain will be needed to calculate the probability that our system remains in each of the states and the later achievable throughput. The analysis of this system goes through the Markov equations development.

The example provided in [28] shows a pretty simple approach to this analysis and it will be useful to take a look into, for the basic Markov chain properties and the comprehension of further analytical model developed.

Figure 3.10 shows the Markov Chain of a certain system. In here, the memoryless property can be clearly understand. The proposed system is finite, positive irreducible and periodic.

Irreducible means that all the system states can be reached between them. When the system states are able to communicate with each other it is said that the states belong to the same class, so irreducibility implies that the system is formed by single class states.

By definition a finite and irreducible Markov chain is also recurrent. The recurrence implies
that the system is able to enter the same state in which it has started. Recurrence can be either positive or null. If the number of states is finite, as our example, then the system is positive-recurrent. Otherwise (infinite states) the system is null-recurrent [29].

Lastly, the periodicity of a state makes reference to the number of steps that takes between accessing one and state and returning to the same one. If the number of steps is multiple of a certain integer, then the system is periodic, in other case, the system would be aperiodic. Regarding our example system, the number of steps that would take to return to an state would be multiples of 2, so it can be said that the system is periodic with a period of 2.

The main objective here will be to obtain the long-run fraction of time in which the system remain denoted as $\pi_s$ where $s$ represents a specific system state. Due to the properties of this Markov Chain, the time-reversibility equations can be used. That means that for example when analyzing two states $i$ and $j$ the rates into state $i$ coming from $j$ has to be equal to the rate out of $i$ going to $j$. We can formally state that as:

$$\pi_s q_{ij} = \pi_j q_{ji} \quad (3.4)$$

Departing from this equations, the Markov system equations can be built:

$$\begin{cases}
\lambda \pi_0 = \mu \pi_1 \\
\frac{\lambda}{2} \pi_1 = \mu \pi_2 \\
\frac{\lambda}{3} \pi_2 = 2 \mu \pi_3
\end{cases}$$

In addition, the normalizing condition will be needed, the sum of the probabilities of being in each state has to be 1; $\sum \pi_s = 1$

By substitution method and applying the condition the probability of each state can be obtained: $\pi_0 = \frac{12}{p^3 + 6p^2 + 12p + 12}$, $\pi_1 = \frac{12p}{p^3 + 6p^2 + 12p + 12}$, ... Where $p = \frac{\lambda}{\mu}$. 

33
Inter-WLANs interaction modeling

As it has been said, the CTMC model is able to describe the interactions between neighboring WLANS and to compute to long-term fraction of time the system remains at each state upon the assumption of exponentially distributed back off\cite{22}-\cite{23}. Although it constitutes an accurate model, its performance precision decreases as collisions\footnote{Collisions probability is defined in CSMA/CA IEEE 802.11 networks as the probability that the back off timer or two of more nodes expires simultaneously} became significant, which makes the model performance in IEEE 802.11 WLANS that uses the slotted back off counter, not precise in the case of large number of contenders or small contention windows. The main reason for that is that the model needs to assume a continuous back off timers. Such limitations makes the model in need of a revision for their use in next-generation HDW.

The first step of the model developing is to identify the environment of HDW. Consider that the scenario consists in multiple WLANS deployed in a certain area. WLAN $i$ consist in $N_i$ nodes, the AP and $N_i - 1$ associated Stations. The transmission of any WLAN is stopped when the channel is sensed busy and continuous when the channel is detected free again. The expected duration of the back off is $\frac{1}{\lambda_i}$. At every transmission WLAN $i$ sends $L$ bits and the channel is occupied for an expected duration of $E[T] = \frac{1}{\mu}$.

The CTMC defined is a WLAN-centric model in which the states are defined as the possible subset of WLANS that can transmit simultaneously without interference or in other words, when they are not overlapped.

With $\Omega$ defined as the collection of all the feasible system states, the transition rates between two system states $s$ and $s' \in \Omega$ are defined as:

$$q(s', s) = \begin{cases} 
\lambda_i & \text{if } s = s' \cup \{i\} \in \Omega \\
\mu & \text{if } s = s' \setminus \{i\} \\
0 & \text{otherwise.}
\end{cases} \quad (3.5)$$

Defining $S_t \in \Omega$ as the system state at time $t$, $(S_t)_{t \geq 0}$ is a continuous-time Markov process. The process is aperiodic, irreducible and, since the state space $\Omega$ is finite, positive recurrent.
Therefore the process can be analyzed with the previous developed Markov equations where the value for the probability distribution $\pi_s$ can be found. Particularizing $s$ with the system states, the fraction of time that each states is active can be computed.

Due the Markov Chain properties the time-reversibility equations can be applied (3.4). Once the transition rates are clear, the detailed balance relationship for two adjacent system states $s$ and $s \cup \{i\}$ can be written as:

$$\frac{\pi_{s \cup \{i\}}}{\pi_s} = \frac{\lambda_i}{\mu} = \theta_i$$

The adjacent states relation, implies that for any $s \epsilon \Omega$

$$\pi_s = \pi_{\phi} \prod_{i \epsilon s} \theta_i$$

Where $\phi$ denotes the system state where none of the WLANs is active. Applying the normalizing condition the value for $\pi_{\phi}$ can be found:

$$\pi_{\phi} = \frac{1}{\sum_{z \epsilon \Omega} \prod_{j \epsilon z} \theta_j}$$

Putting together both equations the final expression of $\pi_s$ can be written as:

$$\pi_s = \frac{\prod_{i \epsilon s} \theta_i}{\sum_{z \epsilon \Omega} \prod_{j \epsilon z} \theta_j}, s \epsilon \Omega$$

Once the distribution of probability is found, the next step would be the computation of the achievable Throughput of each WLAN. The throughput of WLAN $i$ is given by

$$x_i = \left( \sum_{s \epsilon \Omega: i \epsilon s} \pi_s (1 - \gamma_{i|s' \rightarrow s}) \right) \mu L$$

(3.6)

Where $1 - \gamma_{i|s' \rightarrow s}$ is the probability that the data transmitted by WLAN $i$ in state $s$ (moving from state $s'$, in which WLAN $i$ is not active) is successfully received. We consider there are not transmission errors (collisions only depending on the back off) and all packets are lost during a collision.

Finding the value of $\gamma_{i|s' \rightarrow s}$ is not trivial. The previous step is to find the achievable through-
CHAPTER 3. PROJECT DEVELOPMENT

put of WLAN i when its contending in \( \kappa_{i|s'} \). This is given by the following equation

\[
y_{i|s'} = \frac{d_{i|s'} L}{a_{i|s'} T_e + b_{i|s'} E[T] + c_{i|s'} E[T_c]} \quad (3.7)
\]

Where

- \( a_{i|s'} = (1 - \tau_{i|s'})^{k_{i|s'} + N_i} \) is the probability that back-off slot remains empty.
- \( b_{i|s'} = (k_{i|s'} + N_i)(1 - \tau_{i|s'})^{k_{i|s'} + N_i - 1} \) is the probability that slot results in successful transmission.
- \( c_{i|s'} = 1 - a_{i|s'} - b_{i|s'} \) is the probability that slot results in collision.
- \( d_{i|s'} = N_i \tau_{i|s'}(1 - \tau_{i|s'})^{k_{i|s'} + N_i - 1} \) is the probability that a slot results in successful transition from WLAN i.
- \( T_e = \) Duration of an empty slot.
- \( E[T_c] = \) Duration of a collision.

For that, the computation of \( \tau_{i|s'} \) (probability of transmitting in a given slot) is needed. To obtain it, the next equation system must be solved by fixed-point method.

\[
\begin{cases}
E[B_{i|s'}] = 1 - p_{i|s'} - p_{i|s'} (2p_{i|s'})^m \frac{CW_{\text{max}}}{CW_{\text{min}}} - \frac{1}{2} \\
p_{i|s'} = 1 - (1 - \tau_{i|s'})^{k_{i|s'} + N_i - 1} \\
\tau_{i|s'} = \frac{1}{E[B_{i|s'}] + 1}
\end{cases}
\]

Where

- \( p_{i|s'} = \) collision probability.
- \( m = \log_2(\frac{CW_{\text{max}}}{CW_{\text{min}}}) \) relation between maximum and minimum contention windows.

After compute both variables we get to the final equation to find \( \gamma_{i|s'\rightarrow s} \)

\[
\gamma_{i|s'\rightarrow s} = 1 - \frac{y_{i|s'}}{\mu L \left( \frac{\theta_1}{\theta_1 + \sum_{j\in \kappa_{i|s'}} \theta_j} \right)} \quad (3.8)
\]

Where \( \theta_i = \frac{\lambda_i}{\mu} \) and \( \lambda_i = N_i \frac{2}{CW_{\text{min}} - 1} \frac{1}{T_e} \)

As it can be seen, the analytical model is a simple approach for the inter-WLANS characterization, although it gets a bit more complex when it comes to analyze the probability of collision and the successive derived equation (3.7)-(3.8).

Before getting to the implementation, it can be a good idea to propose simple example and apply the recently developed model.
Example

Consider a scenario in which there are three WLANs, all of them with overlapping coverage-ranges. To simplify, assume that all WLANs have the same number of nodes $N$ and share same value for $\lambda$ and $\mu$. Such assumption will be made as well for the later simulations.

Regarding the state definition in this case, our state space is $\Omega = \phi, A, B, C$. Since the three WLANs overlapped, they cannot transmit without interference hence there are no shared system states.

Considering the Equation 3.5 and the states, the Markov Chain can be designed. Figure 3.10 illustrates the scenario and the Markov Chain modeling.

![Markov Modeling of a 3 WLANs system](image)

Once the Markov Chain model is conceived the distribution probability can be computed by developing the Markov Chain equations.

$$
\begin{align*}
\lambda_A \pi_\phi &= \mu \pi_A \\
\lambda_B \pi_\phi &= \mu \pi_B \\
\lambda_C \pi_\phi &= \mu \pi_C
\end{align*}
$$
Applying the normalizing condition \( \sum_{s \in \Omega} \pi_s = 1 \), and the assumption \( \lambda_A = \lambda_B = \lambda_C = \lambda \) the value for \( \pi_\phi \) can be found.

\[
\pi_\phi = \frac{1}{1 + 3\theta}
\]

Where \( \theta = \frac{\lambda}{\mu} \).

This expression can be found also by applying directly the general equation for \( \pi_\phi \) before stated.

Now that the value of the distribution for the state \( \phi \) is computed, the distribution for the others system states can also be computed.

\[
\pi_A = \pi_B = \pi_C = \frac{\theta}{1 + 3\theta}
\]

Once the distributions are computed and following the analytical model development, the next step is to find the achievable throughput of each WLANs using the equation (3.6). That equation basically consist in the product of the data rate (product of \( \mu \) with \( L \)) with all the distributions that includes the WLAN that is being analyzed. Taking into account the probability of collision depending the state.

For example, in the case of computing the TH for the WLAN A that is going to be the WLAN of interest, in this same scenario, the data rate should be multiplied by the distribution \( \pi_A \) and the probability of collision taking into account the state from where it comes (\( \phi \)).

\[
x_A = \left( \frac{\theta (1 - \gamma_{A|\phi\rightarrow A})}{1 + 3\theta} \right) \mu L
\]

And in this scenario case together with the assumptions taken, \( x_A = x_B = x_C \) As it can be seen, the scenarios with high number of WLANs imply a extend number of system states (created as well in relation of which WLANs are overlapped or not) and a high computation cost.

Further developing of the example is no needed, since when it comes the Markov analysis, the collision of probability makes everything much more complex and the simulations are going to be run in the simplest cases.
3.4 Scenarios implementation

In this section, the process on how the scenarios had been implemented into the software, departing from the mathematical models previously exposed and the already existing code, will be detailed.

For the successful implementation of those scenarios, the comprehension of the basic operation of the program and learn the MATLAB guide basis [30] were key factors.

3.4.1 Microwave Oven Scenario

The MWO scenario had been implemented having in mind the next basic aspects:

- Non-continuous interference source with 16.67 ms of period and 6ms of duration in the ON cycle
- 2.4 GHz Working Frequency Band
- Isotropic Radiation pattern with 5dBm average EIRP

The first step for the MWO implementation was make the Non-continuous type interference selectable in the Interference Settings windows.

When changing to this new created source, the Transmitter interference power is changed to 5dBm, the radiation pattern to an isotropic one (1 as value will do) and the selectable frequency to the 2.4GHz Band. If the current set flat model is the default one, the position of the interference source changes automatically to x=11 and y=5.

In addition a new created variable `scenario` changes its value from the default scenario (Normal interference) to this one.

Once those simple parameters changes were done the next step was to characterize the signal and subject the interference measures to the non continuity of the source.

For that purpose a new function was created to calculate the Air time\(^7\) and later, model the interference measures according to it. The function distinguishes the current scenario settings and it will be used as well for the new added scenarios. In this scenario case it creates the occupation in terms of the transients times, swept time and ON-OFF period time. Those parameters are not currently modifiable through the GUI but later simulations will be performed changing the values in the same function.

\(^7\)The channel Air Time is defined as the percentage of time that an specific interference source is active independently of the type of interference source (Non-data or data transmitters).
At this point, the non-continuous property was already characterized but the measures were not taking into account that. For that purpose two new Windows were created. The first one was the Data Rate with interference. The previous Data Rate window was only taking into account the transmitter parameters. In this new case, the SINR is computed and translated to Data Rate instead of using the SNR.

The other one is the Air Time window. This window uses the \textit{function Air Time calculation} to obtain the percentage of occupation in the channel and represent it graphically. For both normal and MWO interference source, the representation was created using train of pulses with different bandwidth on each case. For more details of the pulse train creation see Appendix D.

Aside from that, the window calculates and represents two new maps. The first one is the Average Data Rate Map that result in combining both the data rate and data rate with interference maps in relation the air time and the second one the decrease of the data rate due to the impact of the interference (subtracts average data rate with the data rate without interference).

By that moment, the obtained results for the average and decrease data rate maps, were not coherent. For example, in the data rate decrease map, negatives rates were detected (it is not possible to increase the data rate with the interference effect). The mistake was detected at the SINR computation. A new calculation method was implemented and the results were this time correct. For the detailed new method see D.

With those new features the MWO scenario implementation was considered concluded.
3.4. SCENARIOS IMPLEMENTATION

3.4.2 Neighboring Interferer Hotspots Scenario

This scenario has been by far the most difficult practical part to develop due to the complexity when it comes to the comprehension of the analytical model and its integration into the software.

As in the MWO interference the first step was to include this source as a selectable in the Interference Settings Window. The new source name is "Neighbor Hotspots (Markov Modeled Interference)". When the user selects that source, the variable scenario changes according to it. In the window the new interference source 'Number of interference Hotspots' is made visible. This setting with a default value of 1 allows, to the user to select the number of neighboring WLANs that will be included in the environment from 1 to 8, and saves the value to the variable interferer neighbors. This maximum value is given by another variable that by default is set with 8.

Once the number of interferer WLANs was made a selectable parameter, the next step was to enable the position settings for each of them.
For that purpose a new array variable was created. The variable Neighbor pos list contains the x-y coordinates for each neighbor as a matrix. That list is filled with the inputs of position that the user introduces. It takes into account the selected number of neighbor and the specific neighbor the user has selected.
It’s important to state that each neighbor shares same parameters (Tx power, radiation pattern, etc.) with the others, except the position of course.

The next step, was to be able to visualize properly the flat layout with the plotted selected neighbors.
The neighbors are plotted in a for loop every time the user changes one of the positions. The loop iterates the same number of times as the selected number of neighbors and in each iteration the position list is updated, checking which interferer is selected, and the position is plotted along a text indicator and a specific shape and color marker. The shape and colors are obtained from a new variable Color array initialized at the start of the program.
Lastly, a new flat model had to be created with the drawing tool, in order to simulate a neighbor environment. This new flat model is the number 7, has dimensions of 45x45 and is formed by 9 squares of exact size and designed with concrete material.
This new model, is automatically set when the Markov interference source is selected in the menu. In addition, the device (AP) is set in the middle of the layout analyzing the neighborhood limits, considering this way the center square as the flat of interest.
CHAPTER 3. PROJECT DEVELOPMENT

Figure 3.12 shows a graphic example of the multiple neighbors plotting with the new flat model

![Diagram of interference position settings and grid with multiple neighbors plotted.]

Figure 3.12: Flat model 7 with multiple interferer neighbors

The saving and reset of settings process on that window was made following the previous principle. While the user is in the window, the new parameters are saved in temporal variables. Once the user saves the current settings, those temporal variables values are translated to the variables used in simulation (generally named as current variables). When the user reset the settings the default value is set for all of the temporal variables and saving implies overwriting the current variables with the temporal.

Once the multiple interferer settings were implemented the next step was to include them in the measurements in which the interference source takes part (Interference Strength, SNIR and so on).
In the first place, as the most basic measurement, that feature was implemented in the interferer strength window.
In there, each interferer is analyzed separately, obtaining its position and building its own
signal strength Map. The maps are created in a for loop that iterates same number as the number of neighbors obtained through the variable `interferer_neighbors`. In each loop a map is generated and properly saved with its own name.

Once all the maps are calculated, the next step is to combine all of them in a final map. To combine the maps, since they are created in logarithmic scale it is necessary to convert them in lineal scale. For that another for loop was created in which each map is converted into linear and is summed to the total map. After the for loop the final map containing all the summed interference maps, is converted into logarithmic scale again.

Last step was to plot the positions and names of the neighbors following the same principle as the Interferer Settings window.

Figure 3.13 shows an example of interference strength simulation with two neighbors.

![Interference Strength Simulation](image)

Figure 3.13: Interference strength simulation with 2 interferer neighbors

The same feature has been implemented in the interference-related measures such as SNIR and Data Rate with interference allowing the user to perform those measures with multiple sources as well.

At this point the next step to take was to implement the Markov modeling itself. A new window called Interferer Hotspots Markov Analysis was designed. The idea was to show the flat layout with all the interferer neighbors, together with its Markov chain model and both distribution and throughput results.
CHAPTER 3. PROJECT DEVELOPMENT

To calculate and display the right results in every case the software had to receive two inputs, the number of neighboring WLANs and which are overlapped or not. The first one was already know with the `interferer_neighbors` variable value. For the second one, the `function OverlappedWlans` was created. The first idea was to assume in the simulations that each WLAN overlaps with all the immediate neighbors, so for example in the flat model 7, the WLAN of interest (called from now on WLAN A) would overlap with all of the interferer WLANs since it is in the middle.

With this assumption in mind, the coverage ranges of each WLAN were created as circles with a certain radius. There is an specific value for the radius of WLAN A and another one for all of the rest WLANs and both are initialized at the start of the program.

With this coverage areas design, calculating the overlapping was a mere task of geometrical analysis. The function calculates which WLANs are overlap or not, using as input the number of interferer neighbors and the position and radius of all the WLANs (including the transmitting one). The output, is a matrix that contains 0 and 1 according if the WLANs are overlapped or not with the rows and columns representing the ordered WLANs. It calculates the matrix up to 8 interferer neighbors as it was the maximum value assumed.

For the detailed function code see Appendix D.

After that, `function Markov Chain Analysis` was created in order to perform the Markov Chain analysis. This function has as input `interferer_neighbors` and the matrix `overlapped wlans`. By reading both inputs the function creates the system states, and calculates the distribution of probability for each one. The distributions are calculated according the previously defined Markov equations. It also calculates the achievable TH by WLAN A as the WLAN of interest.

The calculations are implemented in all the cases possible cases up to 2 neighbors. The simplest case has been assumed for the TH computation (negligible collision probability).

Both functions are called in Interferer Hotspots Markov Analysis. In that window, the results are analyzed and properly displayed. The flat layout is displayed together with all the WLANs and its coverage range created as circumferences. For the detailed coverage range creation see Appendix D. After that, depending on the case the Markov chain modeling is displayed as an image to illustrate the system states. The images displaying distinguishes every case up to 3 neighbors and all of its combinations. With 4 neighbors the images are not created yet.
3.4. SCENARIOS IMPLEMENTATION

The Markov chain graphics were created with an external software called yEd Graph Editor. All the images are contained in the new folder Markov Images along with the code folder.

Figure 3.14 shows the Markov analysis in the case of 3 interferer neighbors, after running a simulation.

As it can be seen the distribution and TH calculation numerical results are empty since they are still not implemented.

Both images and Markov analysis results were not implemented for more than 3 neighbors because of its implementation complexity (the number of states and the possible combination increases really fast).

To try to automatize all the calculations, some other features were included in the Markov Chain analysis as a base for a hypothetically future implementation. For example, through combinatorics in the same function Markov Chain Analysis the number of possible states up to 8 neighbors. It also finds how many non-overlapping WLANs are. The idea is that with these two things; calculate, automatically the exact number of states in relation the overlapped WLANs. For more details see Appendix D.

The last step was to translate the obtained results in the analysis into the Air Time window and other measures.
CHAPTER 3. PROJECT DEVELOPMENT

The Air Time window and his associated function Air Time calculation had to be modified in order to integrate the new Markov calculation and results. A new box was created to show the % channel usage. In there, the % that each state occupies the channel is showed. It is identified as well, if the state corresponds to a single active or multiple active WLANs (shared channel).

The % of time the channel is busy is calculated summing all the distributions except the state $\phi$ (no WLANs active). After that, the channel airtime is properly represented with different colors depending the state (indicate with legend). To represent the occupying time in the Air Time graphic, patches (squares) are built with its parameters (position, size and color) totally automatized depending the number of states and its distribution (different square coordinates each time).

The related measures such as Interference Strength and SINR are performed taking into account the % of time that each WLAN is active, and hence condition the later Data Rate degradation.

In each Data Rate calculation, the obtained achievable TH is translated to the translation Map and set as the maximum value of the TH, following the same ratio of degradation. Creating this way a new Translation Map for the Markov case scenario.

For detailed code of the new translation Map building, patches, coloring and more features details see Appendix D.

After that the Markov modeled interference source implementation was considered successfully concluded.

3.5 TUWIPA© Version 4.5 other new features

In this section other new features that have been implemented in the software will be listed. Some of the new features includes, Quality of Service (QoS) new measurement, null interference source or exceptions that improves the performance of the software.

Appendix C includes a more detailed description of these extra new features for TUWIPA©.
4 | Results

In this chapter the obtained results in simulations will be exposed and analyzed. In each scenario a set of cases that include different settings of the interference sources, will be tested with the aim of check the software new features proper performance and the coherence of the results.

4.1 Micro Wave Oven scenario

Settings

Frequency Band = 2.4 GHz (2.45 GHz used value in simulations)
Tx Interference Power = 5 dBm
ON-OFF period: $T = 16.67ms$ (Fixed value)
Transient signal duration (single): $T_t$
Frequency Sweeping signal duration: $F_t$
ON cycle signal duration: $T_o = (2 \times T_t) + F_t$ (Average duration 6ms)
Duty Cycle: $D_t = \frac{T}{T_o}$ (Has to be less than 50%)

Each case considers slightly different values for the transient and frequency sweeping signal durations, always respecting the condition of the Duty cycle

Case 1

$T_t = 1ms, F_t = 4ms, T_o = 6ms, D_t = 35.9\%$

Figures 4.1 and 4.2 shows the data rate computation in both cases with and without interference (not taking into account the non-continuity).
CHAPTER 4. RESULTS

The degradation of data rate is quite evident, comparing both markers we can see that decrease at similar positions is around 60 Mbps.

Next step is to obtain the channel % occupation and see if the results matches departing from these obtained maps.
As it can be seen in Figure 4.3 the air time is properly represented (two periods). In addition the channel occupation matches with the theoretical duty cycle.

In figure 4.4 the final results can be observed. The average data rate maps shows coherent values taking into account both maps in Figures 4.1 and 4.2. In the previous analyzed point now the data rate is around 90 Mbps.

The decrease data rate map also seems correct since on the one hand, the areas next to the transmitter and far from the interference the decreasing is really low or even zero, and on the other hand, the higher data rate decreases are in areas in which the interferer signal is still strong and the transmitter starts to degrade.

With the obtained values, it can be confirmed that all the calculations and the non-continuity characteristic are properly implemented.
CHAPTER 4.  RESULTS

Case 2

$T_i = 1.5ms$, $F_t = 4.5ms$, $T_o = 7.5ms$, $D_t = 45\%$

In this case the duty cycle is a little bit higher. This should be reflected on the channel occupation and on both average and decrease data rate maps.

![Channel Air Time](image1)

**Figure 4.5: Channel Air Time case 2**

![Average and decrease data rate maps](image2)

**Figure 4.6: Average and decrease data rate maps case 2**

The Channel air time shows the increase of the interference ON cycle duration and matches the theoretical value of the duty cycle. In Figure 4.6 although at first sight the maps do not look different, the degradation of data rate is noticeable in the center areas where the interference has still pretty strength.
4.2 Neighboring Interferer Hotspots Scenario

Settings

The values of the settings are provided in [22]. All the simulation cases uses the same settings.

Channel Bandwidth: BW=40MHz
Modulation: 64-QAM
Coding rate: 3/4
Packet Size: L= 768 Kbits
Expected Duration of successful TX (channel occupation): E[T]=1/µ= 6.63 ms
Expected Duration of a collision: E[Tc]=E[T]=6.63ms (It is assumed that the RTS/CTS mechanism is not used)
Duration of an empty slots: Te=9µs Value obtained from [23].
Number of Nodes WLAN i: Ni=2
Number of Stations: STA=Ni-1=1
Minimum backoff contention window CWmin= 32
Relation CWmax and CWmin: m=5
Expected active back-off WLAN i: \( \frac{1}{\lambda_i} \)
Where \( \lambda_i = Ni \frac{2}{CW_{min}-1} \frac{1}{Te} = 7.16\times10^3 s^{-1} \)
Detailed balance relationship for two adjacent system states: \( \frac{\pi_{s\cup\{i\}}}{\pi_s} = \frac{\lambda_i}{\mu} = \theta_i = \theta \)
Assumed negligible collision probability: \( \gamma_{i|s'\rightarrow s} = 0 \) Maximum data rate= 113.12 Mbps (In the case WLAN A is active 100% of the time).

Case 1

\( \Omega = \phi, A, B \) with A-B not overlapped.

With the coverage assumption this case should not be take into account but it was considered worth analyzing since it was implemented and it is interesting to see the overlapping effect in the simplest case.

Since WLANs A and B are not overlapped and they not interfere each other, hence it should be a system state in which both WLANs are active.

Figure 4.7 shows the obtained results in this case.
CHAPTER 4. RESULTS

Figure 4.7: Markov analysis with WLANS A and B not overlapped

The overlapping WLANs matrix indicates that A and B are not overlapped with the 0 values. The distribution of probability shows that the system stays the majority of time (around 96%) in the state AB and 2% on each single active WLAN states. Therefore, the achievable TH that by WLAN not much conditioned by the interferer neighbors (4 Mbps of reduction).

Figures 4.8 and 4.9 shows the obtained results from the Markov analysis translated to the Air Time channel and data rate computing.

Figure 4.8: Channel Air Time in Markov case 1

As it can be seen, the channel occupation is 99.95% corresponding to all of the states with active WLANs (in state $\phi$ the channel is considered free). The wlan usage displays all the % of each of the states and indicates correctly if the state is shared or not.

In the data rate map, the previous obtained achievable TH value sets the upper limit and the rate decreases proportionally to the degradation of signal (that is degraded by the WLAN B in the active state). The walls that separates every hypothetical flat, introduces a penetra-
4.2. NEIGHBORING INTERFERER HOTSPOTS SCENARIO

Figure 4.9: Data rate decrease in Markov case 1

ation loss that cancels the signal strength (and hence the data rate) in almost all the locations.

Case $\Omega = \phi, A, B$ with A-B overlapped was omitted from the results since it does not provide any interesting facts in front the next cases.

Case 2

$\Omega = \phi, A, B, C$ with A-B-C overlapped.

Analyzing the results in Figure 4.10, all the values are considered valid. Since the are three different system states that corresponds to single active WLANs and the transition rates are assumed to be the same independently of the case, the distribution of each one is the same. In addition the achieved TH, this time is highly reduced taking into account that WLAN A is transmitting only around $1/3$ of the time.

Case 3

$\Omega = \phi, A, B, C$ with A-B and A-C overlapped but B-c not overlapped.

In this case the results shows in Figure 4.11 as well coherent values. This time, WLANs B and C are not overlapped, hence there is a shared state between them. The system remains there the majority of time. Therefore, in this case the active time of WLAN A is really low resulting in an enormous data rate degradation.
CHAPTER 4. RESULTS

Figure 4.10: Markov analysis with WLANs A, B and C overlapped

Figure 4.11: Markov analysis with WLANs B-C not overlapped
Further Cases

Although it has been said before that the Markov analysis cases that has more than 3 neighbors were not implemented, Figure 4.12 shows that the overlapping calculation works for any number of neighboring WLANs.

Figure 4.12: Markov analysis with 7 neighboring WLANs
5 | Conclusions and future development

During the thesis development, the initially objectives, that were mainly characterize new interference sources and add some new features, have been fulfilled.

The results shows that the implementation of the new characterized interference sources has been successful, with the obtaining of coherent numerical values. That being said, the Markov interference source has been implemented considering the simplest cases, that fact wards off the obtained values from what could be considered hypothetical empirical obtained values from a real cases. Despite this the implemented cases are considered overall satisfactory as a basic approach for those cases and as a base for the complex ones.

TUWIPA© can be improved in a lot of ways, some of the future developments are:

- Implement the Markov Chain as a general case that allows to simulate larger interferer WLANS and all the possible combinations.

- Create more complex flat models, that can include neighborhood models combined with different flat models and characteristics in each neighbor flat.

- Implement the possibility of using different combinations of types of interference sources at the same time.

- Implement parameters such as MIMO, more IEEE standards and so on.

- Coverages ranges should be created departing from a coverage analysis of each WLAN (table used in QoS) instead of using theoretical perfect circles.

- Adjust the devices or interference parameters to another ones more realistic such as implementing specific radiations pattern depending the device or interference source.
Bibliography


Glossary

- WLAN: Wireless Local Area Network
- TUWIPA: Technische Universität Wien Indoor Performance Analyzer
- GUI: Graphic User Interface
- OSI: Open System Interconnection
- ISO: International Organization for Standardization
- ISM: Industrial, Scientific and Medical
- ITU: International Telecommunication Union
- NFC: Near Field Communication
- CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance
- MIMO: Multiple Inputs Multiple Outputs
- MWO: Microwave Oven
- HDW: High Density WLANS
- ECDF: Empirical Cumulative Distribution Function
- SNR: Signal-to-Noise Ratio
- SNIR: Signal-to Noise and Interference Ratio
- QoS: Quality of Service
- MCS: Modulation and Codification Scheme
- CTMC: Continuous Time Markov Chain
Appendices
## A Work Packages

<table>
<thead>
<tr>
<th>Definition of Scenarios</th>
<th>WP ref: 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major constituent: Literature lectures and research</td>
<td>Sheet 1 of 5</td>
</tr>
</tbody>
</table>
| **Short description: Basic Research about the related concepts and definition of the cases** | Planned start date: 13/03/2017  
Planned end date: 15/04/2017  
Start event: 17/03/2017  
End event: 01/05/2017 |

<table>
<thead>
<tr>
<th>Internal task T1: Read about interference related concepts (different types or sources, how they affect the service, etc.) as well as other recommended papers</th>
<th>Deliverables:</th>
<th>Dates:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal task T2: Define a model for emitted power pattern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal task T3: Think and derive the different possible scenarios of interest</td>
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<td></td>
</tr>
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</table>
### Implementation

<table>
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<th>WP ref: 2</th>
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<td></td>
</tr>
<tr>
<td>Planned end date: 1/05/2017</td>
<td></td>
</tr>
</tbody>
</table>

#### Short description:
Implement into the already existing MATLAB tool the new functions and the defined scenarios.

#### Internal task T1:
Take a first look at the MATLAB code provided and get familiar with the code for some new concepts (for example GUI)

#### Internal task T2:
Understand the background of the MATLAB code provided and its functionality

#### Internal task T3:
Implement the code to the already existing program and test the functionality

### Measurements

<table>
<thead>
<tr>
<th>Major constituent: Simulation</th>
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<td></td>
</tr>
<tr>
<td>Planned end date: 22/05/2017</td>
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</tr>
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</table>

#### Short description:
Once the new functionalities are implemented, simulate the different scenarios and measure the performance in each one.

#### Internal task T1:
Define the measurement setup

#### Internal task T2:
Perform the measurement in each scenario
### APPENDIX A. WORK PACKAGES

#### Results

<table>
<thead>
<tr>
<th>Major constituent: Conclusions</th>
<th>WP ref: 4</th>
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<tr>
<td>Sheet 4 of 5</td>
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| Short description: Analyze the obtained results and conclude the scenario implementation. | Planned start date: 15/05/2017  
Planned end date: 15/06/2017 |
| Start event: 18/09/2017  
End event: 2/10/2017 |           |
| Internal task T1: Obtain results on different scenario cases in order to check different settings. | Deliverables: |
| Internal task T2: Conclude the scenario implementation by analyzing the coherence of the results. | Dates: |
|                              | T2:Final MATLAB code  
T2:20/09-30/09 |           |

#### Dissemination

<table>
<thead>
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<tr>
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<td></td>
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</tbody>
</table>
| Short description: Document all the information sources that have intervened in the thesis as well as the deadlines documents required | Planned start date: 13/03/2017  
Planned end date: 15/07/2017 |
| Start event: 05/03/2017  
End event: 15/10/2017 |           |
| Internal task T1: Project Proposal and Work plan | Deliverables:  
T1:DOC1_PPW.doc  
T2:included in the memory |
| Internal task T2: Bibliography | Dates: 23/03/17 |
| Internal task T3: Critical Review | T3:DOC2_CR.doc  
28/07/17 |
2/10-8/10 |
| Internal task T5: Final Presentation | T5:FinalPresentation.pwt  
15/10 |
B.1 Propagation Model tables

Tables B.1 and B.2 show the variables power loss coefficient and floor penetration factor values for the 2.4 and 5 GHz bands.

<table>
<thead>
<tr>
<th>Frequency Band (GHz)</th>
<th>Residential Area</th>
<th>Office Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>28/30 (apartment/house)</td>
<td>31</td>
</tr>
</tbody>
</table>

Table B.1: Power Loss coefficient $N$

<table>
<thead>
<tr>
<th>Frequency Band (GHz)</th>
<th>Residential Area</th>
<th>Office Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>$4n$</td>
<td>$15+4(n-1)$</td>
</tr>
<tr>
<td>5</td>
<td>$4n$</td>
<td>16</td>
</tr>
</tbody>
</table>

Table B.2: Floor penetration factor $P_f(n)$
B.2 Wall Materials table

<table>
<thead>
<tr>
<th>Material</th>
<th>2.4GHz</th>
<th>5 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin concrete</td>
<td>18 dB</td>
<td>26 dB</td>
</tr>
<tr>
<td>Thick Concrete</td>
<td>30 dB</td>
<td>55 dB</td>
</tr>
<tr>
<td>Brick</td>
<td>10 dB</td>
<td>15 dB</td>
</tr>
<tr>
<td>Thin glass</td>
<td>1-3 dB</td>
<td>0.07 dB</td>
</tr>
<tr>
<td>Thick glass</td>
<td>3-5 dB</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>Wood</td>
<td>10 dB</td>
<td>-</td>
</tr>
</tbody>
</table>

Table B.3: Penetration losses of different materials

B.3 SNR to MCS Conversion Table

Figure B.1: SNR to MCS conversion table for different protocols and channel widths
## B.4 MCS to Data Rate Conversion Table

<table>
<thead>
<tr>
<th>MCS index</th>
<th>Spatial streams</th>
<th>Modulation type</th>
<th>Coding rate</th>
<th>Data rate (Mbit/s)</th>
<th>20 MHz channel</th>
<th>40 MHz channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>BPSK</td>
<td>1/2</td>
<td>6.50</td>
<td>7.20</td>
<td>13.50</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>QPSK</td>
<td>1/2</td>
<td>13.00</td>
<td>14.40</td>
<td>27.00</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>QPSK</td>
<td>3/4</td>
<td>19.50</td>
<td>21.70</td>
<td>40.50</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>16-QAM</td>
<td>1/2</td>
<td>26.00</td>
<td>28.90</td>
<td>54.00</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>16-QAM</td>
<td>3/4</td>
<td>39.00</td>
<td>43.30</td>
<td>81.00</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>64-QAM</td>
<td>2/3</td>
<td>52.00</td>
<td>57.80</td>
<td>108.00</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>64-QAM</td>
<td>3/4</td>
<td>58.50</td>
<td>65.00</td>
<td>121.50</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>64-QAM</td>
<td>5/6</td>
<td>65.00</td>
<td>72.20</td>
<td>135.00</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>BPSK</td>
<td>1/2</td>
<td>13.00</td>
<td>14.40</td>
<td>27.00</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
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<td>1/2</td>
<td>26.00</td>
<td>28.90</td>
<td>54.00</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>QPSK</td>
<td>3/4</td>
<td>39.00</td>
<td>43.30</td>
<td>81.00</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>16-QAM</td>
<td>1/2</td>
<td>52.00</td>
<td>57.80</td>
<td>108.00</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>16-QAM</td>
<td>3/4</td>
<td>78.00</td>
<td>86.70</td>
<td>162.00</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>64-QAM</td>
<td>2/3</td>
<td>104.00</td>
<td>115.60</td>
<td>216.00</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>64-QAM</td>
<td>3/4</td>
<td>117.00</td>
<td>130.00</td>
<td>243.00</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>64-QAM</td>
<td>5/6</td>
<td>130.00</td>
<td>144.40</td>
<td>270.00</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>BPSK</td>
<td>1/2</td>
<td>19.50</td>
<td>21.70</td>
<td>40.50</td>
</tr>
<tr>
<td>17</td>
<td>3</td>
<td>QPSK</td>
<td>1/2</td>
<td>39.00</td>
<td>43.30</td>
<td>81.00</td>
</tr>
<tr>
<td>18</td>
<td>3</td>
<td>QPSK</td>
<td>3/4</td>
<td>58.50</td>
<td>65.00</td>
<td>121.50</td>
</tr>
<tr>
<td>19</td>
<td>3</td>
<td>16-QAM</td>
<td>1/2</td>
<td>78.00</td>
<td>86.70</td>
<td>162.00</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>16-QAM</td>
<td>3/4</td>
<td>117.00</td>
<td>130.00</td>
<td>243.00</td>
</tr>
<tr>
<td>21</td>
<td>3</td>
<td>64-QAM</td>
<td>2/3</td>
<td>156.00</td>
<td>173.30</td>
<td>324.00</td>
</tr>
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<td>22</td>
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<td>3/4</td>
<td>175.50</td>
<td>195.00</td>
<td>364.50</td>
</tr>
<tr>
<td>23</td>
<td>3</td>
<td>64-QAM</td>
<td>5/6</td>
<td>195.00</td>
<td>216.70</td>
<td>405.00</td>
</tr>
<tr>
<td>24</td>
<td>4</td>
<td>BPSK</td>
<td>1/2</td>
<td>26.00</td>
<td>28.80</td>
<td>54.00</td>
</tr>
<tr>
<td>25</td>
<td>4</td>
<td>QPSK</td>
<td>1/2</td>
<td>52.00</td>
<td>57.60</td>
<td>108.00</td>
</tr>
<tr>
<td>26</td>
<td>4</td>
<td>QPSK</td>
<td>3/4</td>
<td>78.00</td>
<td>86.80</td>
<td>162.00</td>
</tr>
<tr>
<td>27</td>
<td>4</td>
<td>16-QAM</td>
<td>1/2</td>
<td>104.00</td>
<td>115.60</td>
<td>216.00</td>
</tr>
<tr>
<td>28</td>
<td>4</td>
<td>16-QAM</td>
<td>3/4</td>
<td>156.00</td>
<td>173.20</td>
<td>324.00</td>
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<td>4</td>
<td>64-QAM</td>
<td>2/3</td>
<td>208.00</td>
<td>231.20</td>
<td>432.00</td>
</tr>
<tr>
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<td>4</td>
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<td>3/4</td>
<td>234.00</td>
<td>260.00</td>
<td>486.00</td>
</tr>
<tr>
<td>31</td>
<td>4</td>
<td>64-QAM</td>
<td>5/6</td>
<td>280.00</td>
<td>288.80</td>
<td>540.00</td>
</tr>
</tbody>
</table>

Figure B.2: MCS to Data Rate conversion table
QoS Window

This window calculates the Quality of Service (QoS) in terms of SINR and SNR. Two maps are plotted corresponding to the QoS with and without interference (using SNR and SINR) to allow the user to see the impact of the interference in the quality of service. It analyzes the relations strength and gives the result in a new scale that gives the quantity of signals bars. It takes into account the scenario and the channel air time function for the QoS with interference. The plot colors were created as a new map that shows more graphically the quality of signal (green for good signal and red for bad signal).

Figure C.1 shows an example of QoS with a normal interference source. Notice that the selected scale of signal quality is shown at the left box of the figure.

Figure C.1: QoS measurement with a normal interference source
Null interference source

When this interference source is selected in the interference settings menu, all the numerical parameters values are set as 0 and the position assigned as NaN (Not-a-Number). In this case, if the user tries to access the interference strength measure, an exception shows not allowing the access to this measure (since there is no interference). In addition, the SINR map gives the same value as the SNR map.

This interference source it was created with the idea use the subscriber function without interference (hypothetic scenario) and perform the proper analysis.

Exceptions and other implementations

During the scenario implementation, few changes were introduced in order to improve the efficiency of the program or avoid unexpected behavior.

For example, the option check-point, it was previously implemented in a way that it was necessary to simulate the two times (one to visualizes and the other to place each check-point). With the new feature, the created map is saved in an external variable and the check point function just takes this variable value and analyzes the point you select.

Other new features includes different exceptions such as, not allowing the user to place interferences or devices outside the flat limits (See Figure C.2) or don’t allow the access to the Markov analysis window in scenarios different than the Markov modeled interference.

![Error message](image)

Figure C.2: Incorrect position value exception
D | Code

This appendix chapters digs into some interesting parts of the developed code during this thesis. The subsections includes, depending the case, different parts of the code or entire function code with the comments included.

**SNIR calculation**

Note: map Interference Strength Lineal contains the total interference strength in lineal scale (independent if there are one or multiple interference sources).

```matlab
mapInterferenceStrengthLineal=10.^(mapInterferenceStrength./10);
noise_floorlineal=10^(noise_floor/10);
db=(10.*log10(mapInterferenceStrengthLineal+noise_floorlineal));
mapSINR=mapSignalStrength-db;
```

**MWO train pulse creation**

```matlab
T=2*current_totaltime;
%Duration 2 MWO periods (totaltime contains one ON-OFF cycle)
t=0:T/1E4:T;
% 60 Hz repetition frequency (ON-OFF cycle)
d=0:1/60:T;
%BW of the pulses (duration of occupation)
BW=current_occtime;
y=pulstran(t,d+BW/2+0.05E-3,’rectpuls’,BW);
axes(handles.axes1)
area(t,y);
```
WLANs position and coverage ranges plotting

%plot the coverage range for the TX and WLAN name

plot(tx_posx,tx_posy,'xk');
h=viscircles(center_list(1,:),tx_coverage_radius,'LineStyle','--','Linewidth',1);
h.Children(1).Color = 'k';
txt1=' Wlan A';
text(tx_posx,tx_posy,txt1,'Color','k');

%Plot flat layout
for i=1:size(X,2)
    hold on
    plot([X(1,i),X(2,i)], [Y(1,i),Y(2,i)] , 'Color',Colors(V(i)),'LineWidth',LineWidths(V(i)));
    hold on
end

%Plot Neighbor position and WLANS coverage
current_interferer_neighbors=evalin('base','interferer_neighbors');
Color_array =evalin('base','Color_array');
Neighbor_letters=[‘B’,'C','D','E','F','G','H','I'];
for i=1:current_interferer_neighbors
    j=i*2;
    current_Neighbor_pos_list=evalin('base','Neighbor_pos_list');
x=current_Neighbor_pos_list(i,1);
y=current_Neighbor_pos_list(i,2);
plot(x,y,strcat(Color_array(j-1),Color_array(j)),'MarkerSize',7.5) ;

%plot the color and shape with color array
txt1=[’ Wlan ’,Neighbor_letters(i)];
text(x,y(txt1,'Color',Color_array(j));
center=[x,y];
h=viscircles(center,coverage_radius,'LineStyle','--','Linewidth',1);

%Coverage ranges
h.Children(1).Color = Color_array(j);
%assign the centers to the list
center_list=evalin('base','center_list');
center_list(i+1,:)=center;
assignin('base','center_list',center_list);

Function Overlapped WLANs

function [overlapped_wlans] =
    function_OverlappingWlans(current_interferer_neighbors,center_list,
    coverage_radius, tx_coverage_radius)

    % This function calculates the overlapping wlans taking into account the
    % coverage radius of each one and their position.

    overlapped_wlans=zeros(current_interferer_neighbors+1,current_interferer_neighbors+1);

    % SIZE: current_interferer neighbors+1 X current_interferer neighbors+1 (includes Tx and
    % Now, let's check if the current WLAN overlaps with the others with the following

    % Two circles intersect if, and only if, the distance between their centers is between
    % the sum and the difference of their radii. Given two circles (x0,y0,R0) and (x1,y1,R1),
    % 0 <= SQRT((x0-x1)^2+(y0-y1)^2) <= (R0+R1)
    % Once we assign all positions, we can compare all of them and fill the
    % matrix with values according to the overlapping

for i=1:(current_interferer_neighbors+1);
    % We go over the list and check the overlap of each one with the others.
    for N=1:current_interferer_neighbors+1

        if N==i;
            overlapped_wlans(N,N)=1;
            % (Diagonal of the Matrix)
        else

72
%Compare and check if they are overlapped

% distance between WLANS
d = sqrt((center_list(N,1)-center_list(i,1))^2+(center_list(N,2)-center_list(i,2))^2);
if N==1 || i==1
    % in this case one of the analyzed WLANs is A so we have to take the TX radius
    R0=tx_coverage_radius;
    R1=coverage_radius;
else
    R0=coverage_radius;
    R1=R0;
end

if d<=(R1+R0) % they overlap
    overlapped_wlans(N,i)=1;
    overlapped_wlans(i,N)=overlapped_wlans(N,i);
else
    overlapped_wlans(N,i)=0;
    overlapped_wlans(i,N)=overlapped_wlans(N,i);
end
end
end

hold on
end
New Translation map

This code shows the creation of a new translation map in the Markov scenario, in which the maximum theoretical data rate value is limited with the achievable one, obtained through the Markov Analysis.

```
%Create a new translation MAP conditioned at the achievableTH
%obtained by Markov.
%If new future features includes different maps
%for protocols its needed a switch-case here

translationMap = [0 0;
11 14.4;
14 28.9;
16 43.3;
19 57.8;
23 86.7;
27 115.6;
28 130;
29 144.4];

%lets calculate the % that each position represents
%with the maxTH as a reference
%(EX: 130/maxTH) maxTH=144.4
%This is just to calculate how much % the Data rate
%is reduced in by the SNR or SNIR degradation
%we can apply it to the new map

percentageTranslationMap=0;
%take the max value of the MAP (144.4 in this case)
maxTH=translationMap(size(translationMap,1),2);
percentageTranslationMap(size(translationMap,1))=1;
for i=2:size(translationMap,1)-1
    percentageTranslationMap(i)=translationMap(i,2)/maxTH;
end

newTranslationMap=zeros(size(translationMap,1),size(translationMap,2));

%Multiplicate the percetage Map (values from 0 to 1) with the achievable TH obt
```
for i=1:size(translationMap,1)
    newTranslationMap(i,1)=translationMap(i,1);
    newTranslationMap(i,2)=achievableTH*percentageTranslationMap(i);
end
translationMap=newTranslationMap;

Number of possible states calculation
This part of code is included inside the function Markov Analysis.

%To calculate the number of possible states we have to use combinations:
%We don’t take all the elements / Order doesn’t matter / Elements doesn’t
%repeat

%C^m_n = m!/n!(m-n)!
%This way we will know the possible combinations taking n elements from m
%(n<=m). So if we have m=4 interferer neighbors. We will have to iterate
%from n=1 to n=4 to know all the possible states in groups of 1, 2, 3 and
%then 4.
m=interferer_neighbors;
possible_states=0;
for n=1:m
    possible_states=possible_states+(factorial(m))/((factorial(n)*factorial(m-n)));
end
possible_states=possible_states+2; %A and 0
Channel Air time representation in Markov case

Note: in this code, wlanUsage contain in the first column the system states and in the second, the distribution of probability of each state calculated by the Markov chain analysis.

```matlab
%Wlanusage distribution extraction and conversion to double
%(for plotting purposes)
distdouble=zeros(size(wlanUsage,1),1);
for i=1:size(wlanUsage,1)
    distdouble(i)= str2double(wlanUsage(i,2))/100;
end

%Wlanusage states extraction and conversion to str (for plotting purposes)
for i=1:size(wlanUsage,1)
    states(i)= (wlanUsage(i,1));
end

%Create coordinates matrix for the plotting (using patch)->the
%number of states is the number of polygons to plot. We are
%using squares so we need to define 4 vertex (4 X and 4 Y for
%each polygon)

X=zeros(4,size(wlanUsage,1));
Y=zeros(4,size(wlanUsage,1));

%Where wlanUsage
%Fill them in loop (each loop fills each polygons coordinates)
for i=1:size(wlanUsage,1)
    Y(:,i)=[0,0,1,1];
    if i==1
        lastx=0;
    else
        lastx=X(2,i-1);
    end
    X(:,i)=[lastx,distdouble(i)+lastx,distdouble(i)+lastx,lastx,lastx];
end
```
axes(handles.axes1)
ylim([0 1.5]);
xlim([0,1]);
title('Channel Air Time')

% Divide the entire spectrum of the Colormap depending the number of states. 
% We will take one color each an integer number n, determined by the division 
% of the spectrum and the n° of states.

k=100;
Colormap=parula(k);

% Create Color Array from colormap Parula (one of the used in SNR)
Color=zeros(size(wlanUsage,1),3);
n=round(k/size(wlanUsage,1));
for i=1:size(wlanUsage,1)
    if i==1
        Color(i,:)= [1,1,1];
        % set white color as first position
        % (will be for the first state 0 so it will appear graphically empty)
    else
        Color(i,:)=Colormap((n*i,:),);
    end
end

for i=1:size(wlanUsage,1)
    x=transpose(X(:,i));
    y=transpose(Y(:,i));
    patch(x,y,Color(i,:)) ;
    hold on
end

% Create a legend that will represent each state and its color
legend(states);
This thesis does not develop any kind of prototype so the object of this budget won’t include components list, prototyping cost or any kind of financial viability.

The software that has been used during the development includes MATLAB and yED Graph Editor. MATLAB has been used under UPC license with no cost, and yED is an open-use software.

Therefore, the total cost of this project will consist in an estimation of workload evaluated at cost of a junior engineer.

The base salary of a junior engineer is taken as 10 € per hour. The workload is estimated as a regular assistance timetable of 5 hours per day (excluding weekends and three weeks of August) from first week of March to first week of October (7 months). Thus, the estimated total dedication in hours is around 625 and the total cost of the project 6250 €.
### F.1 OSI model

<table>
<thead>
<tr>
<th>Layer</th>
<th>Data unit</th>
<th>Function[3]</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Application</td>
<td>Data</td>
<td>High-level APIs, including resource sharing, remote file access, directory services and virtual terminals</td>
<td>Mail, Internet Explorer, Firefox, Google Chrome</td>
</tr>
<tr>
<td>6. Presentation</td>
<td></td>
<td>Translation of data between a networking service and an application; including character encoding, data compression and encryption/decryption</td>
<td>ASCII, EBCDIC, JPEG</td>
</tr>
<tr>
<td>5. Session</td>
<td></td>
<td>Managing communication sessions, i.e. continuous exchange of information in the form of multiple back-and-forth transmissions between two nodes</td>
<td>RPC, PAP, HTTP, FTP, SMTP, Secure Shell</td>
</tr>
<tr>
<td>4. Transport</td>
<td>Segments</td>
<td>Reliable transmission of data segments between points on a network, including segmentation, acknowledgement and multiplexing</td>
<td>TCP, UDP</td>
</tr>
<tr>
<td>3. Network</td>
<td>Packet/Datagram</td>
<td>Structuring and managing a multi-node network, including addressing, routing and traffic control</td>
<td>IPv4, IPv6, IPsec, AppleTalk, ICMP</td>
</tr>
<tr>
<td>2. Data link</td>
<td>Bit/Frame</td>
<td>Reliable transmission of data frames between two nodes connected by a physical layer</td>
<td>PPP, IEEE 802.2, L2TP</td>
</tr>
<tr>
<td>1. Physical</td>
<td>Bit</td>
<td>Transmission and reception of raw bit streams over a physical medium</td>
<td>DSL, USB</td>
</tr>
</tbody>
</table>