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SCHOOL OF ENGINEERING

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Index Modulation in OFDM Systems and Impact on Signal Spectrum

Diploma Thesis

Vangeli Efstathoula

Supervisor: Argyriou Antonios

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ

ΠΟΛΥΤΕΧΝΙΚΗ ΣΧΟΛΗ

ΤΜΗΜΑ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ ΚΑΙ ΜΗΧΑΝΙΚΩΝ ΥΠΟΛΟΓΙΣΤΩΝ

Διαμόρφωση Δείκτη σε συστήματα OFDM και Επιπτώσεις στο Φασματικό Αποτύπωμα

Διπλωματική Εργασία

Βαγγέλη Ευσταθούλα

Επιβλέπων: Αργυρίου Αντώνιος

Βόλος 2020

ΥΠΕΥΘΥΝΗ ΔΗΛΩΣΗ ΠΕΡΙ ΑΚΑΔΗΜΑΪΚΗΣ ΔΕΟΝΤΟΛΟΓΙΑΣ ΚΑΙ ΠΝΕΥΜΑΤΙΚΩΝ ΔΙΚΑΙΩΜΑΤΩΝ

«Με πλήρη επίγνωση των συνεπειών του νόμου περί πνευματικών δικαιωμάτων, δηλώνω ρητά ότι η παρούσα διπλωματική εργασία, καθώς και τα ηλεκτρονικά αρχεία και πηγαίοι κώδικες που αναπτύχθηκαν ή τροποποιήθηκαν στα πλαίσια αυτής της εργασίας, αποτελεί αποκλειστικά προϊόν προσωπικής μου εργασίας, δεν προσβάλλει κάθε μορφής δικαιώματα διανοητικής ιδιοκτησίας, προσωπικότητας και προσωπικών δεδομένων τρίτων, δεν περιέχει έργα/εισφορές τρίτων για τα οποία απαιτείται άδεια των δημιουργών/δικαιούχων και δεν είναι προϊόν μερικής ή ολικής αντιγραφής, οι πηγές δε που χρησιμοποιήθηκαν περιορίζονται στις βιβλιογραφικές αναφορές και μόνον και πληρούν τους κανόνες της επιστημονικής παράθεσης. Τα σημεία όπου έχω χρησιμοποιήσει ιδέες, κείμενο, αρχεία ή/και πηγές άλλων συγγραφέων, αναφέρονται ευδιάκριτα στο κείμενο με την κατάλληλη παραπομπή και η σχετική αναφορά περιλαμβάνεται στο τμήμα των βιβλιογραφικών αναφορών με πλήρη περιγραφή. Αναλαμβάνω πλήρως, ατομικά και προσωπικά, όλες τις νομικές και διοικητικές συνέπειες που δύναται να προκύψουν στην περίπτωση κατά την οποία αποδειχθεί, διαχρονικά, ότι η εργασία αυτή ή τμήμα της δεν μου ανήκει διότι είναι προϊόν λογοκλοπής».

Η Δηλούσα

Βαγγέλη Ευσταθούλα

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Declarant

Vangeli Efstathoula

September 2020

ΠΕΡΙΛΗΨΗ

Τα τελευταία χρόνια, η κίνηση των δεδομένων και η κατανάλωση ενέργειας στις ασύρματες επικοιννίες έχουν αυξηθεί ραγδαία, δημιουργώντας μία ανάγκη για πιο αποτελεσματικές τεχνολογίες. Η τρίτη (3G) και η τέταρτη γενία (4G) των ασύρματων δικτύων έχουν αποδεικτεί ανεπαρκείς στο να ικανοποιήσουν αυτές τις απαιτήσεις κι έτσι η το δίκτυο πέμπτης γενιάς (5G) αναπτύχθηκε το 2019 και θεωρείται πως θα χρησιμοποιείται παγκοσμίως μέσα στα επόμενα χρόνια. 5G εμπεριέχει πολλές τεχνικές, μέσα στις οποίες και τη Ορθογωνική Πολυπλεξία Διαίρεσης Συχνότητας (OFDM), η οποία έχει ήδη αποδειχθεί πολύ κερδοφόρα στην αύξηση του διαφορισμού χώρου κι χρησιμοποιείται ευρέως σε πολλές εφαρμογές. Η κεντρική ιδέα του ΟΦΔΜ είναι ότι τα δεδομένα μεταδίδονται από διαφορετικές υποφέρουσες, ορθογώνιες μεταξύ τους, μειώνοντας την διασυμβολική παρεμβολή (ISI) και απλοποιώντας τον πομπό και τον δέκτη. Βασιζόμενοι σε αυτήν την τεχνολογία, με Διαμόρφωση Δείκτη (OFDM-IM) έχει αναπτυχθεί, με σκοπό να αυξήσει τη φασματική αποδοτικότητα και να βελτιώσει την απόδοση των σφαλμάτων. OFDM-IM ακολουθεί το τηλεπικοινωνιακό σύστημα πολλαπλής φέρουσας αλλά έχει στόχο την υψηλή διεκπεραιωτικότητα με τη χαμηλότερη ενέργεια, ενεργοποιώντας συγκεκριμένες, με δείκτες, υποφέρουσες ενώ οι θέσεις των μη ενεργοποιημένων παρέχουν επιπρόσθετη πληροφορία. Ο σκοπός αυτής της διπλωματικής εργασίας είναι, κυρίως, να επικεντρωθεί στο OFDM-IM στο πεδίο της συχνότητας και να παρουσιάσει τις διαφορές μεταξύ του κλασσικού OFDM και του OFDM-IM. Υπολογοίζουμε το ρυθμό σφαλμάτων bit (BER) ενός OFDM-IM και ενός OFDM σε δύο διαφορέτικά κανάλια μετάδοσης, ένα κανάι με Αρθροιστικό Λευκό Γκαουσιανό Θόρυβο (AWGN) κι ένα γραμμικά χρονικό μεταβλητό (LTI) κανάλι, με διαμόρφωση ολίσθησης φάσης (PSK) και ορθογώνια διαμόρφωση πλάτους (QAM), και να εξετάσει τις επιπτώσεις στο φασματικό αποτύπωμα.

ABSTRACT

In the past years, the data traffic and energy consumption in wireless communication has increased rapidly, creating a need for more effective technologies. The third (3*G*) and fourth-generation (4*G*) of wireless networks are proven inadequate to meet these requirements, so the fifth-generation (5*G*) network was deployed in 2019 and is believed to be used worldwide in the next few years [1]. 5*G* contains many techniques and, among others, the Orthogonal Frequency Division Multiplexing (OFDM), which has already been proven very profitable for increasing space diversity, and it is widely employed on many applications. The OFDM's central idea is that data are transmitted by different subcarriers, orthogonal to each other, reducing the intersymbol interference (ISI) and simplifying the transmitter and the receiver. OFDM with Index Modulation (OFDM-IM) has been developed based on this technology to increase the spectral efficiency and improve the error performance. OFDM-IM follows the multicarrier communication system but aims to high throughput with low energy consumption by activating specific, indexed subcarriers while the deactivated ones' positions carry additional information. This thesis aims to focus mainly on OFDM-IM in the frequency domain and present the differences between the classic OFDM and OFDM-IM. We calculate the Bit Error Rate (BER) of an OFDM and an OFDM-IM in two different channels, an Additive White Gaussian Noise (AWGN), and a linear-time invariant (LTI), with Phase-Shift Keying (PSK) modulation and Quadrature Amplitude Modulation (QAM), and examine its impact on the signal spectrum.

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From the bottom of my heart, thank you!

CONTENTS

CHAPTER 1

INTRODUCTION

Due to the fast evolution of smart communication terminals and in order to meet the explosive increase of mobile traffic, high-rate transmission schemes have attracted increasing attention from both the academia and industry [2]. In recent years, in 4G wireless networks, the multicarrier transmission has become a key technology for wideband digital communications. It has been included in many wireless standards to satisfy the increasing demand for high rate communication systems operating on frequency selective fading channels. Orthogonal Frequency Division Multiplexing (OFDM) has been the most popular multicarrier transmission technique in wireless communications and has been the backbone of IEEE 802.16 standards, namely Mobile Worldwide Interoperability Microwave Systems for Next-Generation Wireless Communication Systems (WiMAX) and the Long Term Evolution (LTE) project [3]. Besides all its advantages, OFDM symbols suffer from the drawback of the high peak-to-average power ratio (PARP), leading to inevitable nonlinear distortion by the transmitter (TX) power amplifier [2]. Additionally, in frequency selective fading channels with mobile terminals reaching high vehicular speeds, the subchannel orthogonality is lost, leading to inter-channel interference (ICI), which affects the system implementation and performance considerably [3]. Multiple-input Multiple-output (MIMO) systems were proposed instead of single-antenna systems, for being more effective and primarily Spatial modulation (SM), a MIMO transmission method which considers the transmit antennas as spatial constellation points to carry additional information bits [4] and described entirely in [5].

As far as these are concerned, there is an urgent need for a technology capable of increasing spectral efficiency, energy efficiency, and reliability while reducing complexity, complying with 5G networks' needs. Orthogonal frequency division multiplexing with index modulation (OFDM-IM), an extension of OFDM, is a promising technique which seems to solve these problems. More specifically, unlike conventional communication schemes, only a fraction of certain indexed resource entities, e.g., subcarriers, antennas, time slots, or channel states, are activated for data transmission. In contrast, the others are kept unused by the associated transmission, where additional information bits are conveyed implicitly by the index usage or activation patterns [2]. As a result, more bits are received consuming the same energy, and the Bit Error Rate (BER) is considerably reduced compared to the classical OFDM system. The advancements and a complete overviews of this technology are presented in many papers, among others [6] and [7].

The rest of this thesis is organized into three chapters, as referred below. In the second chapter, the system models of an OFDM and an OFDM-IM are fully described. In the third chapter, we use Matlab code to demonstrate the results of the simulation for both of the systems in AWGN and LTI channels. We mainly use plots to present and help the reader understand the differences between the two systems' performances. Finally, the third chapter contains the conclusions of our whole thesis.

CHAPTER 2

SYSTEM MODEL

2.1 OFDM

OFDM's primary system model that we designed and used in this thesis is presented in Figure 2.1 and thoroughly described below and is based on the OFDM system presented in [2].

The transmitter (TX) gets a vector of binary bits as input. The bits are modulated with M-PSK or M-QAM, where M is the modulation scheme's cardinality and practically the number of every possible symbol we can get after the modulation. The result of this is a vector $\vec{X} = [\ X_1,\ X_2, \ldots,\ X_N\ ]^T$ containing symbols, with length equal to the number of bits/$log_2(M)$, where $log_2(M)$ is the number of bits that are needed for every symbol. $\vec{X}$ is then passed through a serial-to-parallel converter (S/P) before fed into the N-point fast Fourier transform (IFFT), and adds the cyclic prefix (CP) of length L_CP to the vector in order to combat the inter-block interference (IBI). The transmission is passing through a fading channel defined as $\vec{h} = [\ h_1,\ h_2, \ldots,\ h_{L_h}\ ]^T$, where L_h the number of channel's coefficients.

At the receiver (RX), the received signal, $\vec{Y}$, after the addition of the white Gaussian (AWGN) noise, is given by the following expression:

$$\vec{Y} = \vec{h} * \vec{X} + \vec{W}$$

where $\vec{W}$ is the vector of added noise. The RX has to follow the inverse operations than the TX, so first comes the CP removal. Then follows the N-point fast Fourier transform (FFT) and the outcome goes through a parallel-to-serial converter (P/S). The outcome vector is fed into the corresponding constellation demapper for demodulation and with the Maximum Likelihood (ML) detector to calculate the errors and the rate between transmitted bits and those received.

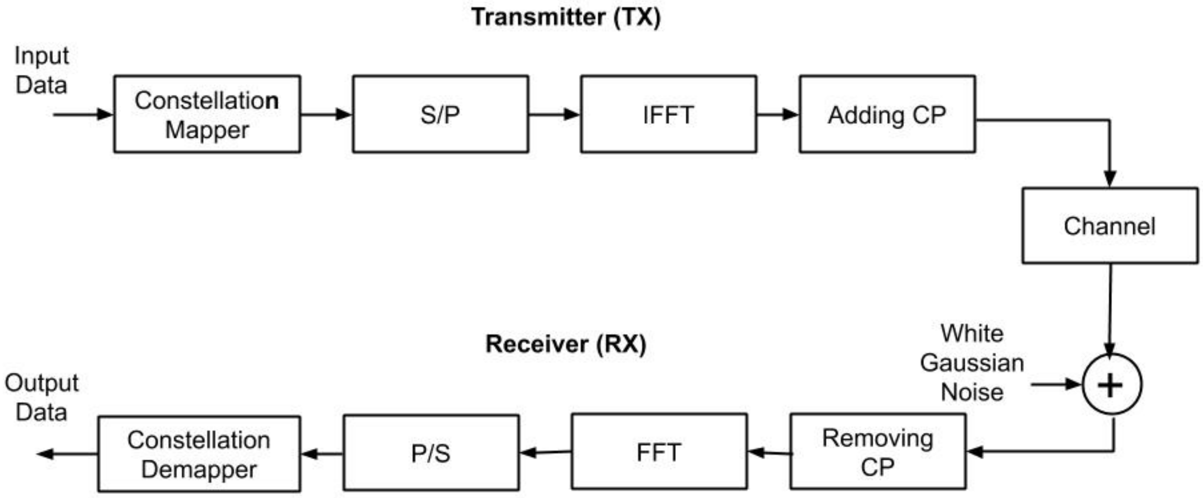


Figure 2.1: OFDM system diagram.

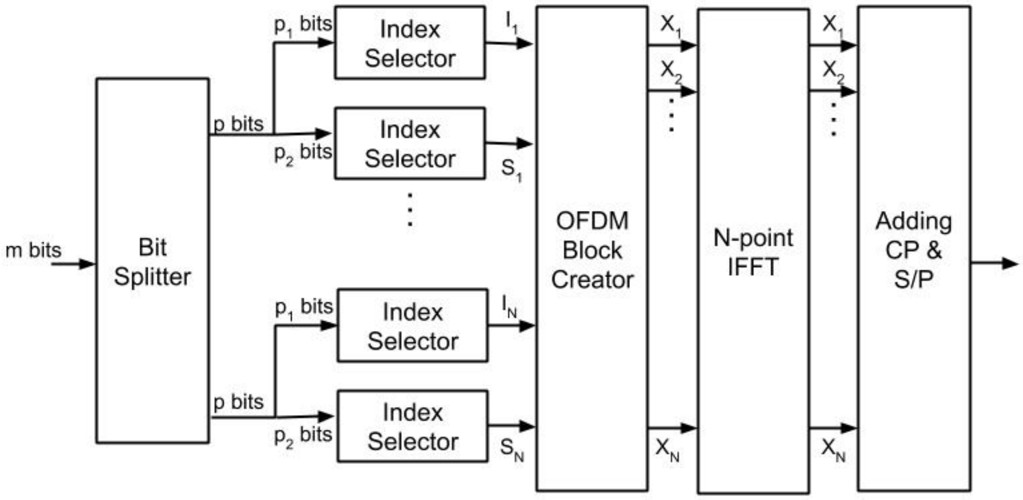
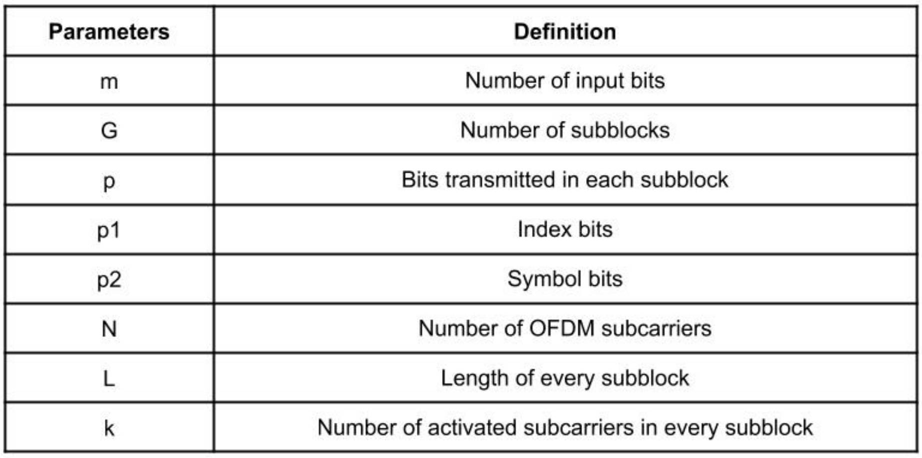


Figure 2.2: OFDM-IM Transmitter diagram [3].

2.2 OFDM-IM

On the other hand, OFDM-IM follows the general idea of the classic OFDM system that we have just described but creates OFDM blocks before feeding them into the N-point IFFT and from there to the rest elements of the OFDM's transmitter, as shown in Figure 3.2. The necessary parameters for this scheme are summarized in Figure 2.3.



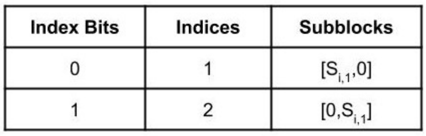
Parameters	Definition
m	Number of input bits
G	Number of subblocks
p	Bits transmitted in each subblock
p1	Index bits
p2	Symbol bits
N	Number of OFDM subcarriers
L	Length of every subblock
k	Number of activated subcarriers in every subblock

Figure 2.3: OFDM-IM parameters.

The OFDM-IM's TX receives as input m bits and divides them into G groups, each containing p bits, meaning $m = pG$. The length of every OFDM-IM's subblock is given by $L = N/G$, where N is the number of subcarriers. Every group of p-bits is further split into p_1 bits and p_2 bits; therefore, we have $p = p_1 + p_2$. The p_1 bits are the index bits, the number of bits that mapped onto the active indices of each subblock, equals to $p_1 = log_2(L)$ The p_2 bits are the symbol bits, the number of bits needed for the M-ary signal constellation, equals to $p_2 = log_2(\mathrm{M})$. Correspondingly, the N subcarriers are also divided into G subblocks with the same length.

The p_2 bits pass through the constellation mapper to create the vector containing the modulated symbols $\vec{S} = [\ S_1,\ S_2, \ldots,\ S_k\ ]$, where k is the activated subcarrier in every subblock and the selected indices are given as $\vec{I} = [\ I_1,\ S_2, \ldots,\ I_k\ ]$. By combining the according element of these vectors for every subblock, the OFDM block generator creates an $Nx1$ OFDM-IM symbol as $\vec{X} = [\ x_1,\ \ldots,\ x_k\ ]^T$. Unlike the conventional OFDM symbol, the OFDM-IM's contains some zero terms but, their positions carry information.

In this thesis and the simulations we ran, we assume that $L = 2$ so $p_1 = 1$ and the active subcarriers in each subblock is $k = 1$. Table 2 shows the possible values of an i subblock.



Index Bits	Indices	Subblocks
0	1	$[S_{i,1},0]$
1	2	$[0,S_{i,1}]$

Figure 2.4: OFDM-IM subblock with $p_1 = 1$, $L = 2$, $k = 1$.

CHAPTER 3

RESULTS

In our simulation, we use two modulation methods, M-PSK, for $M = 2, 4, 8, 16$, and M-QAM, for $M = 8, 16, 32, 64$, and compare the performance of OFDM AND OFDM-IM systems in an AWGN and a LTI channel.

In every simulation that we ran, the TX gets as input a vector of randomly generated bits and transmits them through a channel for different values of SNR. The AWGN, which is added to the transmitted signal, follows the normal distribution with zero mean and noise power $N_o/2$. The RX receives the altered by the noise signal, and after reversing the equivalent processes of TX, it calculates the BER for very value of SNR. The input vector contains $K * N * 10^5$ bits, where K is the number of bits needed for every M-ary symbol and N is the number of the subcarriers. In the LTI channel, in both OFDM and OFDM-IM systems, we generate 50 different channels for every value of SNR and sum the different values and get the average value by dividing with the number of channels.

To focus on the performances of the two systems, we make the following assumptions for our system designs used in the simulations. For the LTI channel, we take as granted that the channel $\vec{h} = [\ h_1,\ h_2, ...,\ h_{L_h}\ ]^T$, where L_h the number of channel's coefficients, is known to the RX and there is no need for channel estimation techniques. In addition to this, we establish that the pattern for the activated indices, shown in Figure 2.4, is also known to the RX, which is required to decode the information carried in the empty subcarriers.

3.1 Performance in AWGN channel

First of all, we focus on the performance of OFDM in comparison with OFDM-IM in an AWGN channel, for both M-PSK and M-QAM modulations. In Figure 3.1 and Figure 3.2, we can see that for all M-PSK modulation the BER is reducing faster, for example for BPSK, in OFDM the BER = 10^{-7} for SNR = 11 while in OFDM-IM we get the same value of BER for SNR = 8.

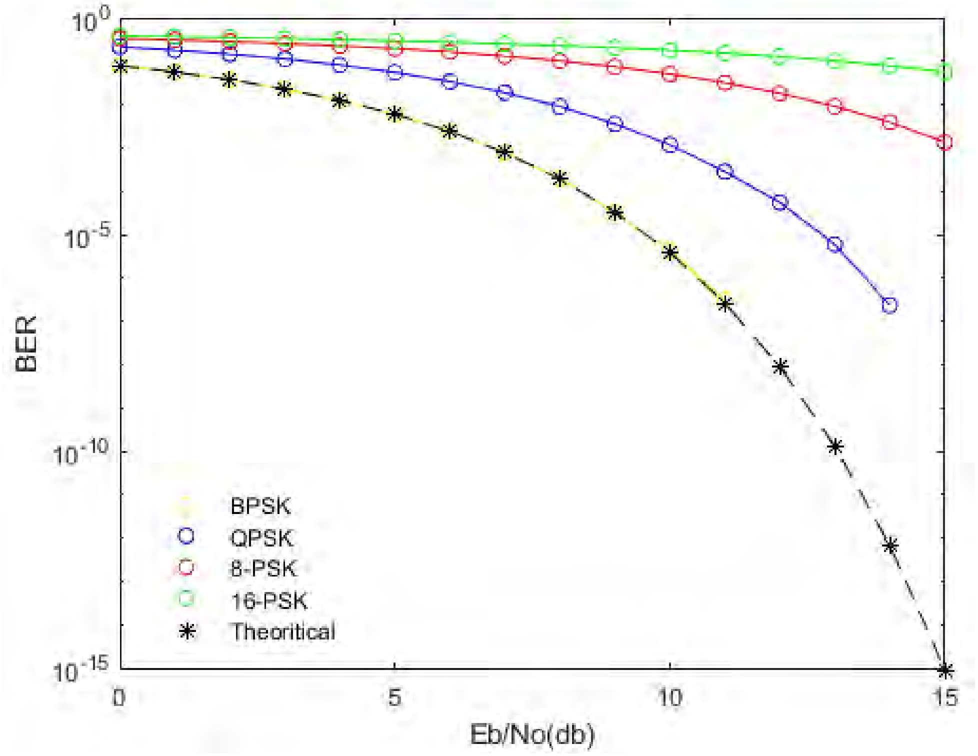


Figure 3.1: OFDM with M-PSK modulation in AWGN channel.

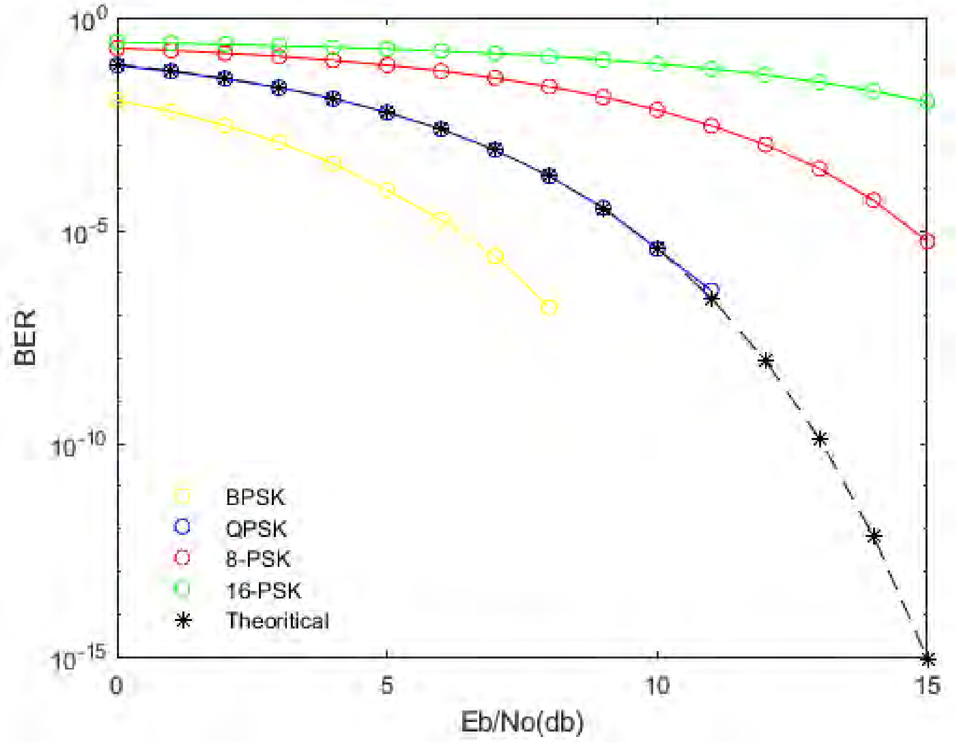


Figure 3.2: OFDM-IM with M-PSK modulation in AWGN channel.

We also get the same behaviour for M-QAM, as shown in Figure 3.3 and Figure 3.4 and at the same time increasing the difference of BER between different M for the same SNR. IN OFDM (Figure 3.3), for SNR = 10 the 8-QAM and the 16-QAM are almost equal to 10−1 but for the same SNR's value in OFDM-IM (Figure 3.4) the 8-QAM's BER $\simeq 10^{-2}$ and 16-QAM's BER $\simeq 10^{-1}$.

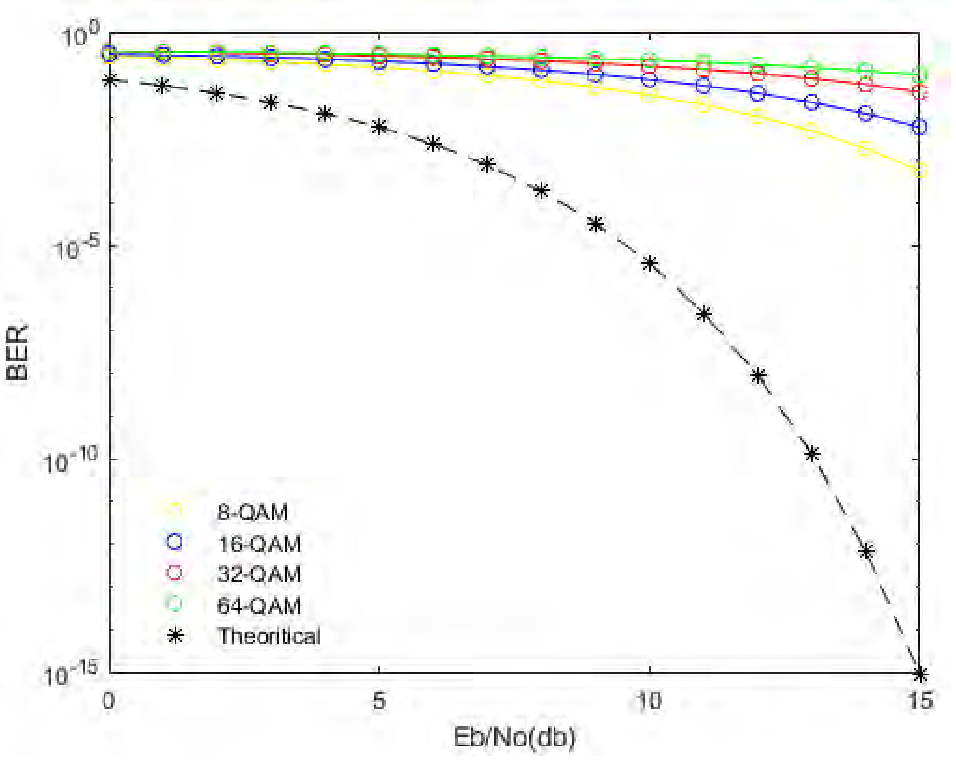


Figure 3.3: OFDM with M-QAM modulation in AWGN channel.

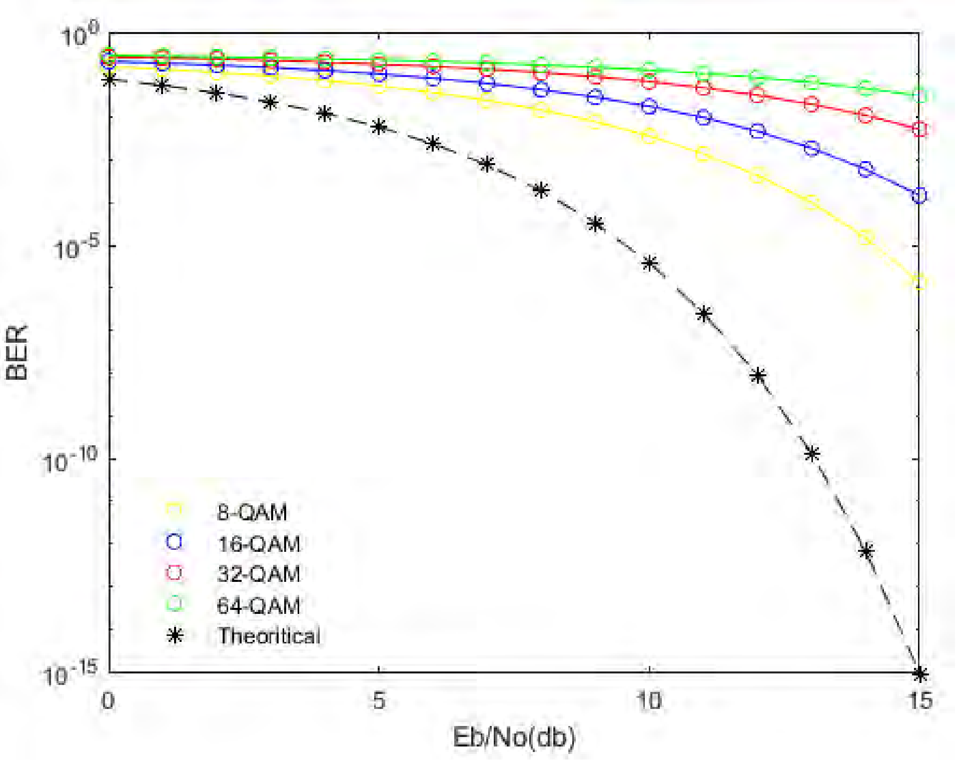


Figure 3.4: OFDM-IM with M-QAM modulation in AWGN channel.

3.2 Performance in LTI channel

In the LTI channel, we use different values of the SNR from the AWGN'S ones in order to get better and more understandable results. The diagrams may appear some abrupt increase or decrease, such as in Figure 3.5 for SNR = 20 the BPSK and the 8-PSK curve, due to the hardware's limitations used for running the simulation that did not allow us to increase the number of channel samples.

Apart from that, it is easy to spot that the BER using both modulations decreases when OFDM-IM is used. More specifically, for M-PSK modulation, considering Figure 3.5 and Figure 3.6 we can see that in OFDM-IM there is a shift of all the curves towards the Theoretical BER line, moving both the BPSK and the QPSK curve under the Theoretical one.

As long as M-QAM modulation is concerned, the OFDM-IM system is, again, more efficient than the classic OFDM. Figure 3.8 present the decline of the BER for every M-ary modulation to such a degree that 8-QAM line is almost identical to the Theoretical.

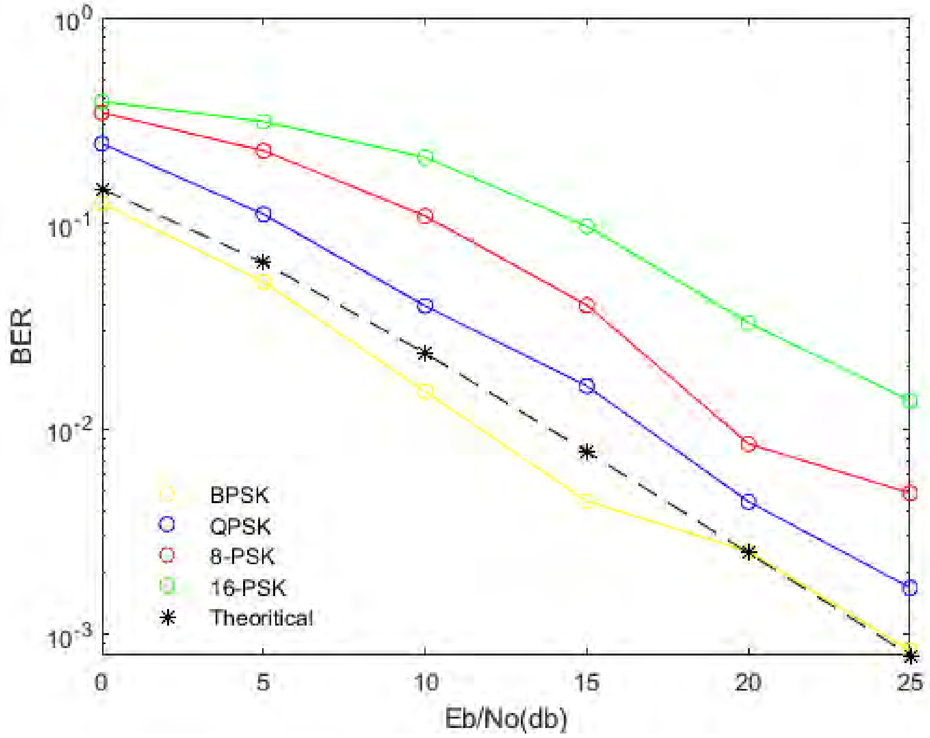


Figure 3.5: OFDM with M-PSK modulation in LTI channel.

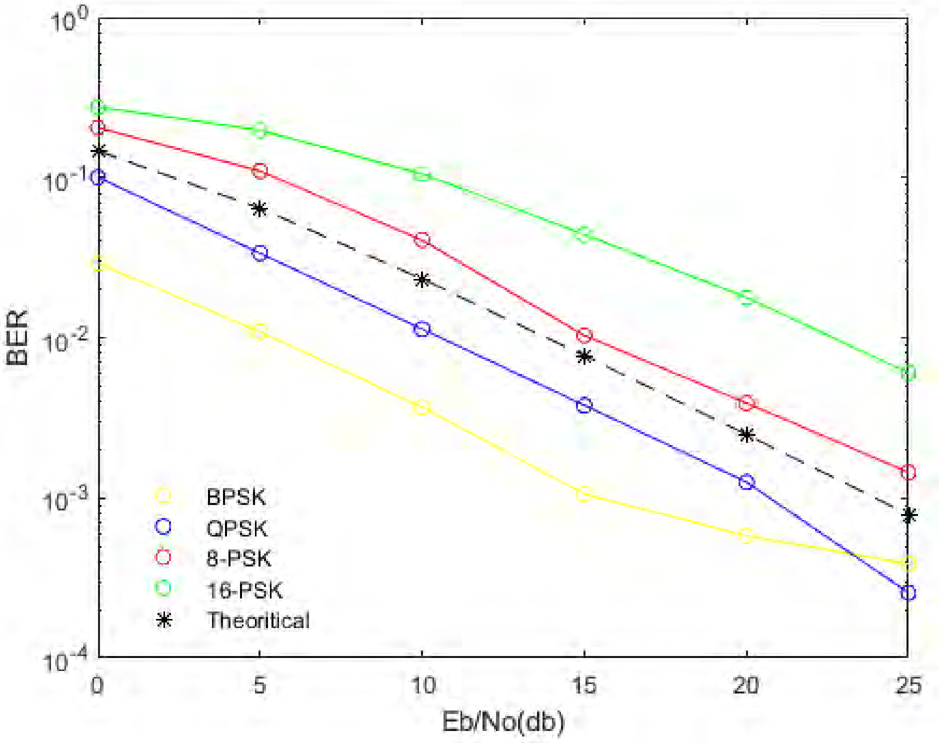


Figure 3.6: OFDM-IM with M-PSK modulation in LTI channel.

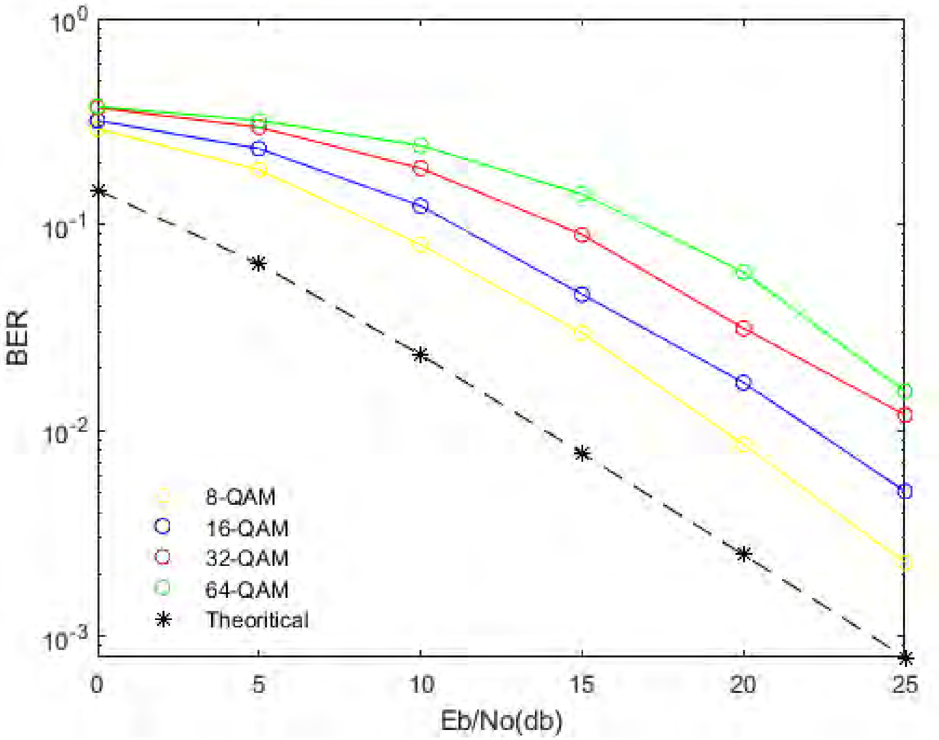


Figure 3.7: OFDM with M-QAM modulation in LTI channel.

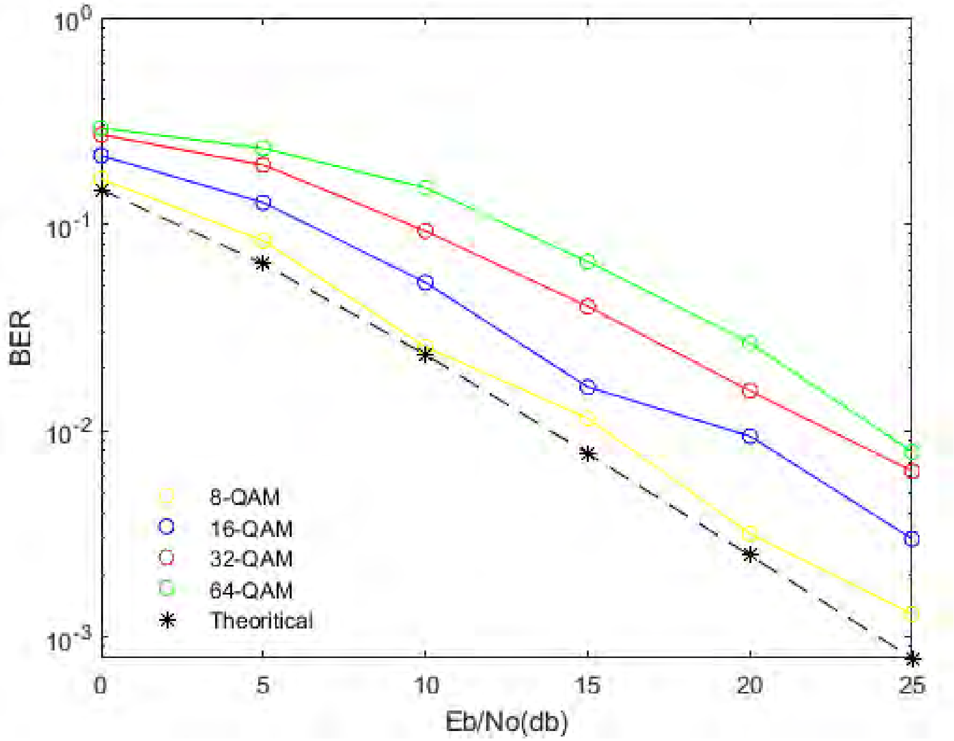


Figure 3.8: OFDM-IM with M-QAM modulation in LTI channel.

CHAPTER 4

CONCLUSIONS

In this thesis, we described OFDM-IM scheme, an extension of the classic OFDM scheme. The main difference between the different systems is that OFDM-IM splits the transmitted bits in index and symbol bits and by combining them it creates an OFDM-IM symbol, which may contain zero elements but their positions carry the information. A fully detailed presentation of both systems contributed to highlight their differences, their similarities and ensure a deeper understanding of simulations' results that followed. Through diagrams of SNR-BER we evaluate the performances of the two systems in an AWGN and a LTI channel and establish that OFDM-IM surpassed OFDM in every case. This is due to the fact that the index bits are encoded by the pattern we follow to create the subcarriers' subblocks. The channel or the additive noise does not alter them, so the RX is able to decode them correctly reducing the overall BER. It is safe to assume from our results and the papers referenced in this thesis that there is room for BER's further improvement if we use more bits for the indices. In conclusion, the OFDM-IM is an unquestionable promising technique that can offer better outcomes without requiring more advance processes or energy than an OFDM system. It can be the answer to the problems of high cost and computational complexity while having much application in mobile and optical communications [2].

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ACRONYMS AND ABBREVIATIONS

3G Third Generation

4G Fourth Generation

5G Fifth Generation

AWGN Additive White Gaussian Noise

BER Bit Error Ratio

BPSK Binary Phase Shifting Keying

CP Cyclic Prefix

FFT Fast Fourier Transform

IBI Inter-Block Interference

ICI Inter-Channel Interference

IFFT Inverse Fast Fourier Transform

IM Index Modulation

ISI Intersymbol Interference

LTE Long Term Evolution

LTI Linear- time Invariant

MIMO Multiple-Input and Multiple-Output

ML Maximum Likelihood

OFDM Orthogonal Frequency-Division Multiplexing

OFDM-IM Orthogonal Frequency Division Multiplexing with Index Modulation

S/P Serial-to-Parallel Converter

PARP Peak-to-Average Power Ratio

P/S Parallel-to-Serial Converter

RX Receiver

PSK Phase Shift Keying

QAM Quadrature Amplitude Modulation

SM Spatial Modulation

SNR Signal to Noise Ratio

TX Transmitter

WiMAX Worldwide Interoperability Microwave Systems