Tampere University

Javier Sancho Vázquez

DESIGN AND TESTING OF A TRANSMITTER-CHANNEL-RECEIVER MODEL USING MATLAB 5G TOOLSET.

Science and Engineering
Bachelor’s Thesis
May 2019

ABSTRACT

Javier Sancho Vázquez: Design and Testing of a Transmitter-Channel-Receiver Model
Using Matlab 5G Toolset
Bachelor's Thesis
Tampere University
Science and Engineering
May 2019

Make possible new incoming services and enhance the current ones in order to improve our lives, is the common objective of the engineers. In this way, for improving our communications, we have passed through four generations, each of them with its corresponding enhancements. However, the fourth generation has some limitations that must be solved to keep evolving our communications. Hence, the fifth generation (5G) is forecast to be launched in 2020. This thesis is based on 5G and it has approached three different objectives by using Matlab 5G Toolset. First, the study of 5G waveforms has been carried out. These waveforms are W-OFDM, F-OFDM and CP-OFDM and their spectrums have been compared for different bandwidths and subcarrier spacings. Then, a basic transmitter-channel-receiver chain model has been designed and tested in terms of bit error rate. Finally, a new configuration for improving the reliability of 5G communications, based on 3GPP, has been designed and proved. This configuration includes some variations related with the spatial diversity, the HARQ protocol and the code rate.

The analysis of the results has shown that F-OFDM and W-OFDM achieve better spectral efficiency than CP-OFDM. However, W-OFDM presents more out of band emissions. Thus, F-OFDM with a small value of subcarrier spacing presents better performance than CP-OFDM and W-OFDM in terms of spectral efficiency and out of band emissions. In addition, during the testing of the designed model, CP-OFDM has demonstrated better bit error rate than F-OFDM and W-OFDM. Nevertheless, F-OFDM and CP-OFDM present very similar results. In addition, the new 5G configuration proposed was applied into the transmitter-channel-receiver model commented before for CP-OFDM. The new result was compared with the previous one in terms of bit error rate. Finally, this comparation shows that better bit error rate values are achieved with this new configuration. Thus, the reliability of the communications is improved.

Keywords: 5G, communications, reliability

PREFACE

This Bachelor's Thesis has been written during my stay in Tampere as an exchange student at Tampere University. It represents the final work of my bachelor's degree in Telecommunications Systems Engineering at the Polytechnic University of Madrid.

These years have been a challenging journey, where I had to face several difficulties. Thus, I would like to thank many people for their encouragement. I am so grateful for the advices, guidance, patience, help and feedback provided during the development of this thesis by my supervisors Elena-Simona Lohan and Jukka Talvitie. My gratefulness is also to all the people I have met during my student period, to my family and to my friends, because they have always supported me.

Tampere, 13 May 2019

Javier Sancho Vázquez

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AMPS	Advanced Mobile Phone System
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CDL	Clustered Delay Line
CP	Cyclic Prefix
DL-SCH	Downlink Shared Channel
FDMA	Frequency Division Multiple Access
FR	Frequency Range
GP	Guard Period
IFFT	Inverse Fast Fourier Transform
ICI	Inter Carrier Interference
IoT	Internet of Things
ISI	Inter symbol Interference
LDPC	Low Density Parity Check
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
OOBE	Out Of Band Emissions
PAPR	Peak to Average Power Ratio
PDSCH	Physical Downlink Shared Channel
RX	Receiver
SCS	Subcarrier Spacing
SNR	Signal-to-Noise Ratios
TDL	Tapped Delay Line
TDMA	Time Division Multiple Access
TX	Transmitter
UFMC	Universal Filtered Multi-Carrier
URLLC	Ultra-Reliable Low-Latency Communications

N_{RB}	Number of resource blocks
L_{CP}	Length of the cyclic prefix
L_{Ext}	Windowing extension
$g[n]$	Windowing function

1. INTRODUCTION

This chapter is a first approximation to the content of the thesis. This introduction is divided into three sub-chapters and it informs about the background and the three different objectives of the thesis. Finally, the thesis structure is presented.

1.1 Background

In order to keep improving our cellular networks and systems, we have passed through many generations. Each of them has its corresponding enhancements for making possible new services and for meeting new requirements. This transition started forty years ago and since then, cellular communications have experienced several and dramatic upgrades during five generations.

The first generation (1G) was born in the 80's and it was characterized by analogue voice transmissions. It used frequency division multiple access (FDMA), frequency modulation (FM), and its frequency band was around 800 and 900 MHz. In addition, it was based on advance mobile phone service (AMPS) and the data rate was 2 kbps. However, the second generation (2G) provided digital signals. Due the fact that the number of users had increased, new multiple access techniques were used, apart form FDMA: time division multiple access (TDMA) and code division multiple access (CDMA). The principal objective of the third generation (3G) was to improve the data rate to 2 Mbps. After that, the fourth generation (4G) arrived. 4G provides all-IP support, low latency (100 ms) and data rate from 100 Mbps to 1 Gbps depending on the mobility of the device. Finally, the fifth generation (5G) is coming, and it is forecast to be launched the following year, in 2020 [15, 9, 5].

Nowadays, each cellular subscription generates 5 GB of traffic per month on average, and there are about 8 billion of them worldwide [12]. However, there will be an increase of data traffic and devices connected to internet in order to meet the incoming services, such as internet of things (IoT), autonomous cars, etc. Moreover, 4G has some limitations and won't be able to support all those requirements. Even though 4G has high spectral efficiency, it is not good enough to cover the increase in the number of connected devices [7]. Thus, our current networks need several improvements.

1.2 Thesis objectives

During the following sections of the thesis, three different objectives will be discussed. These objectives are:

1) A previous study of the waveforms which 5G Library provides and the investigation of a new one.
2) Design and testing of a basic transmitter-channel-receiver chain model using Matlab 5G toolset (“5G library functions for LTE system toolbox”)
3) Proposal of a 5G configuration which increases the reliability of the communications.

Regarding the first objective, the waveforms which have been tested are three variations of orthogonal frequency division multiplexing (OFDM). These waveforms are explained during the next chapter. The analysis includes how they can be modeled changing some of their parameters (bandwidth and subcarrier spacing (SCS)). In addition, an investigation of the possibility of a new 5G waveform based on 3GPP specifications will be carried out. Moreover, according to the TX-Channel-RX model, its applicability has been proved for 5G (ultra-reliable) communications in terms of the bit error rate (BER). Finally, during the last objective, the main parameters which can modify the reliability of the communications have been changed in order to improve it.

1.3 Thesis structure

To develop all those purposes in a clear and optimal way, this thesis has been divided into four chapters. Chapter two describes all the basic theoretical content needed for approaching the objectives. Chapter three explains the research methodology and the implementation of the objectives. Chapter four shows the achieved results and the analysis and chapter five collects all the conclusions of this thesis.

2. THEORETICAL BACKGROUND

According to current forecast, 5G systems will appear on the market starting with 2020. Such systems will represent a big step forward in order to improve our communications and make possible all the incoming services. There are a huge number of changes regarding the last generation and a lot of new enhancements.

2.1 Data rate

One of the most important enhancements is the data rate that can be achieved. 5G is expected to achieve above 10 Gbps of peak data rate and to reach user data rates of 1 Gbps. Moreover, 5G will allow to offer a fairly good quality of service to those devices moving at speeds above 500 km/h [13].

2.2 Massive connectivity

On the other hand, 5G will also support massive connectivity. Hence, this new generation will be able to handle the huge increase in data traffic and internet-connected devices expected in the incoming years. As a result, all the needed devices for IoT, self-driving, etc., such as sensors or meters can be managed. Less energy consumption and better spectrum efficiency than 4G systems are others important aspects that 5G will enable [7].

2.3 Ultra-reliable and low latency communications

One of the main purposes of future 5G transmissions is to achieve ultra-reliable and high available communications. This means to offer connectivity with incredibly low error rate even in dramatic conditions or scenarios. 5G systems are expected to guarantee availability and reliability rates of 99.99999%. Another important new improvement related with the speed of the future communications is the low latency, which will be ≤ 1 ms. [7, 13].

2.4 Frequency ranges

Regarding to the 5G future spectrum, it will cover not only the range below 6 GHz, which includes the LTE frequency range as well, but also the frequencies above 24 GHz. The purpose of using this new range is to increment the data bandwidth available over reduced and crowded areas [11]. 3GPP establishes in [1] the following frequency ranges (FR):

Table 2.4. *Frequency ranges*

Frequency range designation	Frequency range (MHz)
FR1	450 – 6000
FR2	24250 – 52600

2.5 Frame structure

The frame structure has also experimented changes compared with 4G. In 5G, downlink and uplink transmissions use frames of 10 ms. Each of them consists of 10 subframes of 1 ms and these subframes can contain a variable number of slots depending on the different existing numerologies. Table 2.5. shows these new possible configurations [2].

Table 2.5. *Proposed frame structure in 5G*

Numerology	Subcarrier spacing (kHz)	Symbols per slot	Slots per frame	Slots per subframe
0	15	14	10	1
1	30	14	20	2
2	60	14	40	4
3	120	14	80	8
4	240	14	160	16

Thus, in contrast to the single-numerology utilization in 4G, 5G waveforms are very flexible, allowing lower latencies and higher reliability [9]. 15, 30, and 60 kHz SCS are used for lower frequencies, and 60, 120, and 240 kHz SCS are used for higher frequencies [7].

2.6 Channel coding

According to the channel coding, there are some different candidates for 5G communications. One of them is turbo coding, which is also used in 4G. In addition, there are two more candidates which could be used during the new generation. Those channel-coding schemes are Polar codes and low-density parity check (LDPC). For larger blocks of bits to be decoded, there is not difference in performance between these codes. In contrast, for smaller blocks, Polar codes are better than LDPC and turbo code. They can get lower error rate and high reliability applications. Nevertheless, the implementation experience of LDPC and Turbo code are less limited than polar code. Turbo code have a great flexibility respecting the code rate and block length. On the contrary, LDPC code needs to be designed for a specific code rate and block length. In addition, LDPC and Polar code are less complex to implement than turbo code regarding the decoder [7].

2.7 Channel model

A necessary aspect when one wants to design and test a wireless communication system is the channel model. There are currently two channel models proposed in 5G for link level evaluations: Tapped Delay Line (TDL) and Clustered Delay Line (CDL) [3]. Moreover, each of them has different sub-models in order to represent different channel profiles: TDL-A, TDL-B, TDL-C, CDL-A, CDL-B and CDL-C for non-line of sight (NLOS) model and TDL-D, TDL-E, CDL-D and CDL-E for line of sight (LOS) model. The parameters of each of them can be found in [3].

2.8 5G waveforms

Another important aspect to take into account for the development of this thesis is the type of the waveforms which will be used in 5G. There are several candidates, but in this project just 3 of them will be employed: cyclic prefix OFDM (CP-OFDM), windowed OFDM (W-OFDM) and filtered OFDM (F-OFDM), described in what follows.

2.8.1 CP-OFDM

Baseband OFDM can be expressed as:

$$OFDM\ [k] = \sum_{n=0}^{N+1} d_n\, e^{j2\Pi k\frac{n}{N}}\ , \tag{2.8.1}$$

where N is the number of subcarriers and d_n is the symbol for each subcarrier n. The next step is to add the CP, which is a copy of the last part of the inverse fast Fourier transform (IFFT) sequence. It is placed at the beginning as a guard interval and its length is calculated depending on the maximum delay of the channel to reduce the consequence of inter symbol interference (ISI). Some of the best problems of CP-OFDM is high peak to average power ratio (PAPR) and out of band emissions (OOBE). However, using filtering OOBE can be reduced [4, 6]. This waveform is also used in 4G.

2.8.2 W-OFDM

W-OFDM signal on baseband can be described as follows:

$$W - OFDM\ [k] = \sum_{m=-\infty}^{+\infty} \sum_{n=0}^{N+1} d_{m,n}\, g[k - m(N + L_{CP} + L_{Ext})] e^{j2\pi k \frac{n}{N}}, \tag{2.8.2}$$

where n represents the subcarrier, m the symbol and $d_{m,n}$ the data symbol. In addition, L_{Ext} is the windowing extension, L_{CP} is the CP size and $g[n]$ represents the windowing function. This operation is used on both sides of the symbol. Since outer sub-carriers have more impact on OOBE than inner sub-carriers, edge windowing is used in order to avoid extra windowing and poor spectral efficiency. This method uses the CP duration of the channel to create windows which maintain spectral efficiency [4].

2.8.3 F-OFDM

Baseband F-OFDM is represented as:

$$F - OFDM\ [k] = \sum_{b=0}^{B-1} \sum_{m=0}^{M-1} \sum_{l=0}^{L_b-1} \sum_{n=0}^{N+1} d_{m.n}^{b}\, g_b[l] e^{j2\pi k \frac{n-l-mL_{CP}}{N}}, \tag{2.8.3}$$

Where $d_{m,n}^{b}$ denotes the data corresponding to block b, subcarrier n and symbol m. L_{CP} means the CP length and $g_b[l]$ represents the frequency equivalent windowing function of block b. This waveform allows to reduce OOBE since, after the modulator, it uses a transmit filter cascaded. F-OFDM also requires CP, but if CP is longer than the channel impulse response, it reduces inter symbol interference (ISI) and inter carrier interference (ICI). However, F-OFDM systems are more complex than CP-OFDM. [4, 6]

In addition, these waveforms are supported by the Matlab ”5G Waveform Spectral Analysis” library, which has been used during the first objective. Also, they are used during the second and third objectives as the transmitted waveforms through the chain model.

3. RESEARCH METHODOLOGY AND IMPLEMENTATION

As a methodology to develop the thesis, all the objectives have been covered started from the first one, to the last one, incrementally and in ascending order. The first study has been based on the example called “5G Waveform Spectral Analysis” from “5G library for LTE system toolbox”. However, some modifications have been added to the code in order to perform the analysis in more depth. Then, after checking the 3GPP specifications related with 5G waveforms, an explanation about the possibility of creating a new one has been given.

For the design of the chain model, the transmitter (TX) has been implemented in first instance. When the TX part was totally designed, the channel model was added, and then, the receiver part (RX). It has been done incrementally to facilitate the debugging of the code. This model is based also on “5G library for LTE system toolbox”, as was commented during the introduction of the thesis.

At the end, regarding the second objective of the project, this is the block diagram:

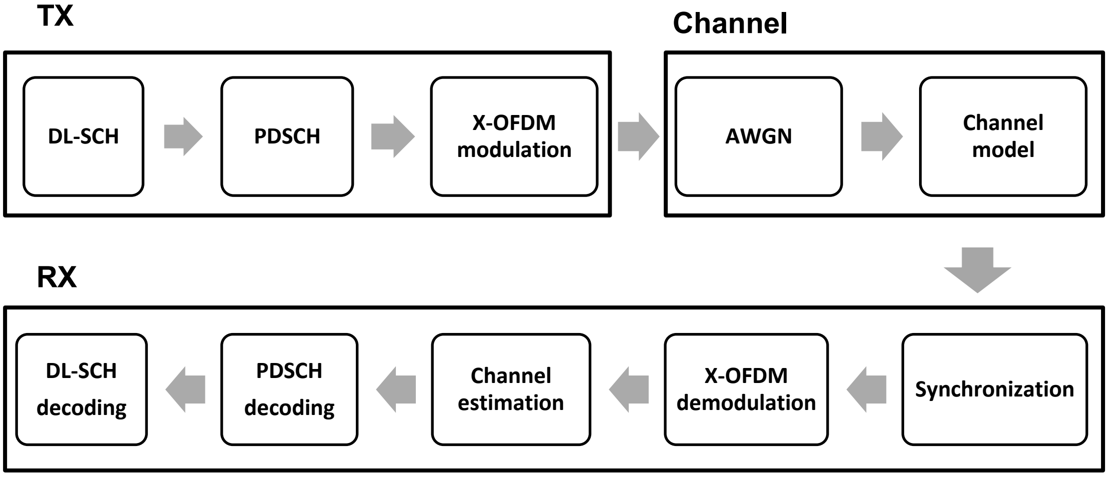


Figure 3.1. *TX-Channel-RX model*

As you can see in figure 3.1, this model is divided into three parts. TX part is composed by three blocks:

- Downlink shared channel (DL-SCH) generation
- Physical downlink shared channel (PDSCH) generation and mapping
- Waveform modulation.

For implementing this modulation, h5gOFDMModulate function has been used. After that, the generated signal is sent through a noisy propagation channel, which can be CDL or TDL. AWGN is added to the generated signal, as we can see in the next block of the chain. Regarding the propagation model, nr5gCDLChannel and nr5gTDLChannel functions have been used respectively for implementing it. They are available in Matlab 5G Toolset.

On the other hand, the RX is formed by 5 blocks:

- Synchronization
- waveform demodulation
- Channel estimation
- PDSCH decoding
- DL-SCH decoding.

According to the synchronization, perfect synchronization is assumed. Furthermore, for implementing the demodulator's block, a function of Matlab is used. It is called, h5gOFDMDemodulate. In addition, the channel estimation block must be added. Perfect channel estimation will be assumed. The perfect channel estimation knowledge will be applied to equalize the received signal through h5gPerfectChannelEstimate function, eliminating gains and the ISI introduced by the propagation channel. Later, during the simulation, the BER is calculated for various Signal-to-Noise ratios (SNR) in order to prove the model. Then, when the simulations were finished, a figure with the results is showed for different modulations. All these results have been discussed and explained in the next chapter.

Finally, as commented in the first chapter, the last objective is to propose a new 5G configuration (TX-Channel-RX) which will increase the reliability of 5G communications. Once again, it will be based on the "5G library for LTE Systems". Also, it is necessary to check 3GPP specifications. First, I have checked all the properties and parameters that influence in the reliability and then, all of them have been applied to the previous design in order to see how the model is affected. At the end of this objective, a result of this more reliable configuration will be shown. Moreover, it will be compared with a similar result of the previous configuration in order to see the differences between them. They will be compared in terms of BER during the next chapter.

4. ANALYSIS AND RESULTS

This chapter discusses about the analysis and results of the three different objectives described in the previous chapters. However, the objective one has been divided into two parts. First, the analysis of the waveforms will be approached. Then, the investigation of a new one, based on 3GPP, will be discussed. Hence, this chapter is divided into four sub-chapters.

4.1 Waveform analysis

During this analysis, various scenarios have been tested in order to know the behaviour of the 3 different waveforms commented above: CP-OFDM, W-OFDM and F-OFDM. The way that their behaviour has been tested is by variating the following parameters:

- Bandwidth, measured in number of resource blocks (N_{RB})
- SCS

The transmission bandwidth configuration N_{RB} for each base station (BS) channel bandwidth and SCS is specified in tables 4.1.1 and 4.1.2 [1], where the gray areas are the ones that have been analyzed.

Table 4.1.1. *Transmission bandwidth configuration N_{RB} for FR1*

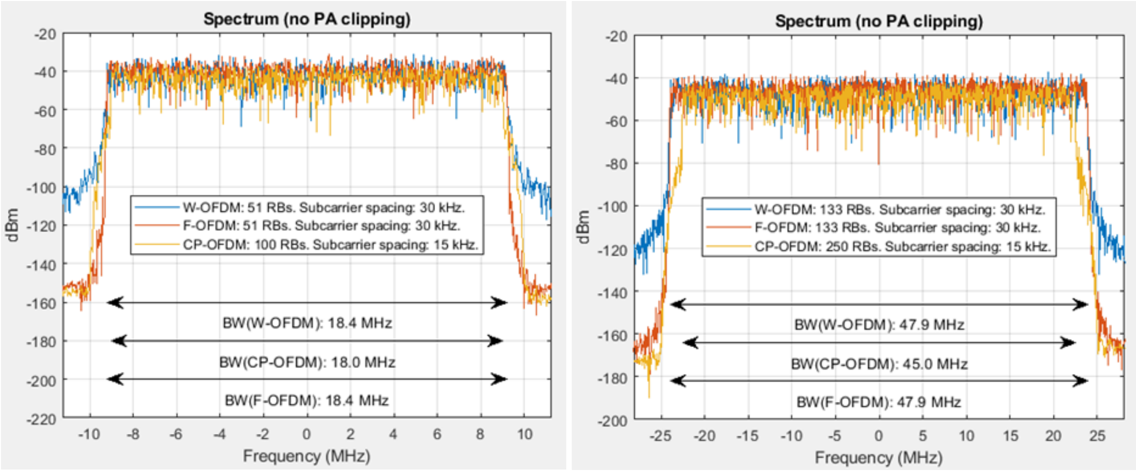
SCS (kHz)	**5 MHz N_{RB}**	**10 MHz N_{RB}**	**15 MHz N_{RB}**	**20 MHz N_{RB}**	**25 MHz N_{RB}**	**30 MHz N_{RB}**	**40 MHz N_{RB}**	**50 MHz N_{RB}**	**60 MHz N_{RB}**	**70 MHz N_{RB}**	**80 MHz N_{RB}**	**90 MHz N_{RB}**	**100 MHz N_{RB}**
15	25	52	79	106	133	160	216	270					
30	11	24	38	51	65	78	106	133	162	189	217	245	273
60		11	18	24	31	38	51	65	79	93	107	121	135

Table 4.1.2. *Transmission bandwidth configuration N_{RB} for FR2*

SCS (kHz)	**50 MHz N_{RB}**	**100 MHz N_{RB}**	**200 MHz N_{RB}**	**400 MHz N_{RB}**
60	66	132	264	
120	32	66	132	264

For evaluating these different scenarios, different cases were considered. The results are shown in figures 4.1.1, 4.1.2 and 4.1.3, which represents each case. On the left column, picture a) of the figures 4.1.1 and 4.1.2, represent the double side spectrum for 20 MHz, while on the left column picture b) of figure 4.1.1 shows the spectrum for 50 MHz and picture b) of figure 4.1.2 represents the spectrum for 40 MHz. However, it is important to highlight that “5G Waveform Spectral Analysis” library uses CP-OFDM as an LTE waveform and this means that there is only one value for its SCS, 15 kHz. In addition, LTE bandwidth has an occupancy limit of 90% and that is the reason why CP-OFDM uses 100 resource blocks (RB) instead of 106 RB as it is specified in table 4.4.1. for 20 MHz.

The spectrum that can be obtained selecting the properly N_{RB}, as it is indicated in table 4.1.1. for different SCS for achieving 20 and 50 MHz is presented in figure 4.1.1. The occupacy limit of 90% of CP-OFDM has been taken into account.



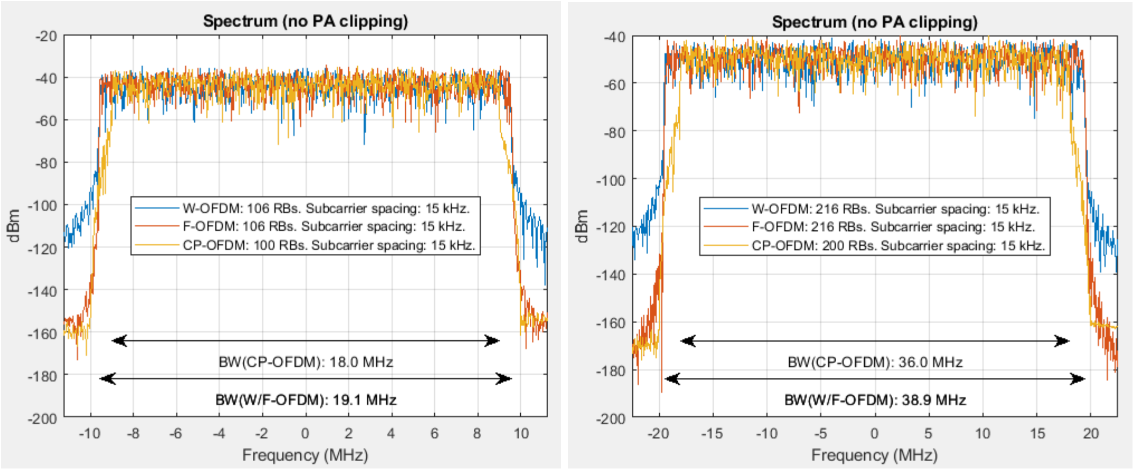
a) 20 MHz

b) 50 MHz

Figure 4.1.1. *Spectrums with different SCS.*

Figure 4.1.1 shows how F-OFDM and W-OFDM achieves bigger bandwidth than CP-OFDM, proving that these two 5G waveforms increase the spectral efficiency beyond the 90%. In addition, CP-OFDM and F-OFDM exhibit a more rapid drop-off in power outside of the useful band. Thus, W-OFDM has more OOBE.

In figure 4.1.2 it is possible to appreciate the spectrums of the three waveforms commented before, but for the same SCS. In this case, the bandwidths are 20 MHz and 40 MHz. The occupacy limit of 90% of CP-OFDM has been taken into account again.



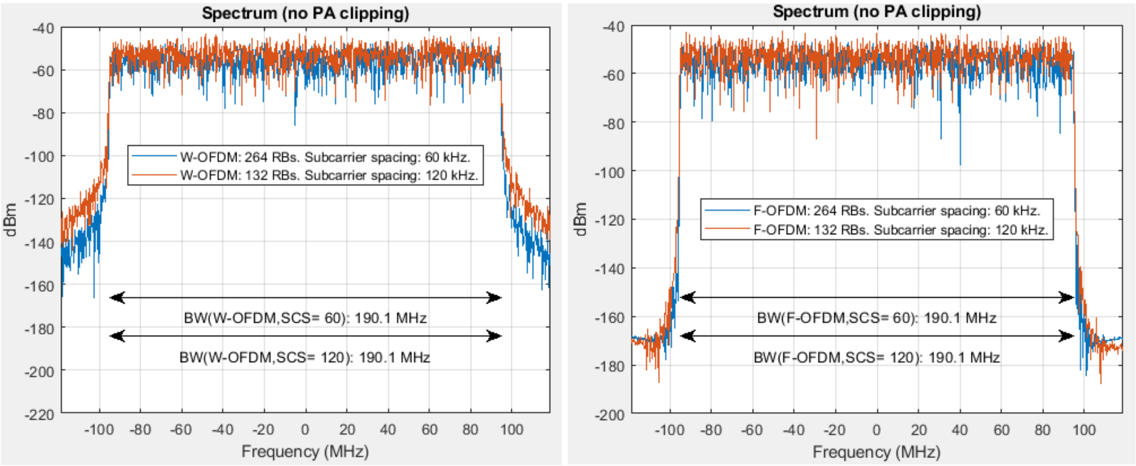
a) 20 MHz

b) 40 MHz

Figure 4.1.2. *Spectrums with same SCS.*

In figure 4.1.2 it is possible to appreciate how CP-OFDM keeps showing less bandwidth than F-OFDM and W-OFDM for the same SCS. In addition, F-OFDM reduces better the amount of OOBE. So that, for the same SCS, W-OFDM and F-OFDM performance is better than CP-OFDM in relation to the bandwidth for the same SCS. However, W-OFDM keeps showing more OOBE.

On the other hand, figure 4.1.3 compares the spectrum of the same waveform for 200 MHz, different SCS and diffrent N_{RB}. F-OFDM and W-OFDM are presented. However, CP-OFDM cannot be included in this case, since achiving 200 MHz of bandwidth with 15 kHz of SCS is not specified in table 4.1.2.



a) 200 MHz and W-OFDM

b) 200 MHz and F-OFDM

Figure 4.1.3. *Spectrums of the same waveforms with different N_{RB} and SCS*

The result of figure 4.1.3 shows that less OOBE for the same bandwidth can be achieved for a specific waveform if the option with less SCS and more N_{RB} is chosen. Moreover, F-OFDM presents less OOBE than W-OFDM.

To sum up and based on the results shown in figures 4.1.1, 4.1.2 and 4.1.3, it is possible to conclude that regarding the waveforms, F-OFDM shows better performance than W-OFDM and CP-OFDM. This waveform also presents a more rapid drop-off in power outside of the useful band than CP-OFDM and W-OFDM. This means that less OOBE is produced with F-OFDM. On the other hand, W-OFDM can achieve more bandwidth for the same SCS than CP-OFDM, but CP-OFDM produce less OOBE. Hence, F-OFDM presents the best performance overall. Moreover, according to the SCS, after analysing the figure 4.1.3, it is possible to conclude that if less SCS is used, less OOBE is achieved. So that, for the analysed cases, F-OFDM with a small SCS value is the best option.

4.2 New 5G waveform

In order to design waveforms that fulfil all the 5G requirements it is necessary to follow some waveform design principles. Among them, it is important to highlight flexible numerology, time and frequency localization, MIMO and high order modulation support, low OOBE and low PAPR. All the waveforms supported by 5G library and that have been commented above, meet 5G requirements, but there are more candidates which could be implemented. Universal Filtered Multi-Carrier (UFMC) is one of them, as it is included by 3GPP TSG-RAN WG1 #84b as we can observe in [18].

UFMC is composed by a group of sub-bands that contains different subcarriers. An IFFT is computed for each sub-band and then, all of them are filtered. The length of this transmission filter is usually set to the same size of the guard interval (GI). Finally, these sub-bands are added to get the final signal to transmit. Also, different filters can be applied to different sub-bands [20].

This waveform is a variant of the traditional OFDM, but it presents some differences. It uses a GI instead of CP, as mentioned above. This GI is filled with zeros and added between the IFFT symbols to avoid ISI [18]. Moreover, it has some advantages, such as, lower OOBE than CP-OFDM and the possibility to use different numerology or signal format to each sub-band. However, it also has some important drawbacks as, for example, the complexity that it requires. This complexity increases because of several facts.

The need to use zero padding and double-sized fast Fourier transform (FFT) at the receiver are two of them [20]. In addition, CP-OFDM and W-OFDM have lower PAPR than UFMC. Nonetheless, F-OFDM has higher PAPR than UFMC [6].

4.3 5G TX-Channel-RX model with AWGN + CDL/TDL

During this sub-chapter the second objective of the thesis is carried out. This objective consists on the design and testing of the TX-Channel-RX chain model with AWGN and propagation channel model. In addition, this channel will be estimated. First, the most important parameters will be presented for giving an approximation about the behaviour of the model. Then, the achieved results will be shown. These results consist on three BER simulations of the different waveforms supported by 5G library:

- CP-OFDM
- W-OFDM
- F-OFDM.

The following part of Matlab’s code shows the main parameters of the model:

```
sp = [];          % Simulation parameters initialization (sp)
sp.NDLRB = 106;    % NRB
sp.CyclicPrefix = 'Normal';
sp.SubcarrierSpacing = 15;   % SCS in kHz
sp.WaveformType = 'F-OFDM';

sp.Alpha = 0.0115;   % Roll off for W-OFDM
sp.FilterLength = 424; % Length of the filters for F-OFDM
sp.ToneOffset = 1.9;  % Tone offset for F-OFDM
sp.CellRefP = 4;  % Number of transmitting antennas
%Creation of PDSCH substructure
sp.PDSCH.TxScheme = 'TxDiversity';
sp.PDSCH.CodingType = 'LDPC';
sp.PDSCH.PRBSet = (0:sp.NDLRB-1)';  % Allocation of PDSCH
sp.PDSCH.TargetCodeRate = 1/2;  % Code rate
sp.PDSCH.CSI = 'On'; % LLR scaling after demodulation
sp.PDSCH.NLayers = 2;

ncw = 1; % Active codewords

nRxAntennas = 2;   % Number of receiving antennas
nTxAntennas = sp.CellRefP;  % Change of variable
```

***Program 1**. Main parameters of the simulation*

It must be remarked that the modulation type is not specified in program 1. This is because the modulation scheme is defined later, during a loop, in order to not have to set all other parameters again for each different modulation, since three modulations have been used. Nonetheless, the waveform type is specified in program 1 as F-OFDM, but the reason is that this parameter has been changed manually to CP-OFDM and F-OFDM later for obtaining the three different results that are shown in figures 4.3.1, 4.3.2 and 4.3.3. Also, we can see that the N_{RB}, which in the code is represented by the variable NDLRB, is 106 and the SCS is 15 kHz. This configuration, as we can see in the table 4.1.1, corresponds to a signal's bandwidth of 20 MHz. In this way, is only necessary to define the new modulation and set the rest of the necessary parameters such as, the gNodeB and the transport block size.

```
GNB = lteRMCDL(sp,ncw); % Generate a default gNodeB prameters
% not specified in sp
pdsch = GNB.PDSCH; % Separate the PDSCH parameters from gNodeb
TBS = pdsch.TrBlkSizes; % Transport block size
waveformInfo = h5gOFDMInfo(GNB); % Provides dimensional
% information related to the OFDM modulation schemes
% implemented by h5gOFDMModulate
```

Program 2. *Setting parameters*

The next step is to add the AWGN to the transmitted signal. Once the chain model with AWGN is designed, the next step is to add the propagation channel models and the channel estimation blocks. In order to implement these new blocks, I have used the functions commented in the previous chapter. For the CDL channel, the nr5gCDLChannel function was used. It returns a CDL channel object. On the other hand, the nr5gTDLChannel function is used for implementing the TDL channel. Finally, the channel estimation is designed by the nr5gPerfectChannelEstimate function.

In addition, during the transmission, 35 frames have been sent for a SNR range from -2 to 15 dB. These SNR values have been selected because they represent a critical scenario for wireless communications, since SNR is the difference between the noise and the received signal measured in decibels. Also, the modulations that have been used are:

- 16QAM
- 64QAM
- 256QAM

Furthermore, it is important to highlight that for this evaluation the CDL-A channel model has been used. In addition, the SCS used, as it is possible to see in program 1, is 15 kHz. So that, each subframe is composed by one slot (14 symbols), as it is specified in table 2.5. In addition, the number of subframes sent for 35 frames is 350, since each frame has 10 subframes. Table 4.3 presents the size in number of bits of each subframe and transport block used for the three different modulations and for each waveform. Transport block sizes have been calculated as given by TS 36.101 Annex A.3.1.

Table 4.3. Bits per each subframe

Waveform	16QAM	64QAM	256QAM
CP-OFDM	22920 bits/subframe	32856 bits/subframe	63776 bits/subframe
F-OFDM	24496 bits/subframe	37888 bits/subframe	66592 bits/subframe
W-OFDM	24496 bits/subframe	37888 bits/subframe	66592 bits/subframe

However, when 64QAM was used for F-OFDM and W-OFDM, the first subframe of every each ten subframes contained 34008 bits, while the other nine subframes contained 37888 bits, as it is specified in table 4.3. On the other hand, figure 4.3.1 shows the BER results that have been achieved for CP-OFDM by using the previous parameters:

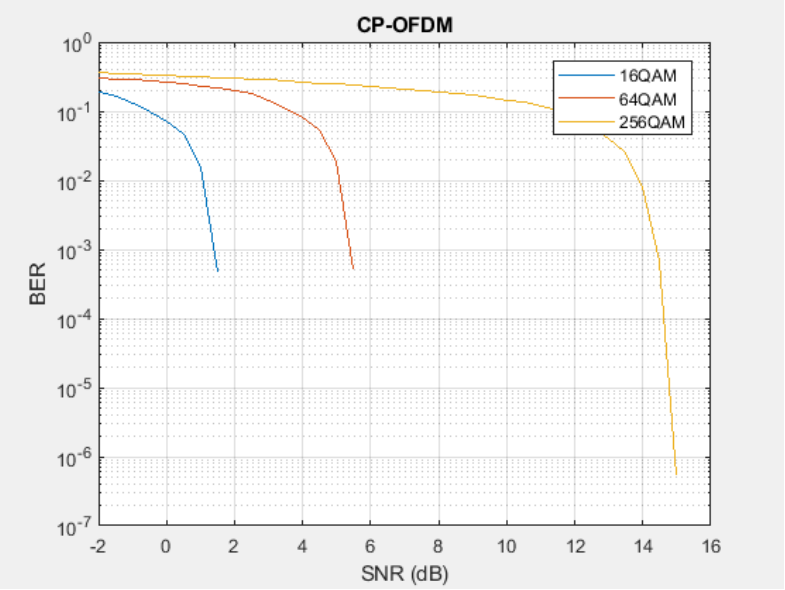


Figure 4.3.1. *BER with AWGN + CDL of CP-OFDM*

As one can see in figure 4.3.1, the BER results show a good behaviour of the model when CP-OFDM is used. In figure 4.3.2, the BER of F-OFDM is represented.

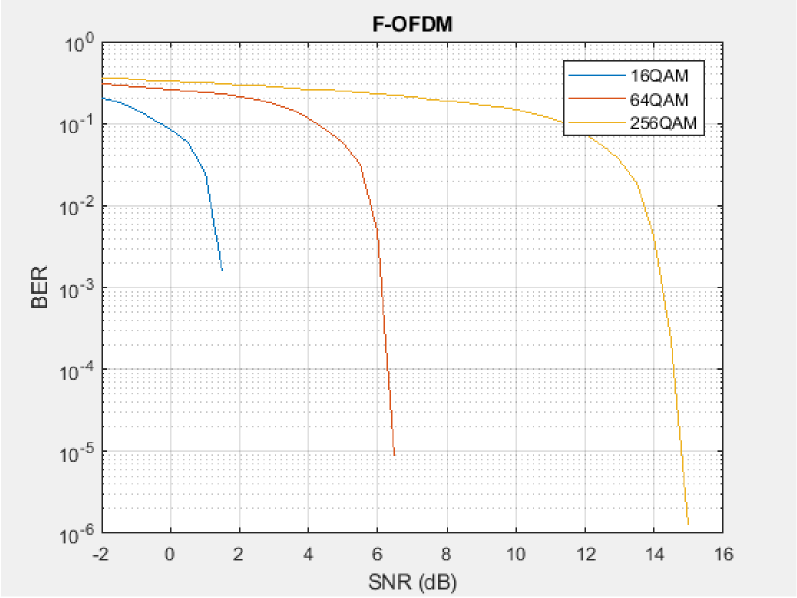


Figure 4.3.2. *BER with AWGN + CDL of F-OFDM*

In figure 4.3.2 it is possible to see the behaviour of the transmission when F-OFDM is sent through the chain model designed before. Similar results are achieved for CP-OFDM and F-OFDM. The result of the figure 4.3.3 is based on W-OFDM. The same modulations are used.

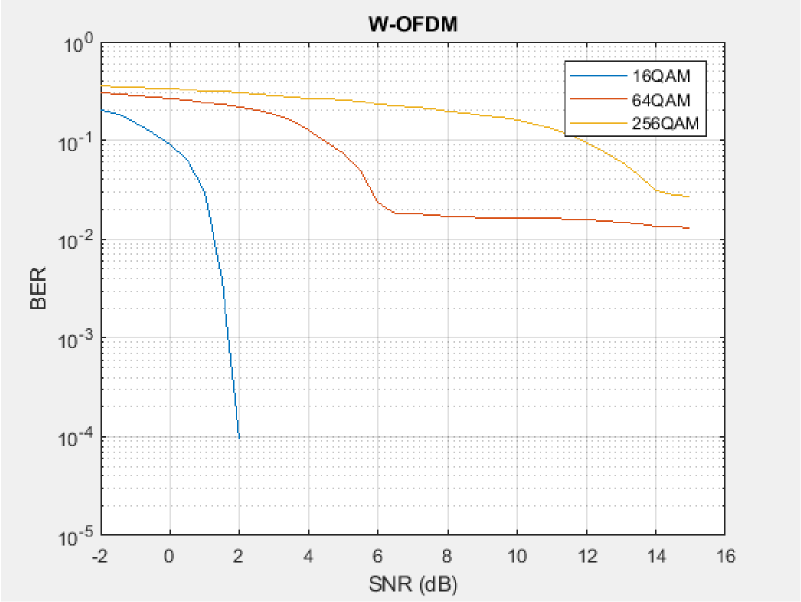
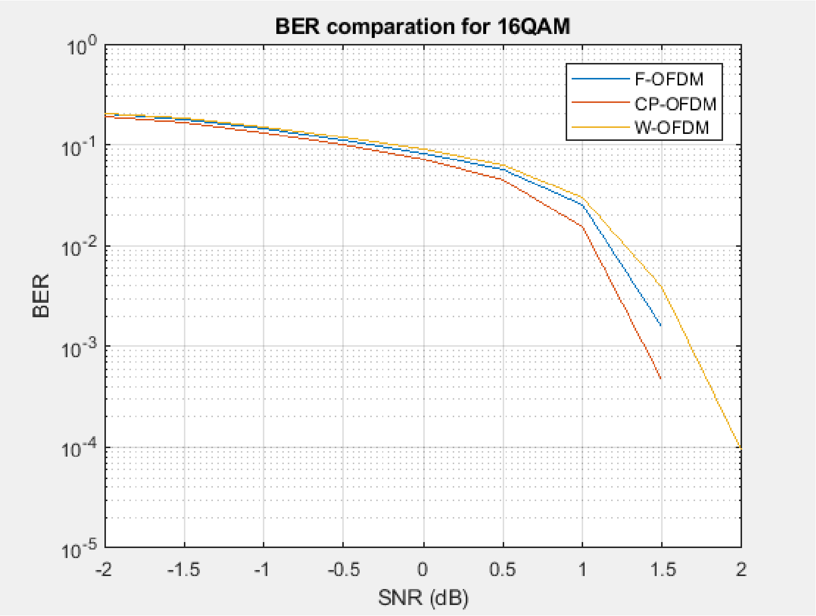


Figure 4.3.3. *BER with AWGN + CDL of W-OFDM*

As one can see in figure 4.3.1, 4.3.2 and 4.3.3, for testing which waveform achieves better results, different BER graphics are represented for a SNR from -2 to 15 dB, as it was commented before. Regarding the three waveforms tested, it is possible to conclude that CP-OFDM achieves a similar result than F-OFDM. This conclusion is based on the values achieved for each modulation for the SNR. However, when CP-OFDM is used, the BER presents better results for all the SNR range. Thus, in general it can be concluded that CP-OFDM has better results than F-OFDM in terms of BER. In addition, W-OFDM presents even a worse BER than F-OFDM. In figure 4.3.4 the BER values of each waveforms are presented for 16QAM in order to see the differences among these three waveforms.



4.3.4. *BER comparation for 16QAM*

Hence, to sum-up, CP-OFDM presents better results in terms of BER than F-OFDM and W-OFDM. In addition, W-OFDM presents the worst result compared with F-OFDM and CP-OFDM.

4.4 5G proposal for more reliable communications

There are several ways to improve the reliability, since this measure is affected by various parameters, such as diversity, modulation, retransmission mechanisms, etc. [10]. Nevertheless, an improvement in the reliability usually causes an increase of the latency because of retransmissions, as it is shown in figure 4.4.1:

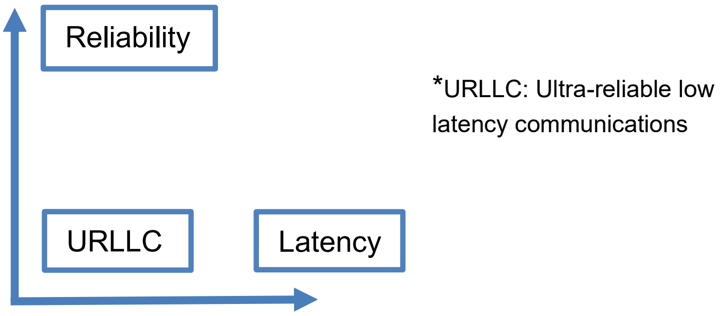


Figure 4.4.1. *Tradeoff between reliability and latency*

However, there are cases where reliability and latency are optimized. Regarding the data rates, it is demostrated that lower rates incur higher reliability and vice-versa [16]. This section discusses about those parameters based on 5G library which can improve the reliability of the TX-channel-RX chain model proposed. These parameters are:

- Spatial diversity
- HARQ
- Coding rate

Regarding spatial diversity, it is important to highlight the possibility of using multiple input and multiple output systems (MIMO) as it is used in the chain model of section 4.3. However, by incrementing the number of transmitting and receiving antennas, it is possible to achieve more reliability [19]. In addition, this spatial diversity technique reduces the power requirements. These enhancements are possible since the transmission information is divided into multiple data streams and sent by each transmitting antenna. Then, the multiple signals reach the receiving antennas. Depending on the different paths the signals have travelled, each one will have been affected by different factors. However, the receiving antennas can reconstruct the data by taking into account the noise, the interferences and the slight time difference between the received signals. Moreover, 5G library can manage this type of transmission, and allow to set different antenna configurations, such as 4x2, that is 4 transmitting and 2 receiving antennas. This can be done by changing the transmission scheme of gNodeB configuration to 'TxDiversity' and modifying the number of antennas.

On the other hand, the previous chain model also can be improved in terms of reliability by adding a hybrid automatic repeat request (HARQ) protocol. The purpose of this protocol is to provide high reliability and efficiency by retransmitting those packets which have been received with errors. Those improvements are possible because HARQ decreases the error rate and avoid the retransmission of the whole packet, only the wrong part of the packet is retransmitted [17]. In addition, this protocol can be employed in 5G library.

Vary the coding rate is another option for improving the reliability of 5G communications. It is important to increment the reliability of every packet for the purpose of minimizing the error rate and the number of retransmissions. This aspect can be managed by variating the coding rate, since it adds extra error checking bits for making that the packets are received correctly. Also, it is possible to select different coding types such as LDPC, Turbo code and Polar code. As it is showed in [14], when the code rate decreases, better reliability is achieved. Thus, for improving the reliability of an TX-channel-RX chain model based on 5G library, the coding rate needs to be decreased. This parameter can be changed in 5G library by variating the variable ‘TargetCodeRate’ of the PDSCH configuration. Then, the transport block sizes will be calculated as given by TS 36.101 Annex A.3.1. Moreover, as it is demonstrated in [14], it is possible to achieve better reliability for different coding rates for LDPC and turbo code than polar code when the block length increases. On the contrary, for smaller block lengths polar code gets better reliability than LDPC and turbo code.

As a result, and because of the aforementioned, in order to improve the reliability of the 5G communications that has been achieved through the previous TX-Channel-RX chain model, some changes are proposed. As the first improvement, more antennas will be added to the system. During the section 4.3, it has been used a 4x2 configuration. Nevertheless, since 5G library can manage 4x4 antennas, this configuration will be used in this case. Moreover, the HARQ protocol will be added and the coding rate will be decreased from 1/2 to 1/3. In figure 4.4.2, one can see the new result in comparison with the previous one for 16QAM. The number of frames that have been sent are 35. These frames have been sent for a SNR range from -2 to 15 dB and the waveform that has been employed is CP-OFDM. In addition, the propagation channel is the same as has been used for all the simulations of the thesis, CDL-A. Table 4.4 compares the differences between the new configuration and the previous one:

Table 4.4. *Different configurations*

Parameters	Previous configuration	New configuration
Antennas	4x2	4x4
HARQ protocol	disenabled	enabled
Code rare	1/2	1/3

The following figure shows the result achieved by this new configuration in comparison with the result achieved in chapter 4.3 for 16QAM when CP-OFDM is used.

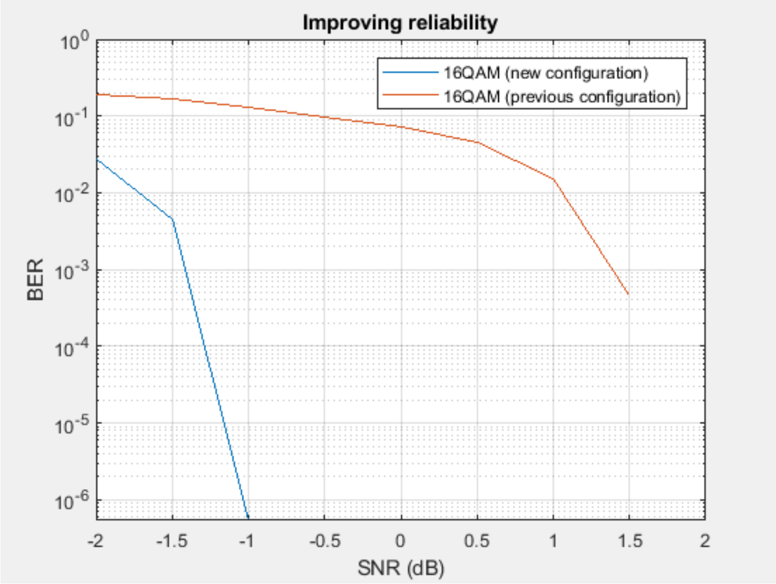


Figure 4.4.2. *BER comparation. The red BER is the modified and improved version of the blue one.*

As one can see in figure 4.4.2, the red BER is the one that has been achieved by the configuration proposed during this section of the thesis, while the blue BER was achieved by the previous configuration. It is possible to appreciate that for the same SNR, the BER corresponding to the new configuration achieves better values than the previous one. Thus, it is possible to conclude that the reliability of the communications has been improved.

4.5 Limitations of 5G Library

During the analysis of the results, some limitations have been found in “5G library for LTE Systems” of Matlab, library which has been used for the development of this thesis.

- The antenna’s configuration can be 4x4 as much. This limitation does not allow to obtain better reliability in the results.
- The model cannot be designed without perfect channel estimation when AWGN is added, because it produces a strange behaviour when the BER is calculated.

Due to these limitations, the results are limited. In addition, there are some variations of the model that cannot be implemented and tested.

5. CONCLUSIONS

During the development of this thesis several conclusions have been reached. First, during the study of the different waveforms supported by 5G Toolset of Matlab, it has been proved how 5G waveforms achieve better spectral efficiency than LTE waveforms. In addition, the study has revealed that F-OFDM presents the best performance for the different scenarios that have been tested. Also, it has been shown that selecting less SCS it is possible to obtain less OOBE. Then, it has been explained that UFMC can be applied for 5G communications.

On the other hand, after the study and investigation commented in the previous paragraph, the design and testing of the TX-Channel-RX chain model based on 5G Toolset was carried out. It has demonstrated that in general, CP-OFDM achieves better performance than F-OFDM and W-OFDM in terms of BER. However, the behaviour of F-OFDM and CP-OFDM is very similar. On the contrary, W-OFDM has shown the worst BER result of the three waveforms tested.

The final objective of this thesis has been to propose a new configuration in order to improve the reliability of the communications. For achieving this challenging objective, the proposal was to develop a new configuration based on the spatial diversity, the HARQ protocol and the code rate. The result achieved by this new configuration was compared with the result obtained by the previous model in order to see how the reliability varied. Regarding the spatial diversity, the new configuration proposed to add more antennas. In this way, two more receiving antennas were added. Also, the code rate was changed to 1/3 and the HARQ protocol was enabled. The achieved result shows how this new configuration improves the reliability of the previous model.

On the other hand, it is important to highlight that as has been commented previously, this thesis is based on 5G Toolset. This means that the characteristics of the designed model are subject to the parameters that this library support. So that, there is a limitation in the results that can be obtained. Hence, it is necessary a more complete research in order to achieve more realistic results.

REFERENCES

[1] 3rd Generation Partnership Project (3GPP) (Dec. 2018). NR; Base station (BS) radio transmission and reception. Technical Specification 38.104, ver. 15.4.0.

[2] 3rd Generation Partnership Project (3GPP) (Jan. 2019). NR; Physical channels and modulation. Technical Specification 38.211, ver. 15.4.0.

[3] 3rd Generation Partnership Project (3GPP) (Jun. 2018). Study on channel model for frequencies from 0.5 to 100 GHz. Technical Specification 38.901, ver. 15.0.0.

[4] A. F. Demir, A. Fatih, M. Elkourdi, M. Ibrahim and H. Arslan (2018). Waveform Design for 5G and Beyond. DOI: 10.1002/9781119333142.ch2.

[5] A. Garg (2014). Digital Society from 1G to 5G: A Comparative Study. *International Journal of Application or Innovation in Engineering & Management*. Volume 3. 186 to 193.

[6] A. Ijaz, L. Zhang, P. Xiao and R. Tafazolli (Dec. 2016). Analysis of Candidate Waveforms for 5G Cellular Systems. *Towards 5G Wireless Networks - A Physical Layer Perspective*. Hossein Khaleghi Bizaki, IntechOpen, DOI: 10.5772/66051. Available at: https://www.intechopen.com/books/towards-5g-wireless-networks-a-physical-layer-perspective/analysis-of-candidate-waveforms-for-5g-cellular-systems

[7] A. Othman (2019). 5G System Architecture & Implementation. DOI: 10.13140/RG.2.2.11793.68966.

[8] A. Yazar, B. Pekoz and H. Arslan (2018). Flexible Multi-Numerology Systems for 5G New Radio.

[9] B. Kalra and D. K. Chauhan (2014). A Comparative Study of Mobile Wireless Communication Network: 1G to 5G. *International Journal of Computer Science and Information Technology Research*. 2. 430-433.

[10] B. Soret, P. Mogensen, K. I. Pedersen and M. C. Aguayo-Torres (2014). Fundamental tradeoffs among reliability, latency and throughput in cellular networks. *2014 IEEE Globecom Workshops (GC Wkshps)*, Austin, TX pp. 1391-1396. DOI: 10.1109/GLOCOMW.2014.7063628

[11] F. Amato (2019). A Primer on 5G.

[12] F. Sharevski (2018). Towards 5G cellular network forensics. *EURASIP Journal on Information Security*. 2018. DOI: 10.1186/s13635-018-0078-7.

[13] G. Nguyen, A. Brunstrom, K. Grinnemo and J. Taheri (2017). 5G Mobile Networks Requirements, Enabling Technologies, and Research Activities.

[14] H. Gamage, N. Rajatheva and M. Latva-aho (2017). Channel Coding for Enhanced Mobile Broadband Communication in 5G Systems.

[15] I. Balapuwaduge and F. Li (2018). Cellular Networks: An Evolution from 1G to 4G.

[16] J. Park and P. Popovski (Dec. 2017). Coverage and Rate of Downlink Sequence Transmissions with Reliability Guarantees. in *IEEE Wireless Communications Letters*, vol. 6, no. 6, pp. 722-725. DOI: 10.1109/LWC.2017.2735974

[17] J. Yeo, S. Park, J. Oh, Y. Kim and J. Lee (2017). Partial Retransmission Scheme for HARQ Enhancement in 5G Wireless Communications. *2017 IEEE Globecom Workshops (GC Wkshps)*, Singapore, pp. 1-5. DOI: 10.1109/GLOCOMW.2017.8269132

[18] P. Gaal (2016). Waveform candidates. *Qualcomm Incorporated*, R1-162199.

[19] P. Patil, N. Muchhal and R. Shankar (2014). An Extensive Review on Spatial Diversity Techniques in Wireless Communication. *International Journal of Computer Technology and Electronics Engineer*ing. Volume 4

[20] X. Zhang, L. Chen, J. Qiu, J. Abdoli (2016). On the Waveform for 5G. *IEEE Communications Magazine*, vol.54, issue 11, pp. 74-80.