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A Novel Multi-Mode OFDM with Index Modulation

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By

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A Novel Multi-Mode OFDM with Index Modulation

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Abstract

Though Orthogonal Frequency Division Multiplexing (OFDM) is the most common modulation scheme, the conventional OFDM cannot meet the requirements of high demand of throughput, Spectral Efficiency (SE) and lower energy consumption for the Next Generation of Wireless Communication systems. OFDM with Index Modulation (OFDM-IM) introduces additional index bits of Index Modulation with classical OFDM symbols to maximize SE. However, OFDM-IM cannot meet the minimum requirement of throughput and SE as OFDM in higher modulation order.

The objective of this study was to review different OFDM-IM variants to resolve the SE issue. Then, a suitable system, Novel Multi-Mode OFDM with Index Modulation (NMM-OFDM-IM) was developed for improved SE with minimum energy consumption at a given BER performance. The proposed Novel MM-OFDM-IM has similar multiple, distinguishable M-ary modulation constellation as MM-OFDM-IM[1]. The results showed, with the introduction of multiple, different constellations, the challenge with throughput and SE was resolved. However, MM-OFDM-IM lacked energy-saving benefits due to skipping inactive subcarriers through Subcarrier Index Selector (SIS). SIS of OFDM-IM keeps inactive subcarriers to save energy for the target of "GREEN G".

Based on the results of other IM variant studies, a Novel MM-OFDM-IM with two index selectors consisting of Subcarrier Index Selector (SIS) and Mode Index Selector (MIS) was proposed. SIS helps to maintain lower power consumption. MIS indicates the pattern of active subcarriers of a subblock taking a specific arrangement of mode constellations. Therefore, it can compete with OFDM even in higher modulation order for enhanced SE, whereby it has a higher energy-saving rate than MM-OFDM-IM. This study explains the MIS design and constellation pattern along with the impact of Energy Saving compared with other systems.BER and SER were simulated in MATLAB. The results showed SIS and MIS are less affected by errors than conventional modulated symbols.

Dedication

To my loving family and friends

especially my mother, Shila Barua

and my daughter, Aurora Barua

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List of Abbreviations

1G	First generation
AMPS	Advanced Mobile Phone System
APM	Amplitude or Phase Modulation
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
bps	bits per second
BW	Bandwidth
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
DL	Down Link
DM-OFDM	Dual-Mode Index Modulation aided OFDM
DMI	Dual Mode Indexing
EDGE	Enhanced Data GSM Environment
EE	Energy Efficiency
ES	Energy Saving
FDMA	Frequency Division Multiple Access
GI	Guard interval

GPRS	General Packet Radio Services
GSM	Global Systems for Mobile Communications
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
ICI	Inter Carrier Interference
IDFT	Inverse Digital Fourier Transform
IFFT	Inverse Fast Fourier Transformation
IM	Index Modulation
ISI	Inter Symbol Interference
LLR	Log-Likelihood Ratio
LO	Local Oscillator
LTE	Long Term Evolution
MIMO	Muti-Input Multi-Output
MIS	Mode Index Selector
MM-OFDM-IM	Multiple-Mode OFDM with Index Modulation
mmWave	Millimeter-Wave
OFDM	Orthogonal Frequency Division Multiplexing
OFDM-HIQ-IM	OFDM with Hybrid In-Phase/Qudrature IM
OFDM-IM	OFDM with Index Modulation
OFDM-IQ-IM	OFDM with In-phase/Quadrature Index Modulation
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation

SE	Spectral Efficiency
SIM	Subcarrier Index Modulatiov
SIS	Subcarrier Index Selector
SM	Spatial Modulation
TACS	Total Access Communication System
TDMA	Time Division Multiple Access
UL	Up Link
UMTS	Universal Mobile Telecommunications Service
W-CDMA	Wideband Code Division Multiple Access

Chapter 1

INTRODUCTION

Wireless communication has brought global connectivity and mobility in our day-to-day life. This communication system can be defined as a process which transmits data using electromagnetic or acoustic waves in place of wires, cables or fiber optics [2]. These transmitting signals can be radio-frequency, infrared or microwaves. In past few decades, the wireless telecommunication service had a paradigm shift from simple push to talk system to seamless end to end cellular and internet service.

1.1 Evolution of Wireless Communication

First generation (1G) was declared in late 1970s that includes many subscribers such as Advanced Mobile Phone System (AMPS) in North America, Total Access Communication System (TACS) in the United Kingdom and Japan [3]. It used analog system to provide basic voice service up to 2.4 kbps with 30 KHz bandwidth and Frequency Division Multiple Access (FDMA) technology.

In early 1990, a digital cellular system was designed for voice communication known as Global Systems for Mobile Communications (GSM) and 2G. It used time division multiple access (TDMA) transmission technology with 200 KHz bandwidth and data rate up to 9.6 kbps. Then General Packet Radio Services (GPRS) technology known as 2.5G improved the data up to 50 kbps with same bandwidth which was brought to compensate the low data rate of GSM. Enhanced Data

GSM Environment (EDGE) improved the data up to 200 kbps by using 8PSK techniques. The main attraction was the multimedia high speed data application and packet-switch service [4].

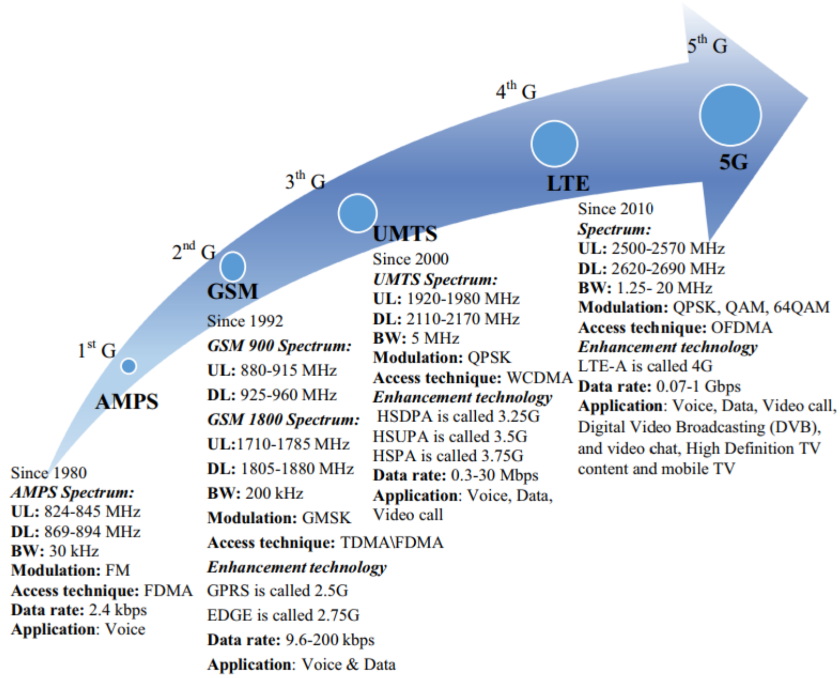


FIGURE 1.1: Generation Evolution of Wireless Communication with main features [3]

3G allowed people to stream video and audio service and browse web through high-speed internet. Hence, Mobile broadband became popular with 3G using Wideband Code Division Multiple Access (W-CDMA) and High Speed Packet Access (HSPA) [5].

Long Term Evolution (LTE) is considered as 4G technology. It is radio access technology with Orthogonal Frequency-Division Multiplexing (OFDM) with multi-antenna transmission. It ensures high quality of service, excellent spectral efficiency due to its orthogonality and noise reduction through adaptive beamforming of antenna arrays. It increased the peak data rate 100 Mbps with 20 Mhz. Increasing number of users pushed towards the need of next generation 5G.

5G communication has promised to provide low latency of 1ms with closed to unlimited data sharing and information of peak data rate 20Gbps [6]. It needs to provide Enhanced Mobile Broadband (eMBB), Ultra-Reliable Lowlatency Communications (URLLC), and Massive Machine-Type Communications (mMTC). The wireless industry is racing to transition from existing 4G technology to 5G that will operate in mmWave spectrum that starts from 24.25 GHz to 52.6GHz [7].

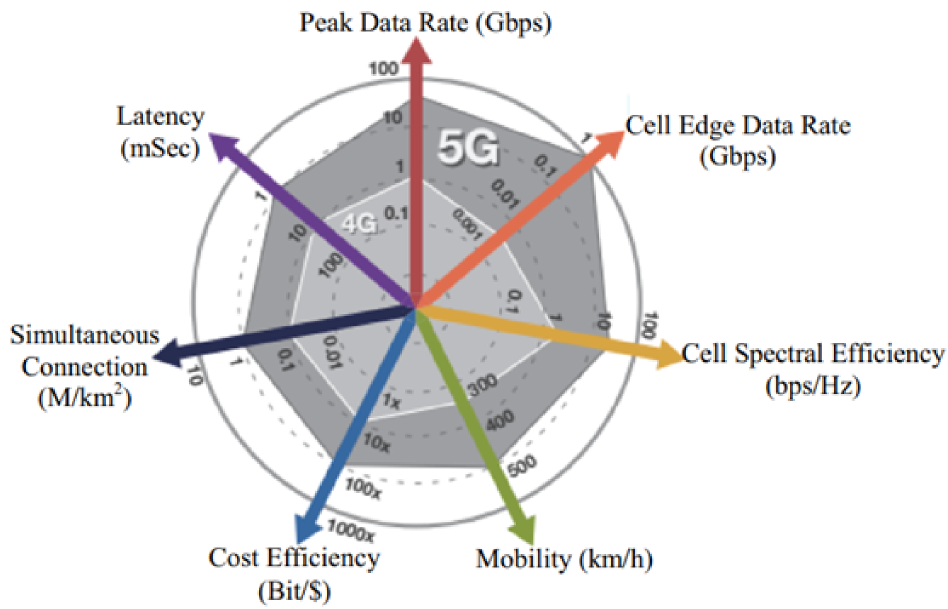


FIGURE 1.2: Evolution from 4G to 5G performance indicator [8]

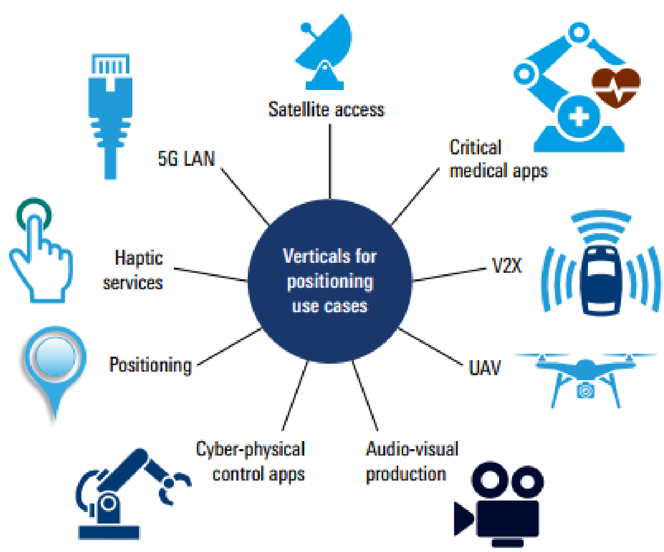


FIGURE 1.3: Enhanced services beyond 5G phase 1[6]

1.2 Multiplexing

Multiplexing is a strategy of sending combined analog or digital signal through a common medium in information and communication network. It splits the communication medium for example, fiber optics, cable or wireless channel into a certain number of logical channels where every single one of them is utilized to move a different message or information stream. Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA) use the Multiplexing Techniques in different norms.

Generations	1G	2G	3G	4G	5G
Data Bandwidth	2 Kbps	64 Kbps	2Mbps	1 Gbps	20 Gbps
Multiplexing	FDMA	TDMA	CDMA	OFDM	Modified OFDM
Primary Services	Analog Phone Calls	Digital phone calls and messaging	Phone calls, messaging, data	All- IP Service (including voice messages)	High speed, high capacity and provide large broadcasting of data in Gbps
Key Differentiator	Mobility	Secure, Mass adoption	Better internet experience	54.67 Faster broadband internet, Lower latency	Better coverage and no dropped calls, much lower latency, better performance
Major Concern	Weak security issues, no roaming	Digital signals were reliant on location and proximity, required strong digital signals to help mobile phones	Need to accommodate higher network capacity	battery use is more, required complicated hardware	Implementation recently started

Table 1.1: Multiplexing techniques with generations [9, 10]

1.2.1 Why Multicarrier Transmission System?

A signal in a wireless channel can propagate in different multipath with different channel gain and time delay while reaching to a user. So, the channel co-efficient will be $h(t) = \sum_{m=1}^{M} a_m \delta(t - T_m)$. This is called Multipath fading. As the earliest component of the signal of Line of Sight and the last arriving signal component can have a time difference which is called delay spread [11]. This can arise the problem of Inter Symbol Interference (ISI) by overlapping to the subsequent symbol. Now, if a single carrier with B=1MHz where symbol time will be $T_s = \frac{1}{B} = 1$ microsecond (μs)

propagate in multipath and have 2 μs delay, it will overlap the next symbol of 1 μs for having total 3 μs of symbol. Hence, rather than having one wideband single carrier of 1MHz, multiple subcarriers with small bandwidths like 100 subcarriers with each having 10KHz are taken. Now, the symbol time will be 100μs where delay spread of 2 μs is negligible. For this reason, multicarrier wireless transmission like FDMA gained popularity in the wireless communication world[12].

1.2.2 FDMA Vs OFDM

FDMA provides a part of the frequency or each subcarrier of the available bandwidth, W to each user. This way, it can transmit data to many users at the same time and there is no ISI due to the carrier spacing of non-overlapping subcarriers. A guard band is placed in between each subcarrier to ensure spacing of carriers and avoid any interference. However, the extra guard bands eventually waste the additional bandwidth which is a limited resource.

Orthogonal Frequency Division Multiplexing (OFDM) took place of FDMA to mitigate this problem. As the subcarriers of OFDM are orthogonal to each other, it can overlap without having any interference. It is possible because when the 1st subcarrier reaches its peak, subsequent subcarriers are null at this point in figure 1.4. For this reason, OFDM is used in 4G LTE service due to its exceptional multiplexing feature.

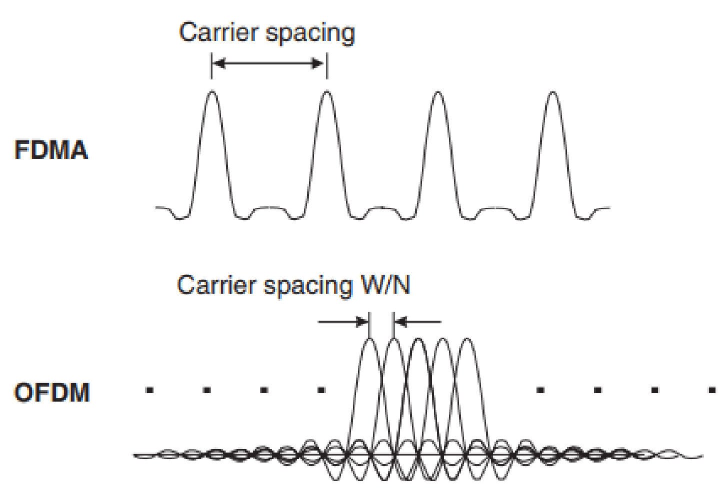


FIGURE 1.4: FDMA Vs OFDM [2]

1.2.3 OFDM

OFDM attracted both the scholarly world and communication industry because of the quick advancement of wireless communication technology and the high demand of data transmission rate to meet the ever increasing mobile traffic in recent times [13]. Main goal of communication system is having the connection at "anywhere and anytime". OFDM has become one of the prominent modulation techniques in 4G communication system. Historical progression and practical implementation are shown in figure 1.5.

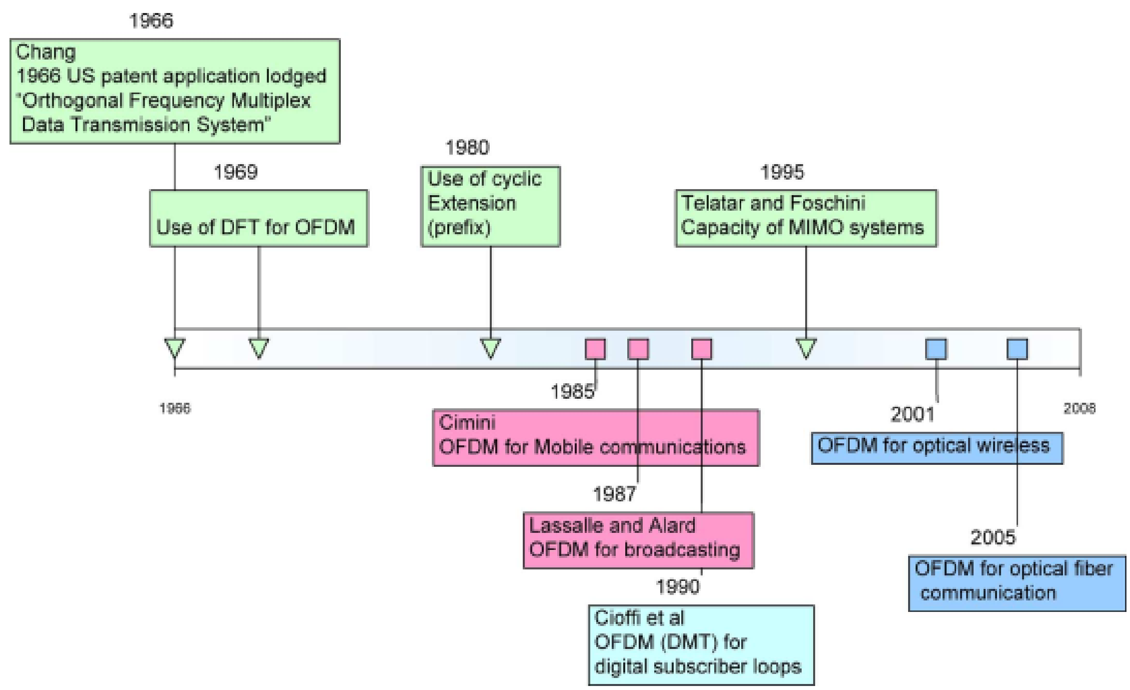


FIGURE 1.5: OFDM's historical progression and its practical implementation [13]

OFDM basically divides high speed data stream into several low speed data streams. Then those data streams are modulated on subcarriers which are orthogonal to each other. In OFDM system, small scale fading and Inter Symbol Interference (ISI) is avoided as the symbol period is larger than delay spread[14]. The subcarriers in OFDM system have significant overlap in frequency domain which results in, very high spectral efficiency.

1.3 Index Modulation

In classical OFDM, the information is conveyed through the modulated symbols in each subcarrier. Meanwhile Index Modulation brought a new concept of transmitting data by activating a portion of indexed resource entities like antennas, subcarriers, or time slots etc. Rest of the transmission entities are kept unused which enhance the spectral and energy efficiency significantly [15]. This is done along with the Amplitude or phase Modulation (APM) . This way, additional bits can be carried out by the position of symbols in subcarriers without any energy consumption. It uses fraction of resources for same throughput as classical OFDM with considerable diversity gain and simple computational detection system. Hence, IM is popular in Wireless Communication system applications and already has been used in (mmWave) transmission [16, 17], massive MIMO [18, 19]and network coding [20]

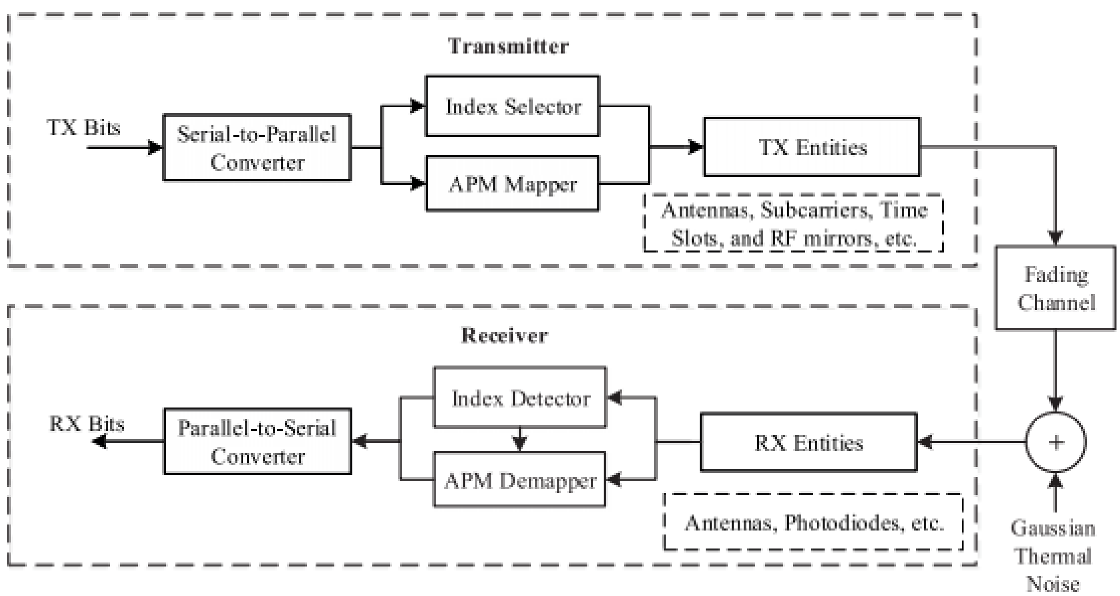


FIGURE 1.6: General IM-aided system design[15]

1.3.1 SIM

Subcarrier Index Modulation (SIM) is very early concept of index modulation on OFDM. It was created from a simple thought of dividing entire incoming bits into two parts where one portion is used for the active subcarrier position indicator and other part is used for conventional information transmission by modulated signal. This was the first step taken to achieve "Green G Communication" [21]. The power consumption reduces due to idle subcarriers with the production of same throughput and BER as conventional OFDM [22]. This was not widely accepted because of its bits propagation error in presence of Additive White Gaussian Noise (AWGN) [23].

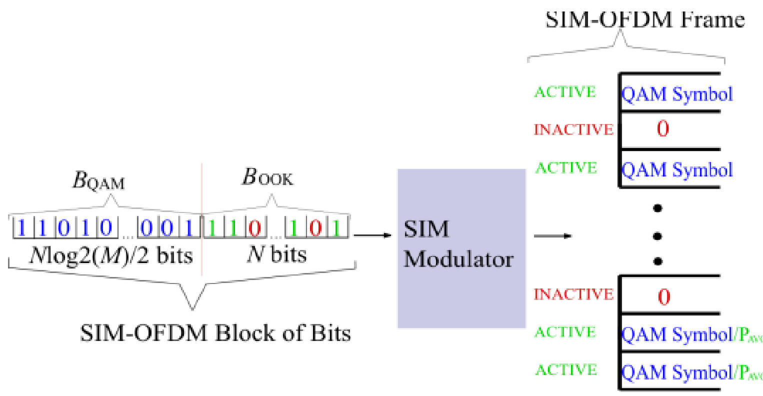


FIGURE 1.7: Basic Concept of SIM [23]

IAs shown in this figure, first portion of incoming bits, B_{OOK} defines the activation of subcarriers and the other part of bitstream B_{QAM} is mapped according to M-QAM constellation to pass though the active subcarriers. The majority bits in between '1'and '0' of B_{OOK} indicates useable subcarriers and others are kept unused.

1.3.2 OFDM-IM

The data rate of OFDM with Index Modulation (OFDM-IM) [24] is the main attraction for the beginning of IM revolution in the research sector. Using the same framework of current wireless system, Index Modulation brings the computational design change in software. It saves energy by not sending modulated symbols through a portion of the subcarriers [25]. Whole subcarriers are divided into small subgroups and then combinatorial methods are used on that size of subblocks for indexing. It not only increases the index transmission bits for higher amount of possible realization but also reduces the chance of getting all subsequent bits wrong as SIM-OFDM .

Greater Spectral Efficiency with little power consumption is its one of the main advantages and it outperforms conventional OFDM in terms of BER and other efficiencies. Nevertheless, data transmission beyond 32-64 QAM is not possible by this method in most of the subblock settings according to the reference paper [25]. It is unable to meet the expected data rate because of inactive subcarriers at the cost of indexing.

1.3.3 OFDM-IQ-IM

OFDM with In-phase/Quadrature phase Index Modulation (OFDM-IQ-IM) [26] came to limelight for solving expected data rate at higher modulation order. The design is the basic of all communication system modulation pattern using in-phase and quadrature phase for sending the symbol in the channel. However, too much independence in symbol positioning in subcarrier pattern resulted in variable energy saving and irregular pattern of the constellation diagram.

1.3.4 DM-OFDM

Dual-Mode Index Modulation aided OFDM (DM-OFDM) [27] also mitigated the problem regarding throughput in the system regarding higher modulation system. It created two different modulation schemes for the indexing but kept all the subcarriers active for system transmission like conventional OFDM. Data boost was the main motivation in this system, and it can work in any modulation order. SE remains unaffected for any types of modulation order. The only drawback is that it has the same power consumption as OFDM and there is no energy saving in this design.

1.3.5 MM-OFDM-IM

Multiple-Mode OFDM with Index Modulation (MM-OFDM-IM) [1] has its unique feature of introducing different constellations per subcarrier. It increases data transmission bits by the factorial of subgroup of subcarriers size. This results in the highest number of producing additional bits through indexing which is even more than combinatorial method. The only drawback of the system is that it uses all the subcarriers like conventional OFDM that leads to no energy saving option. It is still a better option rather than classical OFDM since it outperforms OFDM in case of throughput with similar power consumption and BER[28].

1.4 Thesis Objective and Organization

As the impact of Index Modulation in OFDM system has been discussed, there is no doubt about the necessity of a big change in the existing framework to step into the Next Generation Wireless System. The most desirable way to bring a change is in the software side since hardware change are more expensive and all the devices need to be replaced for its upgradation. For this reason, Index Modulation got the utmost consideration in this field. Many notable systems with index modulation merged with OFDM and their modified variants. These systems were extensively reviewd as part of this work and illustrated in the following Chapter 2. After extensive review of the existing systems and noticing their respective flaws, a modified system named Novel Multi-mode OFDM with Index Modulation (NMM-OFDM-IM) was developed and designed applying the relevant solutions from the existing systems. The development of this proposed NMM-OFDM-IM is described step by step in Chapter 3.

In Chapter 4, all the IM variant systems along with the proposed NMM-OFDM-IM are explained through the data flow in one subblock in order to understand each system and to compare the proposed NMM-OFDM-IM with each system. The process of information bits transforming in transmitted signal with respect to Indexing is explained clearly with block diagram; associated look-up table; total transmitted bits, m and constellation diagram in section 4.1.

The proposed NMM-OFDM-MM-IM was also analyzed based on Total Transmitted Bits with same subblock size and modulation order. NMM-OFDM-IM was compared in respect of Spectral Efficiency and Energy Efficiency with different IM systems in section 4.3 and section 4.4. Mode constellation design was also compared with other constellation in section 4.5 to compare with other variants. At last, in section 4.6 performance of the system is observed in MATLAB simulation along with OFDM-IM and MM-OFDM-IM in order to crosscheck the hypothesis. Bit Error Rate (BER) and Symbol Error Rate (SER) were presented in graph 4.23 which shows they decrease significantly compared to OFDM-IM in high SNR regions.

Chapter 5 highlights the key findings and results of the proposed NMM-OFDM-IM and what can be done in future on the proposed system to attain better further efficiency and performance.

Chapter 2

LITERATURE REVIEW ON OFDM AND INDEX MODULATION VARIANTS

2.1 Index Modulation Family

Orthogonal Frequency Division Multiplexing (OFDM) is the most widely used multi-carrier transmission modulation technique in the current world of wireless communication system for satisfying the increasing demand of high data rate. Since OFDM is the core modulation technique of all the existing system, complete exclusion of OFDM and introduction of a whole new concept of modulation for the next generation wireless communication system is not feasible.

Thus, applying the concept of Spatial Modulation (SM) [29, 30] in the subcarriers of OFDM block i.e., OFDM with Index modulation (OFDM-IM) was brought into the attention as a feasible candidate of 5G wireless communication. OFDM-IM is a modified OFDM modulation technique where the information is transmitted through the M-ary symbols of constellation diagrams as well as with the subcarrier indices. This eventually increases spectral efficiency and saves energy consumption.

Primarily, the concept of sending extra information via the transmission entities was used in Spatial Modulation [29] along with the OFDM system. One of the transmit antenna was kept active from multiple transmit antennas to convey the additional information bits in addition to the conventional modulation symbols. Similarly, in Subcarrier Index Modulation OFDM (SIM-OFDM) [22], subcarriers with majority bits were kept active instead of transmit antenna indices to carry the index bits. Later, Enhanced Subcarrier Index modulation OFDM (ESIM-OFDM) [23] was introduced where half of the subcarrier indices were kept active to increase performance but unfortunately it lacks in spectral efficiency than SIM. So, OFDM-IM [31] came along with the flexible number of active subcarrier combination in the OFDM block which outperforms conventional OFDM.

After that, OFDM-IM had undergone through several modifications to eliminate its limitations of lower spectral efficiency for higher modulation order and surpass the energy consumption which are known as novel OFDM-IM variants [1, 26, 27, 32, 33]. Therefore, a long evolution of OFDM-IM system has occurred from SIM to stand where it is now.

Evolution of OFDM with index modulation	Year
Subcarrier Index modulation OFDM (SIM-OFDM) [22]	2009
Enhanced Subcarrier Index modulation OFDM (ESIM-OFDM) [23]	2011
OFDM with Index Modulation (OFDM-IM) [24, 31]	2013
OFDM with Generalized Index Modulation (OFDM-GIMI, OFDM-GIMII) [32]	2015
OFDM with in-phase/quadrature index modulation (OFDM-I/Q-IM) [26, 32]	2015
Dual-mode index modulation aided OFDM (DM-OFDM) [27]	2016
MultiMode Index Modulation (MM-OFDM) [1]	2017
Quadrature Dual Mode Index Modulation (QDM-OFDM) [33]	2018

Table 2.1: Evolution of OFDM with index modulation

2.2 OFDM

Orthogonal Frequency Division Multiplexing (OFDM) [13] divides high-rate information stream into several low-rate streams. They are sent over parallel narrowband channels that are less affected by the impulse noise than other Multicarrier Transmission system. OFDM allows the subcarriers to overlap with each other without having any Inter Carrier Interference (ICI) . This can be done due to its orthogonality which results in saving large amount of bandwidth than other Frequency Division Multiplexing. This modulation scheme is particularly suitable for high information rate transmission and high Spectral efficiency due to significant overlapping of subcarriers in delay spreading medium [34].

2.2.1 OFDM Transceiver

OFDM is designed with a transmitter and a receiver that send information and then retrieve it from a frequency fading channel in between. Input data is a binary bit stream comprising 1 and 0s are first digitally modulated by M-ary mapper into frequency domain symbols that are mapped into constellation diagrams. There are total M symbols in the constellation, each symbols represent $p = \log_2 M$ bits. It can be said that there are 2^p possible realizations for constellation points. This modulated data stream is then transformed from serial to N parallel low-rate data streams.

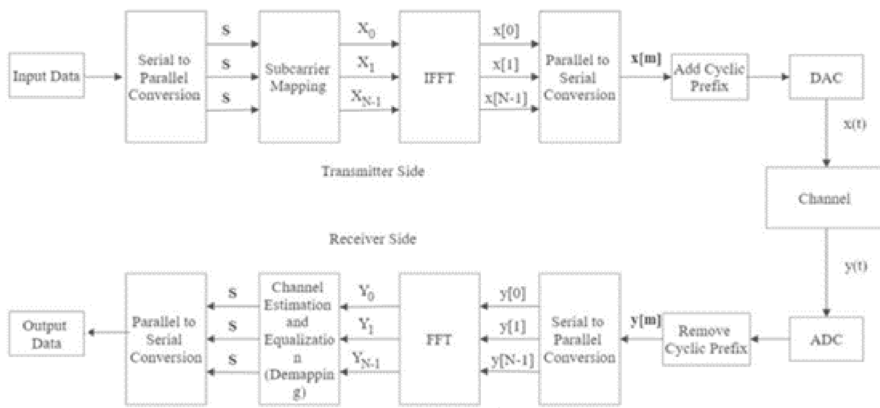


FIGURE 2.1: OFDM Transceiver [10]

After any Amplitude Phase Modulation in M-ary Mapper, complex symbol, X_i goes into IFFT block. X_i is the APM constellation symbols modulated at i^{th}subcarrier. Local Oscillators (LO) at a frequency of $f_l = l\frac{W}{N}$ where $l = 0, 2, \ldots N-1$ modulates the low-rate N data streams in carrier with orthogonality among subcarriers [2]. The transmitted OFDM signal can be represented as [35],

$$x(t) = \sum_{i=0}^{N-1} X_i \, exp(j2_i t); \qquad 0 \leq t \leq T \tag{2.1}$$

where, T is OFDM symbol interval period, $T = NT_s$; $T_s = e$each symbol period. f_i can also be written as, $f_i = f_o + \frac{1}{T}$. the subcarriers will be mutually orthogonal as follows:

$$\frac{1}{T}\int_0^T exp(j2\pi f_i t)exp(-j2\pi f_b t)dt = \begin{cases} 1, & i = b, \\ 0, & i \neq b, \end{cases} \tag{2.2}$$

Where $|f_i - f_b| =, \quad l = 0, 1, ... N-1$

Many Local oscillators has been replaced by computational tool Fast Fourier Transformation (FFT) to reduce complexity and for cost effectiveness. So, Inverse Digital Fourier Transform (IDFT) is done on OFDM signal x(t) at a sample rate of $\frac{T}{N}$

$$x[b] = x(\frac{bT}{N}) = \sum_{i=0}^{N-1} X_i \;\; exp(j\frac{2\pi}{N}ib) \tag{2.3}$$

It eventually indicates the original data symbol of X_I. Discrete Fourier Transform (DFT) is performed at the receiver. This is the main modulation process of OFDM which made it possible to implement in practical world for its calculation simplicity than LO's hardware implementation. IFFT and FFT is used in place of IDFT and DFT for simple computational complexity.

OFDM has been popular due to its reduction of delay spread by N times in multipath channel propagation. Guard interval (GI) , Tc with longer than maximum time delay needs to be inserted to diminish ISI. Though the main feature of OFDM, orthogonality may suffer if there is no sample during GI. So, Cyclic Prefix (CP) which is a copy of input data each OFDM symbol is inserted into GI. Since, time delay spread is less than Tc, signal now inevitable of Inter Carrier Interference (ICI). This OFDM signal has up-conversion in Analog to Digital Converter to a higher carrier frequency to propagate in wireless fading channel. At the receiver all the reverse operation of transmission is done in chronological order.

2.2.2 Advantage

OFDM signals are orthogonal to each other that can save a large amount of bandwidth. It is also possible to integrate computational tool of IFFT and FFT in place of numerous Local Oscillators (LO). Los are difficult to implement because of their high synchronization. Thus IIFT/FFT is less complex and cost-effective method. GI and CP diminish the chance of ISI and ICI caused by time varying fading in wireless channel. Bit error Rate (BER) is as low as 10^{-4} at 5 decibels of Signal to Noise Ratio (SNR).

2.2.3 Disadvantage

OFDM has made its way in the existing Wireless Communication framework of 4G-LTE

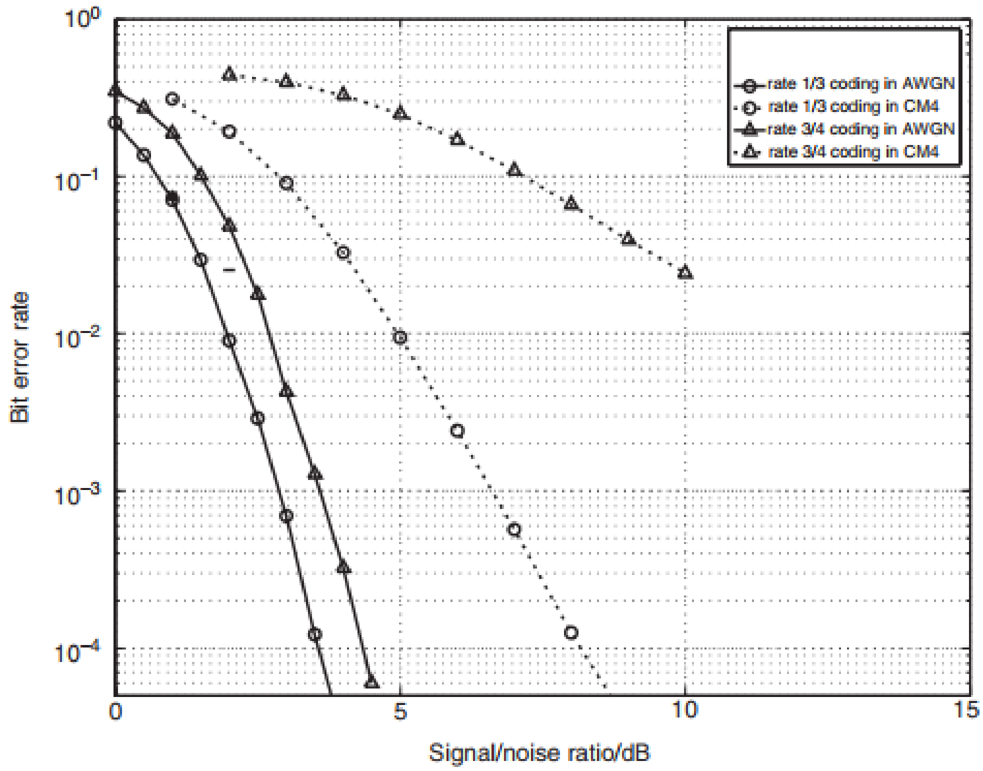
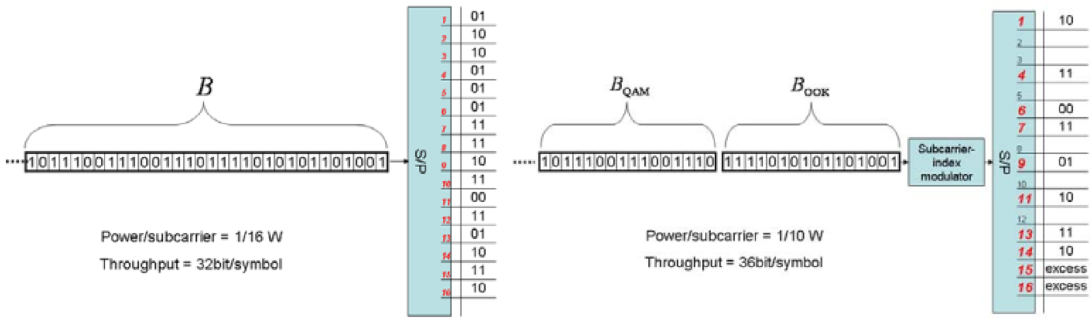


FIGURE 2.2: Bit Error Rate of OFDM [2]

for its numerous advantages. However, as the demand of higher data rate has sky rocketed, OFDM has its limitation of increasing data rate while 20 Gbps peak data rate is expected in 5G. It also has high Peak to Average Power Ratio (PAPR) that affects battery life and BER degradation.

2.3 SIM

Subcarrier Index Modulation (SIM) [22] is the early concept of transitioning from Spatial Modulation (SM) [29] to Subcarrier Modulation. This technology came as a new degree of freedom for better SE to compensate the high demand of increased data rate. In conventional OFDM, input bit streams are modulated by M-ary APM Mapper and divided into N low-rate constellation signal stream to achieve orthogonality among N subcarriers by LO or IDFT and transmitted to the channel after up-conversion. Here, all the subcarriers are active and carry signal stream. Whereas SIM divides the whole input bit stream into two blocks, one of the N bit block determines which of the subcarriers are active and can carry modulated signal stream by its majority bits, N_{maj} and another $\frac{N}{2}\log_2 M$ bit block are modulated by the conventional mapper and goes into the predetermined active subcarriers for other processes of OFDM transmission. Here, $N_{maj} > \frac{N}{2}$ is always maintained and $N_{ex} = N_{maj} - \frac{N}{2}$; these excess control subcarriers are kept in order to de-map majority bit value in the receiver.



(a) Conventional OFDM (b) SIM OFDM

FIGURE 2.3: OFDM and SIM subcarrier mapping part of the respective transmitter[22]

If there are N=16 subcarriers, M= 4 QAM modulation technique is used conventional OFDM, then total $B = N \log_2 M =$ 32 bits are modulated for the transmission shown in figure 2.3. Total throughput =32bits/symbol. On the other hand, N bits are first taken as B_{OOK} for determining which of the subcarriers are going to be kept active for the signal transmission for total N=16 subcarriers. The majority of 1 or 0 bits in that block is counted as N_{maj} bits. In figure 2.3, N_{maj} is the total count of 1 bit in B_{OOK} as ten of them present in the block while six of B_{OOK} bits are 0. Hence, B_{OOK} bit stream is used as On Off Keying to activate ten of the subcarriers out of the sixteen subcarriers. Rest of the bits, $B_{QAM} = \frac{N}{2} \log_2 M = 8 \times 2 = 16$ are modulated by 4QAM just like classical OFDM and goes into first eight active subcarriers. Rest of the two subcarriers for signaling majority bit value carries a signal of average power of 4 QAM, i.e., 4 bits used for excess bits. Hence, total throughput of SIM is 36 bits/symbol without lower power consumption by six inactive subcarriers.

2.3.1 Advantage

A new degree of freedom is added in Spectral Efficiency by sending information through subcarrier activation. It requires less power consumption than conventional OFDM. There are two power policies to allocate inactive subcarrier's power.

- **Power Reallocation Policy (PRP):** Power allocated for the inactive subcarriers are redistributed to active subcarriers. In this way, the power as well as the amplitude of constellation signal points of active ones increase that results in BER improvement as the distance between the constellation points increase, shown in figure 2.4

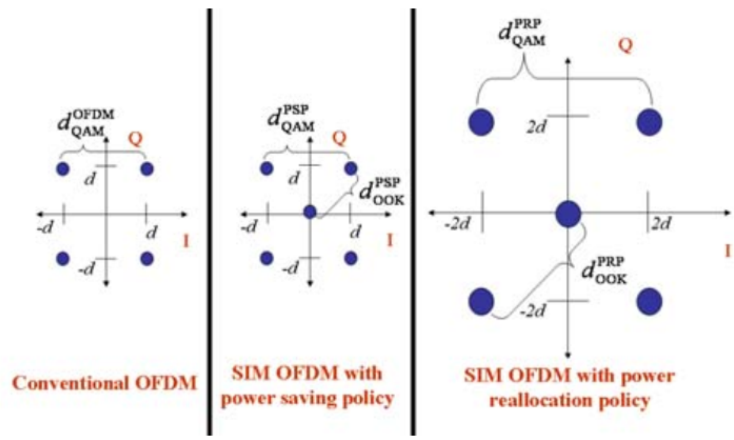


FIGURE 2.4: BER improvement due to PRP policy [22]

- **Power Saving Policy (PSP):** PSP does not carry any power in the inactive subcarriers that results in better power saving in this system than classical OFDM. It was shown in figure 2.3 that the power per subcarrier is lower than power/subcarrier in OFDM by 3.75%. SIM has even better BER performance due to inactive subcarriers as well as Power Reallocation Policy.

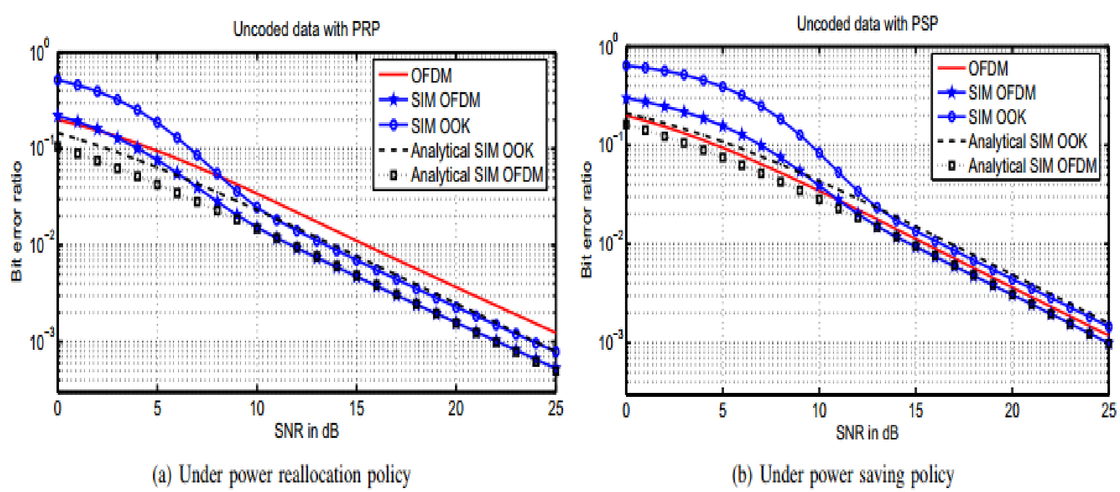


FIGURE 2.5: BER performance comparison for both PRP and PSP [22]

2.3.2 Disadvantage

It has the trade off between better SE and better BER since excess subcarriers does not carry information signal. If any carrier state of activation is incorrectly detected, it can lead to error detection of all the subsequent M-QAM symbols. This is a major drawback of this system. Hence, the subcarriers were divided into small group of subcarriers and symbols were sent via the combination of active indices of that group and M-QAM symbols in that subblock subcarriers in the groundbreaking research of OFDM-IM in 2013 [31]

2.4 OFDM-IM

OFDM-IM[31] reconstructed the idea of Index Modulation on OFDM. Instead of indexing all the subcarriers by a portion of input bit stream like SIM, it introduced Index Selector block and Subcarrier Mapping of subblock [36] in parallel with Modulator in OFDM. In this system, all the subcarriers are divided into small groups called subblocks. Each subblock consists of an Index Selector and Modulator.

When the input bit enters in each subblock, at first a portion of the bits are used to indicate which subcarriers are active from a combination table of the subcarrier indices of the subblock. If there is an error detection in one subblock, it will not affect the other subcarriers like SIM. The erroneous modulated symbols in subsequent subcarriers can be ignored by it. In parallel, other portion of bits dedicated to a subblock are modulated with any APM modulation like OFDM. According to Subcarrier Indexing of Index Selector all the modulated symbols take position in their dedicated subcarriers in each subblock and then form OFDM symbol in OFDM block Creator. Interleaver is also considered for better achievement rate of OFDM-IM [37]. The rest of the operation is the same as OFDM. In the receiver, Index de-mapper needs to be included to retrieve the index bits and position it with the demodulated bits in Bit retriever. This is the only difference between OFDM and SIM.

2.4.1 OFDM-IM System Model Overview

OFDM-IM divides total N subcarriers into g number of small groups named subblock consisting n subcarriers in each of them. K number of subcarriers are kept active out of n subcarriers. The index selector takes $\binom{n}{k}$ number of combinations for the indication of active indices. It uses a look-up table or a combinatorial method for Subcarrier Index Selector (SIS) to calculate the subcarrier activation index patterns. According to the active subcarrier indices, modulated symbols are mapped into $k \times g$ subcarriers.

Let us consider, there is a total m number of input bits. If p number of bits enter in each subblock, then m=pg. p_1 bits enter in Index Selector and p_2 bits enter in the APM Modulator out of p bits. Hence, this system not only transmits $p_2 = klog_2M \times g$ bits for M-ary Modulation but also sends $p_1 = \left\lfloor log_2\binom{n}{k}\right\rfloor \times g$ bits by the activation status of the subcarriers that has zero power consumption. These total bits eventually surpass the total transmitted bits of conventional OFDM $N \log_2 M$ with better SE and minimum power consumption.

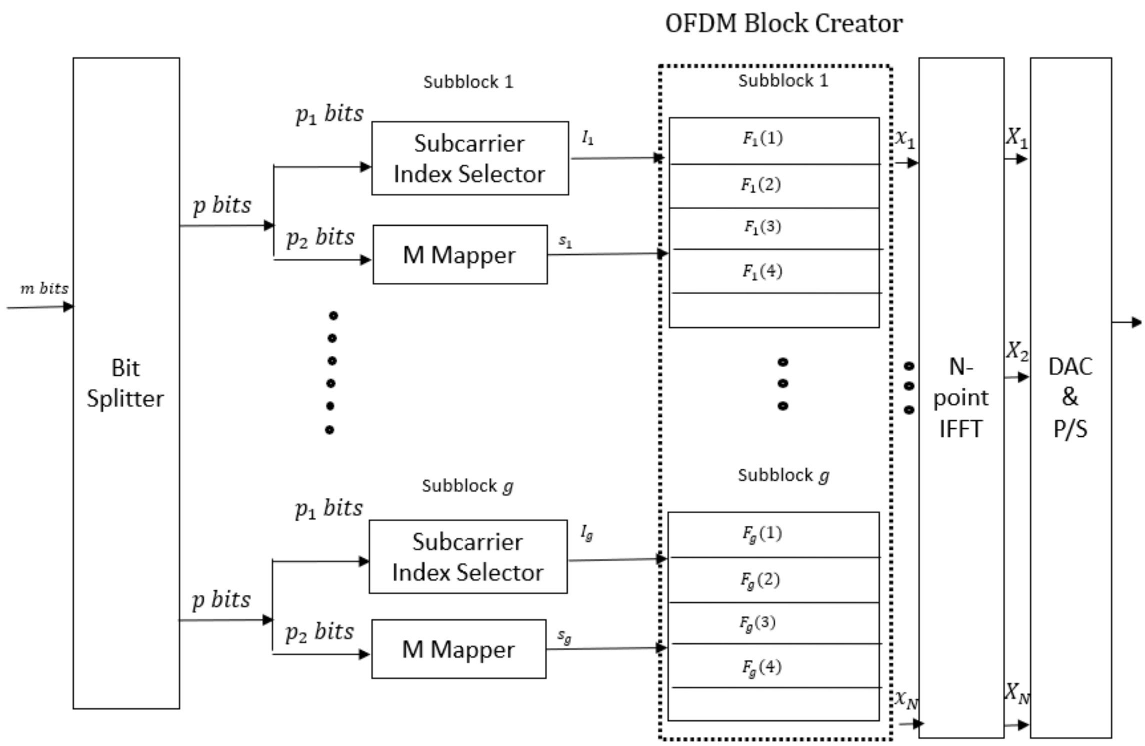


FIGURE 2.6: Modified part of OFDM Modulator block in the transmitter of OFDM-IM system

After generating modulated symbols, s; they are place in dedicated subcarriers by the indices of I. These subcarrier mapping is completed after all the subblock signals, F are put together in OFDM Block Creator and create similar OFDM symbol with less carrier signals. The rest of the operations are same as OFDM such as converting Frequency domain signal, x to Time domain signal, X and so on. Finally, x(t) OFDM signal is transmitted in the wireless channel.

At the receiver side, all the operation is similar to OFDM except after going into FFT operation, only demodulation subcarriers by subcarriers signals cannot provide the original input bits. It needs to extract the index bits too by exterminating the inactive subcarriers. Maximum Likelihood (ML) and Log likelihood Ratio (LLR) detectors are used in this area in addition to the APM Demodulator. ML detector checks every combination of Subcarrier Activation Pattern (SAP) for the closest modulated complex symbols. It compares the Euclidean distance for the symbols of each combination throughout the whole system and chooses the minimum one. LLR detectors indicates the active subcarriers by probabilistic method at first and then determines the symbol. Low complexity detector has been explored in studies by encoding all possible SAP [38]. Practical implementation is already done on OFDM-IM [39]

2.4.2 Advantage

OFDM-IM can deliver more data than OFDM or SIM with the same size of total subcarriers. It adds the new degree of freedom in subcarrier indexing by using the combination of subcarrier indices of subblock. OFDM-IM also has greater Spectral Efficiency compared to OFDM because of the subblock size, number and Modulation order diversity [22]. BER performance shown in figure 2.15 is significantly better than OFDM particularly in high Signal to Noise Ratio [**?**]. Due to the inactive subcarriers like SIM, it also saves energy /power in OFDM-IM.

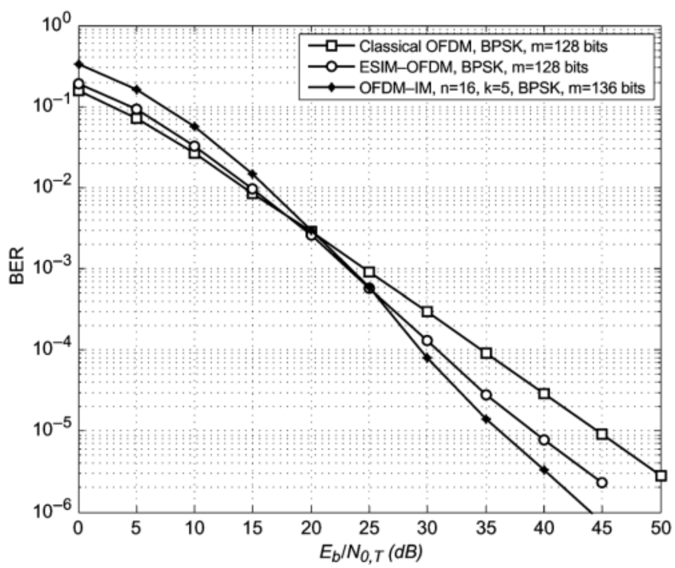


FIGURE 2.7: BER comparison of OFDM-IM with ESIM and OFDM for BPSK[31]

2.4.3 Disadvantage

OFDM-IM cannot outperform or produce same throughput as OFDM in higher Modulation Order due to inactive subcarriers. So, Spectral efficiency is limited as the Modulation increases. The indexing of large subblock size becomes another problem to determine the combinatorically increasing SAP numbers [24].

2.5 OFDM-IQ-IM

OFDM-IQ-IM is similar to OFDM-IM except it applies Index Modulation on In-phase and Quadrature Phase independently. It was proposed in OFDM with Generalized Index Modulation as an extension of Flexible subcarrier selection for each subcarrier as OFDM-GIM2 [32, 40]. It adopted its name later as OFDM-IQ-IM when the performance analysis was done on it [26].

2.5.1 OFDM-IQ-IM System Model Overview

OFDM-IQ-IM[41] has the similar system model as OFDM-IM. Only difference is that it includes two different channels, one of them is In phase and other one is Quadrature phase channel. Each channel includes an Index Modulator and Pulse Amplitude Modulation (PAM) Modulator similar to OFDM-IM. The Index Modulator also done jointly in later named OFDM-HIQ-IM for same design [42].

If total m input bits are entering in the bit splitter, it will take twice of p bits for two channels of OFDM-IQ-IM in place of only p bits in OFDM-IM. In phase and Quadrature phase, p bits are divided into p_1 and p_2 bits. Now, one subblock is considered to explain the methodology for simplicity. For in-phase, $p_1^I = \left\lfloor log_2\binom{n}{k}\right\rfloor$ bits enter in Index Selector to indicate which $I_\beta^I = i_1^I, \ldots., i_k^I$ combination of k subcarriers out of n are active. Besides, $p_2^I = k\ log_2 M$ bits enter in the PAM Modulator to modulate M_I constellation points according to the combination of $I_\beta^I for$ subblock. Same operations happen in Quadrature phase. It also creates $2^{p_1^Q} = 2^{\lfloor log_2\binom{n}{k}\rfloor}$ number of combinations of subcarrier mapping in I_β^Q by Index Selector and modulates $p_2^Q = k\ log_2 M$ bits into symbols to send in mapped k carriers.

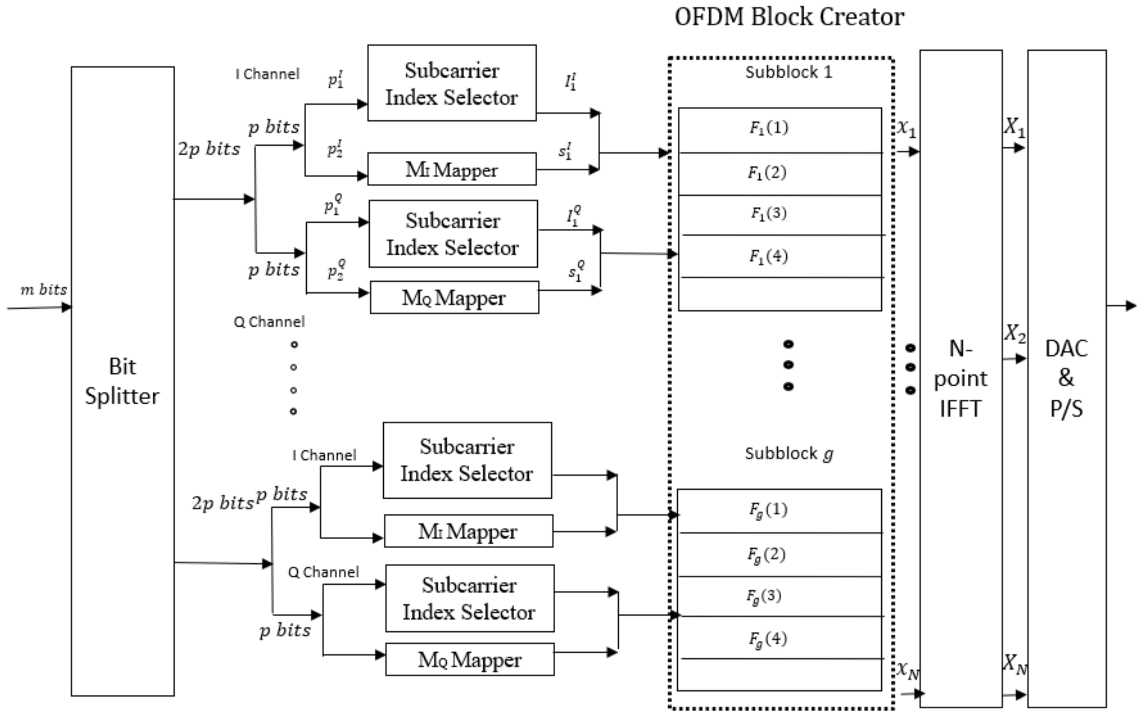


FIGURE 2.8: Modified part of OFDM Modulator block in the transmitter of OFDM-IQ-IM system

The twist in the plot belongs to the subcarrier mapping of k-in phase symbol carrier indices and k-quadrature phase symbol carrier indices. I_β index combination of k carriers of both channels can be same or different as the Index mapping is done independently. So, they can go to k same subcarriers or k different subcarriers. This fact is described and compared with other system in chapter 4 in figure 2.8. This plays a big factor in energy saving characteristics, constellation pattern for this system. After this, all other operations are same as OFDM like IFFT conversion, CP insertion and DAC up conversion. In the receiver side, all the reverse operations are done. It also uses ML or LLR detection separately on each channel. The receiver complexity increases as there are now twice the IS and PAM Modulation calculation than OFDM-IM.

2.5.2 Advantage

The Spectral efficiency for increasing Modulation order is mitigated through OFDM-IQ-IM system for indexing twice rather than OFDM-IM. It also increases the throughput to outperform any other systems. Depending on the in-phase and quadrature phase symbols are going in which subcarriers energy can be saved or it can act like OFDM by placing all the symbols in different subcarriers that leads to activate all of the subcarriers. If they go to the same subcarriers, it can save highest amount of energy by activating lowest number of subcarriers discussed in chapter 4 in table 4.18. BER can also be better if the minimum subcarriers are active shown in figure 2.9

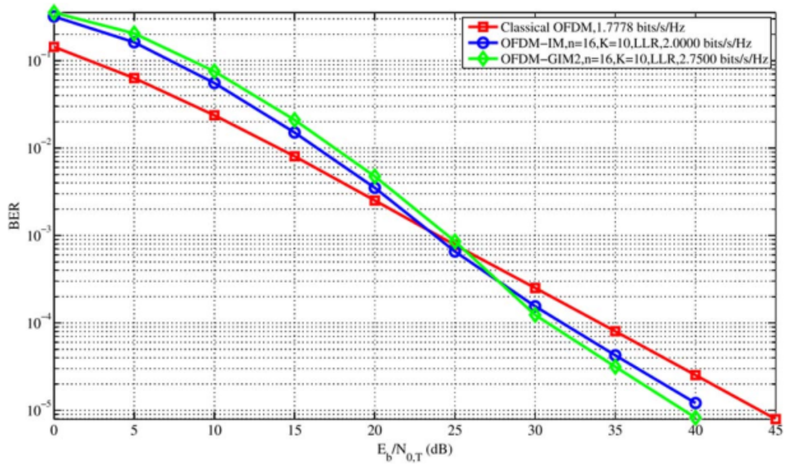


FIGURE 2.9: BER comparison of OFDM-GIM2 i.e., OFDM-IQ-IM [32]

2.5.3 Disadvantage

OFDM-IQ-IM is superior in every sector than other system. The only drawback comes from its main concept of dividing in phase and quadrature phase channel and doing separate operations independently. This independency may result in activating all the subcarriers in the system leading to zero energy saving than OFDM and creating very irregular pattern of constellation discussed in chapter 4 in figure 4.8

2.6 DM-OFDM

DM-OFDM uses two Modulation mappers instead of one mapper compared to OFDM-IM. DM-OFDM works similar to conventional OFDM by modulating across all the subcarriers. The concept of Index Modulation is used by indicating the position of two different constellation or mode symbols in each subblock. Hence, no subcarriers are needed to be kept idle in here that mitigates the problem regarding Spectral efficiency of OFDM-IM and implementation is more practical since the design is close to conventional OFDM.

2.6.1 DM-OFDM System Model Overview

DM-OFDM has the similar design model as OFDM-IM having Index Selector and Modulator in the system. The only difference is that there are two M-ary Modulation or Mode mappers instead of one. This idea has been introduced for the sake of Dual Mode Indexing (DMI) rather than using Subcarrier Activation Indexing (SAI). In SAI, a portion of the subblock subcarriers is kept active and passed through the constellation symbols by active subcarriers according to their SA Indices. This active subcarrier status gives the information about index bits in the receiver. In DMI, two different constellations are used. The whole subcarriers are divided in two groups. One group pass M_a constellation symbols and other one pass M_b symbols. The indexing is done on which subcarrier belongs to which Modulation group. So, all the subcarriers are active in this system.

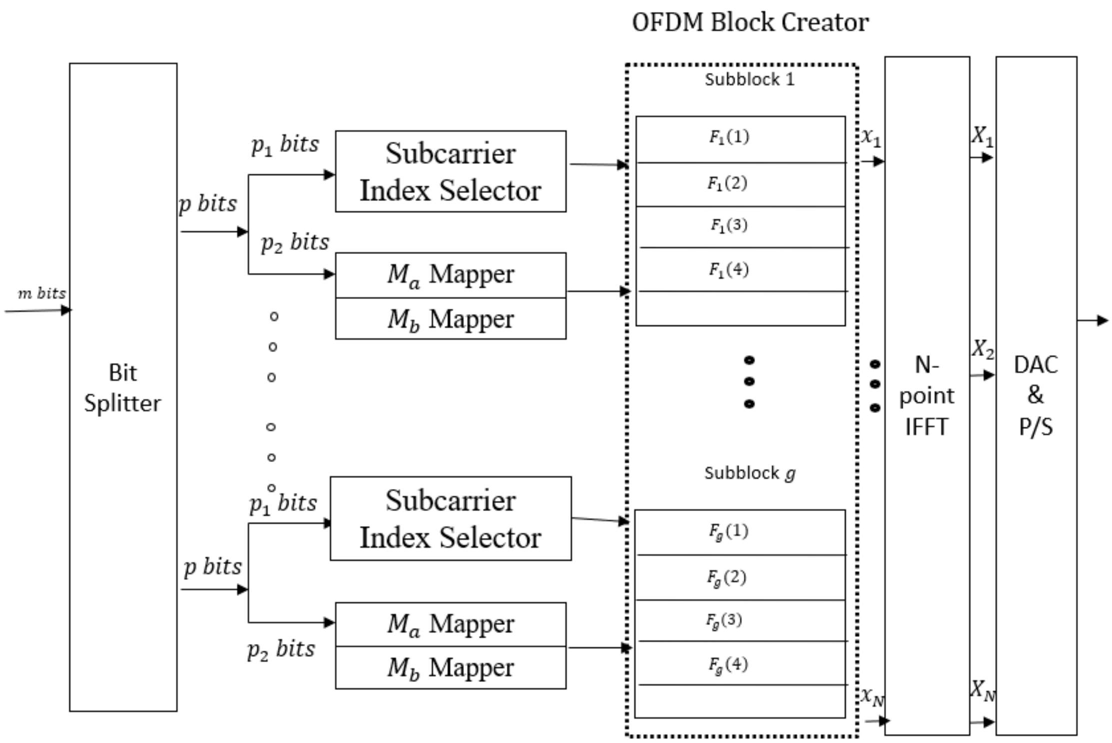
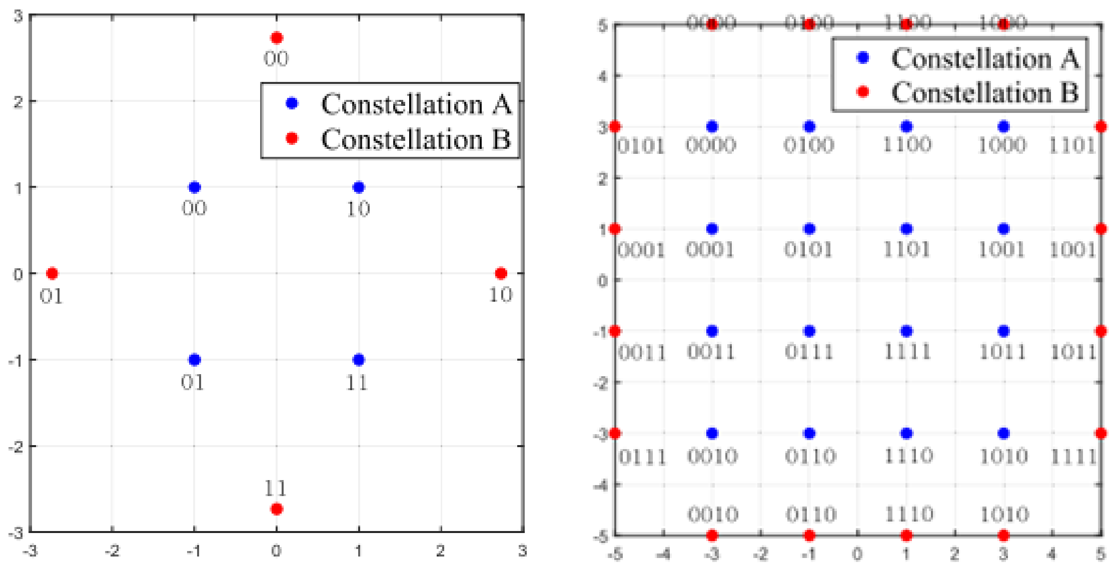


FIGURE 2.10: Modified part of OFDM Modulator block in the transmitter of DM-OFDM system

Let us consider, total N number of subcarriers are partitioned in g subblocks each carrying n subcarriers. Now, this n subcarriers are divided into two groups, generally equally distributed. If the number of subcarriers of the group modulated by M_a is k, the number of other group subcarriers is (n-k) modulated by M_b.

There are m total number of incoming bits going into the bit splitter. They are divided into g number of p bits. Each p bits are divided into two parts, p_1 going in the IS for indexing M_a Mode symbols. $p_1 = \left\lfloor log_2\binom{n}{k}\right\rfloor$ denotes the subcarriers carrying M_a Mode symbols. Other one is $p_2 = klog_2M_a + (n-k)log_2M_b$ bits that are transformed in M_a and M_b modulated symbols to go in their dedicated subcarrier group. The ultimate constellation of two separate Modes are $M_a + M_b = M$ constellation diagram in figure 2.11. The mapping of Modulation pattern has been studied later adding more diversity such as Gray-Coded Pairwise Index Mapping [43].



(A) fig: OFDM-IM

(B) fig: DM-OFDM

FIGURE 2.11: Constellation of DM-OFDM [44]

After going into the subblock, they create one OFDM symbol and passed through all the remaining operations of IFFT, CP insertion [45], P/S transformation and DAC up-conversion. In the receiver, all the operations are same as OFDM-IM; the difference is in detection. ML/ LLR detection needs to determine from which Mode the symbols belong and determine their Indexing with low complexity detcetor design [46]. The symbol detection and symbol to bit de-mapper is similar to OFDM-IM system.

2.6.2 Advantage

DM-OFDM has brought the indexing benefit to compete with OFDM in SE without inactivating any of the subcarriers. This model mitigates all the problem arising from inactivating a portion of the subcarriers e.g. critical throughput loss in higher modulation. The number of subcarriers in each subblock can be alterable for more SE enhancement [47]. It also ignores the complex design lof OFDM-IQ-IM in which the independency of two modulators of in phase and quadrature phase leads to various uncertainty of the system. The BER performance is also better in DM-OFDM in fading channel than other systems.

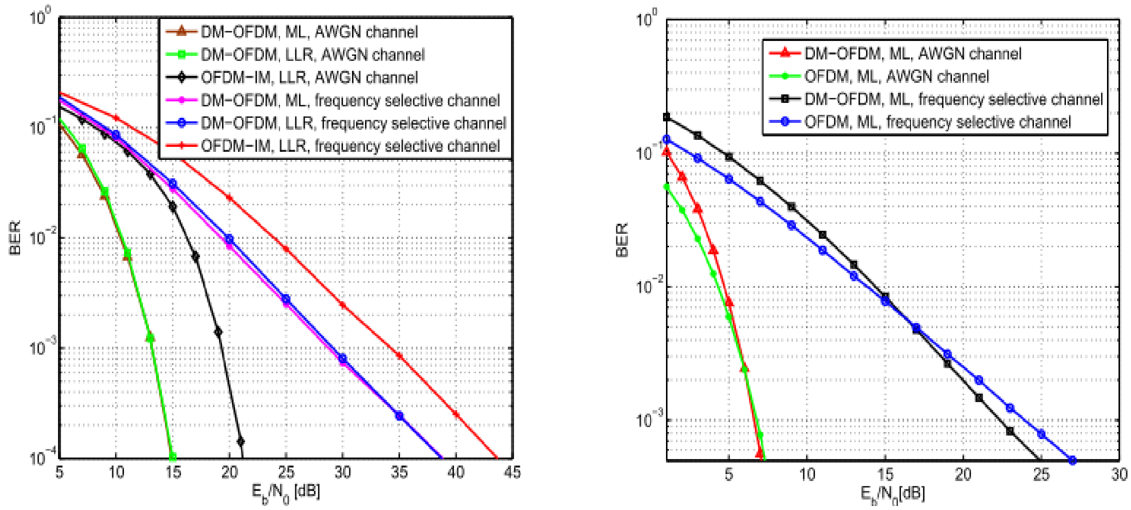


FIGURE 2.12: BER comparison Of DM-OFDM with other systems[27]

Though DM-OFDM outperforms other system regarding SE and throughput. It activates all of the subcarriers that leads to no energy or power saving in the system. The goal to achieve Green G is not served here.

2.7 MM-OFDM-IM

MM-OFDM-IM [1] is different from other OFDM-IM variants. This system includes an index selector that uses permutation scheme for indexing each different constellation for each subcarrier of a subblock that is called each Mode. Hence, it has Multiple Modes or Modulation points that eventually joins in one final constellation with maximum inter and intra symbol Euclidean distances. This is more of one to one mapping.

2.7.1 MM-OFDM-IM System Model Overview

If there are N total subcarriers and they are divided into g subblocks each carrying n subcarriers, then there will be n number of M PSK Modes for each subblock. Each Mode comprises of different constellation than the other and indexing is done on which mode they belong. The n number of PSK constellations are obtained by rotating their angles into $\frac{2\pi\,(b-1)}{nM}$ where, $b = 1,\ .....,\ n$. In this way, there will be no overlapping between n number of constellations.

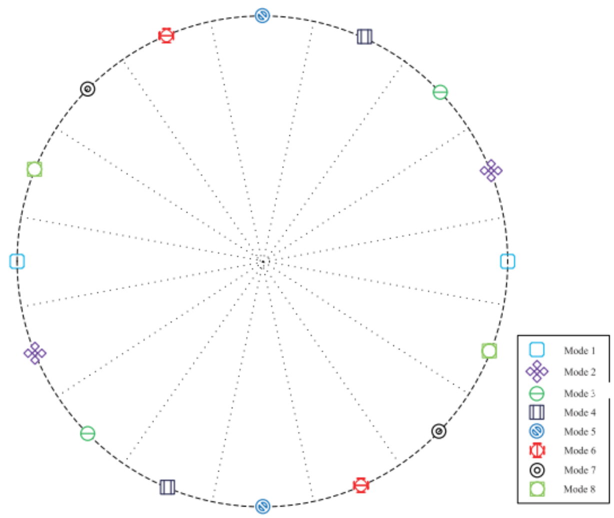


FIGURE 2.13: Final Constellation of MM-OFDM-IM with eight modes and 16 PSK; with each mode representing different constellation [1]

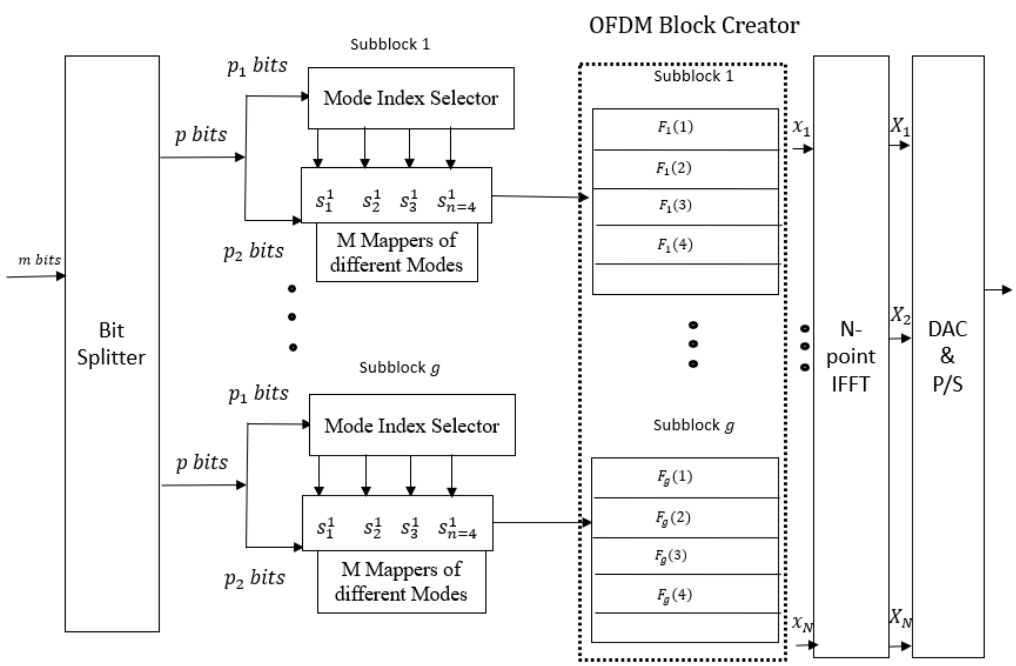


FIGURE 2.14: MM-OFDM-IM transmitter

Let us consider, there are m number of total bits going into bit splitter which splits the bits into g group of p bits. This p bits in subblock are divided into two groups of p_1 and p_2 bits. p_1 bits enter in the Index Selector and $p_1 = \lfloor log_2(n!) \rfloor$ bits are mapped into permutation indices of each Modes. Whereas is $p_2 = n\, log_2 M$ bits are modulated by n number of M-PSK modulation schemes generating n number of different mode symbols.

After each symbols of distinguished mode enters in the subcarriers, the rest of the operation is same as other system and classical OFDM. At the receiver, the only difference is in the detection of indices. Each symbol represents different modes. ML detects the closest combination of the mode it belongs to. It also searches for the closest symbol from the specific mode constellation. It is a very extensive search procedure. LLR detection can also be done [48]. After determining the index and symbol correctly, bits are retrieved from them.

2.7.2 Advantage

MM-OFDM-IM produces the maximum number of index bits due to its possibility of bringing permutation in the system. Due to permutation, it can produce maximum number of index bits. For this reason, modulation bits can be lower than the index bits which helps in getting better BER.

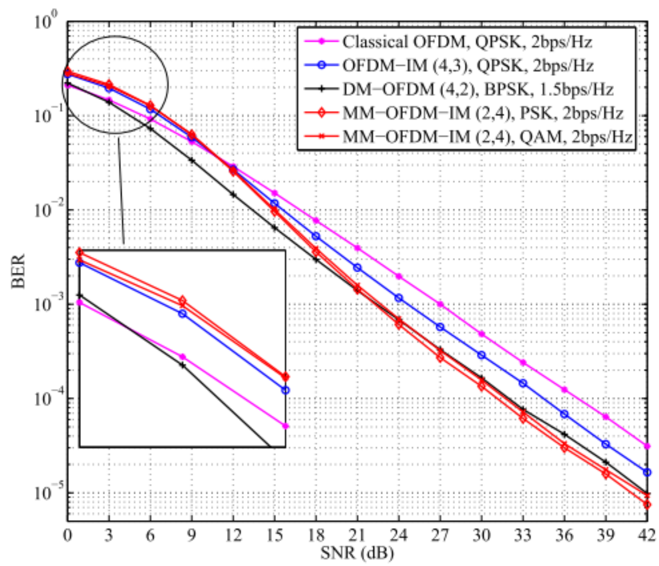


FIGURE 2.15: BER comparison of MM-OFDM-IM with OFDM, OFDM-IM, DM-OFDM [1]

2.7.3 Disadvantage

Since all the subcarriers are active in this system, there are no energy or power saving here.

Increasing number of modes can lead to closely spacing PSK constellation points in MM-OFDM-IM that can eventually lead to poor BER for small decision-making area in constellation.

2.8 Summary of all literature review

The summary of all noteworthy OFDM-IM variants is gathered together. The basic concept of the system and the drawbacks that demanded other systems to be designed have been highlighted in this table 2.2.

Reference Years	IM Variants	Concept	Drawback
2009 [22]	Subcarrier Index Modulation OFDM (SIM-OFDM)	Majority bits indicate active subcarriers	Spectral Efficiency is not up to the mark as OFDM, consecutive BER possibility
2011 [23]	Enhanced Subcarrier Index Modulation OFDM (ESIM-OFDM)	Majority bits that indicate active subcarriers are equal for better Spectral Efficiency (SE)	Cannot compete with OFDM in SE
2013 [31]	OFDM with Index Modulation (OFDM-IM)	Subcarrier Indices are active through combinatorial method with enough flexibility	In higher Modulation order SE fails
2015 [32]	OFDM with Generalized Index Modulation (OFDM-GIM)	Flexible number of subcarriers can be activated	Too many flexibilities can lead to higher complexity
2015 [26, 32]	OFDM with In-phase/ Quadrature-phase Index Modulation (OFDM-IQ-IM)	Complex constellation divided into I/Q M-PAM part to gain diversity by indexing them independently	Constellation is not generic, have impact on Energy loss and BER
2016 [27]	Dual-Mode Index Modulation aided Index Modulation (DM-OFDM)	Two constellation mappers are used for indexing for the diversity gain	All subcarriers active as OFDM, no ES or BER gain
2017 [1]	Multimode-OFDM with Index Modulation (MM-OFDM-IM)	Many possible constellation can be considered for the diversity gain	Very high complexity due to permutation indexing, no ES gain

TABLE 2.2: Literature Review Summary for IM variants on OFDM

Chapter 3

PROPOSED NMM-OFDM-IM SYSTEM MODEL

3.1 Basic Concept of NMM-OFDM-IM

3.1.1 What is the process of NMM-OFDM-IM?

Novel Multi-Mode OFDM with Index Modulation (NOVEL MM-OFDM-IM) is a combination of two methods: OFDM-IM[24] and MM-OFDM-IM[1]. In this NMM-OFDM-IM design, there are two types of Selectors; one for selecting Active Subcarriers and one for selecting Modes. It uses multiple distinguishable constellations for modulation and Mode Index Selection (MIS) in the subblock like MM-OFDM-IM. For this reason, the proposed system is called Novel MM-OFDM-IM. Though it is based on the concept of MM-OFDM-IM for the increased throughput and maximum spectrum utilization; the way of indexing and saving power consumption differentiates the proposed system from MM-OFDM-IM. It uses conventional Subcarrier Index Selector (SIS) like OFDM-IM [31] to keep a portion of subcarriers idle for saving the energy to carry out the mission of 'GREEN G' [49, 50]. This is absent in conventional MM-OFDM-IM.

The SIS configuration is the same as classical OFDM-IM but the Mode Index Selector was modified in the proposed system. In order to do that an equation regarding mode index bits, throughput and Spectral Efficiency was developed as equation 3.7, 4.10 and 4.12. This built one of the basic block diagrams of the transmitter and receiver of NMM-OFDM-IM. MIS look-up tables were generated by using the equation 3.7. It worked for any subblock settings and any modulation order. Then, the whole proposed system was designed keeping in mind three key characteristics and performance. They are Spectral Efficiency, Energy Efficiency, Resultant Constellation Diagram, and Bit Error Rate (BER) for performance. Besides, an extensive detection method was chosen and modified according to the system which was Maximum Likelihood Detection. It is used to detect the symbol for each active subcarrier realisation and compare the inter and intra distance among each mode symbol for minimum BER.

3.1.2 Why a Novel MM-OFDM-IM has been chosen?

OFDM-IM has greater Spectral Efficiency than conventional OFDM due to its extra index bits introduced by Ertuğrul Başar in his remarkable paper [31]. This does not give enough throughput compared to OFDM for higher modulation which played a big part of further proposition of new IM variants like OFDM-IQ-IM [32], DM-OFDM [27], MM-OFDM-IM. The main reason behind it is that enough bits cannot be produced by index bits to beat the inactive subcarriers bits. For example, for 128 subcarriers of OFDM and OFDM-IM having 64 QAM with each subblock consisting of 3 active subcarriers out of 4 subcarriers in figure 3.1; each subcarriers transmits a symbol converted from 6 bits. So, a total of 32 inactive subcarriers lack in 192 information bits than OFDM. It tries to compensate it with 64 index bits which is not enough to beat OFDM system.

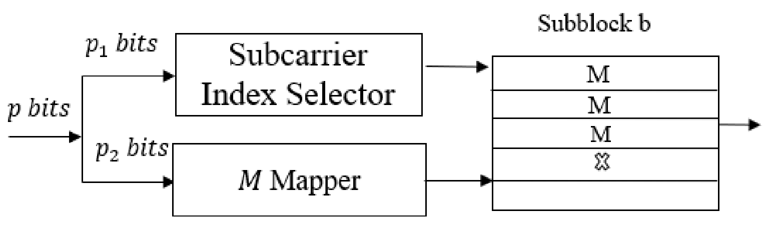


FIGURE 3.1: OFDM-IM Index Selection in one of the subblocks

To beat the SE problem, DM-OFDM keeps all the subcarriers active shown in figure 3.2 which is similar to conventional OFDM. It takes index bits from choice of the modulation scheme that provides sufficient spectral efficiency to beat OFDM. As all the subcarriers are active, it is not energy efficient which is targeted in Next Generation Wireless Communication System such as 5G, 6G and so on.

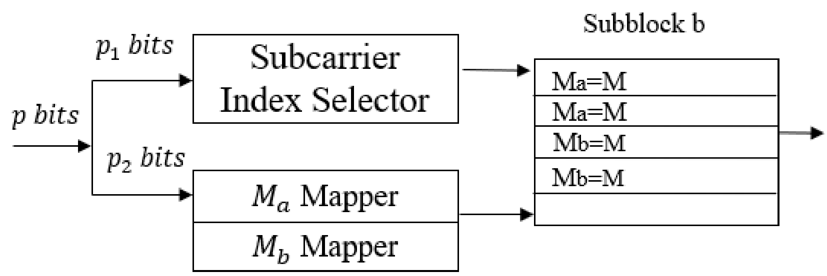


FIGURE 3.2: DM-OFDM Index Selection in one of the subblocks

However, OFDM-IQ-IM allows the modulated symbols from in phase and quadrature phase to travel in the subcarriers of each subblock independently. Therefore, it can produce two different indexing which are enough to suppress the SE inadequacy. These independent symbols can go into the same subcarriers or in different subcarriers. If they go in different subcarriers, there will be no energy saving portion. It will activate all or most of the subcarriers of a subblock shown in 1st subblock of figure 3.3. Consequently, It gives rise to an irregular joint constellation pattern with closer symbol distance pointed out in Section 4.1.3 in figure 4.8. This is not desirable in a practical system.

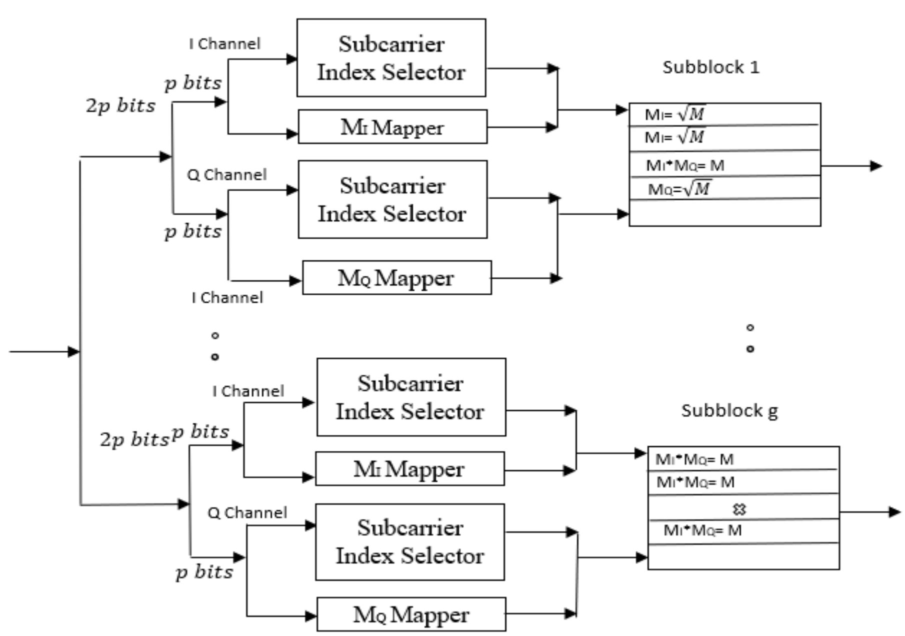


FIGURE 3.3: OFDM-IQ-IM Index Selection in one of the subblocks

On the other hand, MM-OFDM-IM uses multiple different constellations for each subcarrier in a subblock. It not only sends information through conventional modulated symbols from n-mode constellations but also transmits information by the permutation indexing of each subcarrier constellation shown in figure 3.4.

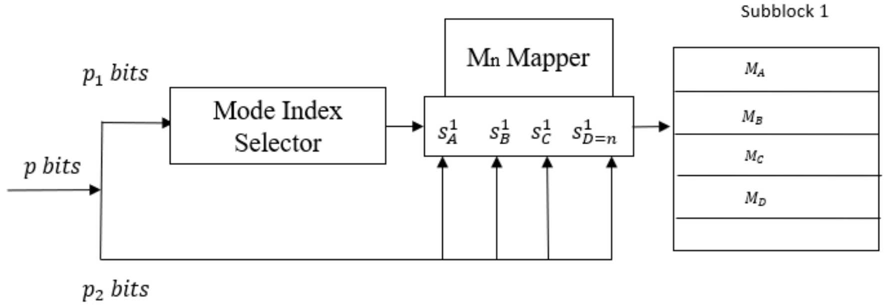


FIGURE 3.4: MM-OFDM-IM Index Selection in one of the subblocks

MM-OFDM-IM acts like conventional OFDM with better SE. So, it is not energy efficient as OFDM-IM. This is one of the main reasons behind proposed NMM-OFDM-IM.

3.1.3 How does NMM-OFDM-IM works?

NMM-OFDM-IM consists of mutiple, distinguishable mode mappers and two different types of Index Selector. Two index selectors are introduced to meet the throughput requirements of OFDM. One of them is conventional Subcarriers Index Selector (SIS). This index selector keeps only k out of n subcarriers active in a subblock and $(n - k)$ subcarriers are kept idle. So, $\lfloor log_2\binom{n}{k}\rfloor$ bits are additionally transmitted by SIS . Another one is Mode Index Selector (MIS) . This index selector takes n- mode distinguishable M constellations for each subcarrier of subblock. Then, it sorts out which subcarrier takes which mode constellation. Generally, $\lfloor log_2\frac{n!}{(n-k)!}\rfloor$ bits are additionally transmitted by MIS but it also depends on quantity of modes. Then, $klog_2M$ bits generate conventional Mode M-QAM constellation symbols for the transmission. Hence, they maximize the throughput and also save energy by keeping some subcarriers inactive. This is a very simple explanation of the proposed NMM-OFDM-IM.

The n mode mappers are elaborately designed in my thesis. One Amplitude Modulation and one PSK modulator have been used to generate expected each Mode constellation. This design is similar to OFDM-IQ-IM where in phase and quadrature phase travel separately to carry out $2\lfloor log_2\binom{n}{k}\rfloor$ index bits along with $klog_2M$ symbol bits. The AM and PSK is same as in phase and quadrature phase of OFDM-IQ-IM [26], but they do not travel independently. They always travel to the subcarriers indicated by MIS. This is done to activate only k number of same subcarriers to avoid the possibility of activating all the subcarriers like figure 3.3 subblock 1 and losing the energy efficiency and having minimum distance in symbols in Joint constellation (figure 4.8). For, non-square QAM Mode; n number of $2\lfloor log_2 \sqrt{Mn} \rfloor$ PAM constellations are used as paper [1] for general use. The mode selection process will be briefly discussed in section 3.2.1.

Generally, number of modes of $Q \geq n$ condition must be satisfied, where n is the subblock size of NMM-OFDM-IM. Here, this is maintained to ensure the success of multimode selection.

3.2 Proposed System Model of NMM-OFDM-IM

3.2.1 NMM-OFDM-IM Transmitter

In this proposed scheme, NMM-OFDM-IM System is operated in a rayleigh fading channel with Additive White Gaussian Noise (AWGN). The transmitter of this system is illustrated in figure 3.5 and input data goes through some specific building blocks to be sent in the channel.

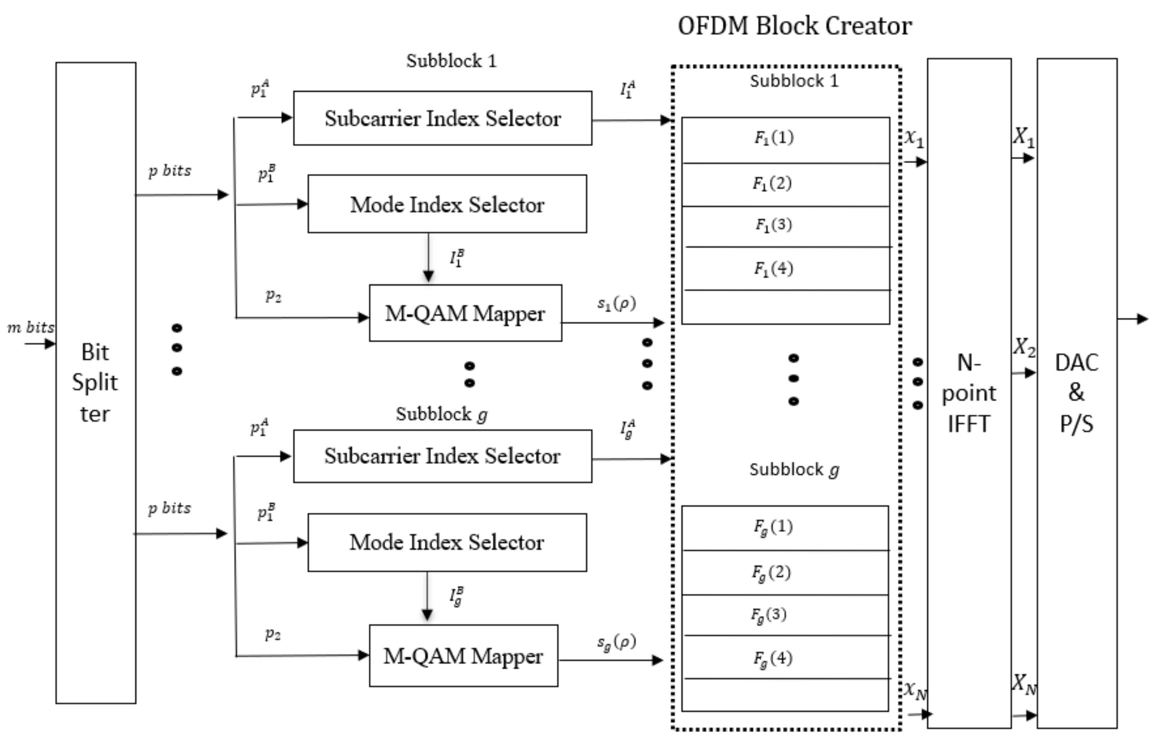


FIGURE 3.5: NMM-OFDM-IM transmitter design

Bit allocation in subblock

Let us consider, m incoming bits enter bit splitter to be partitioned into p groups of bits for g number of subblocks, i.e., $m = pg$. Each group of p bits goes into index selectors as p_1 bits and p_2 bits to be mapped by M- QAM Q number of modes into OFDM subblock of length n, $n = N/g$. There are k number of active subcarriers in each subblock.

There are two index selectors in this system, one is like the traditional Index mapper to map p_1^Abits according to the Subcarrier Index Selector (SIS). This SIS determines which subcarriers must be activated according to the look up table described later in the Subcarrier Mapping Indexing segment 3.2.1. These additional bits reflect through the activated subcarriers in the receiver. This is based on the basic groundbreaking concept of OFDM-IM for Next Generation Wireless Communication system.

Another p_1^B bits are mapped by Mode Index Selector to give the combination of which symbols of the specific active subcarriers are modulated by which Q number of distinguishable constellations. This enhances more indexing bits to compensate SE problem of higher modulation but does not hamper the regular pattern of constellation diagram.

$$m = pg = (p_1 + p_2)g, \tag{3.1}$$

Where,

$$p_1 = p_1^A + p_1^B, \tag{3.2}$$

And,

$$p_2 = p_2^A + p_2^B, \tag{3.3}$$

Another segment of p_2 bits are mapped by Q- modes M-QAM constellations to transmit by traditional modulated symbols like OFDM. This mode constellations can be derived from two in-phase ,M_A AM and quadrature phaseM_B PSK mappers for square QAM modes. This can also be done by the general n number of $2\lfloor log_2 \sqrt{Mn} \rfloor$ PAM constellations with verified inter and intra symbol distance of symbols based on the paper MM-OFDM-IM [1].

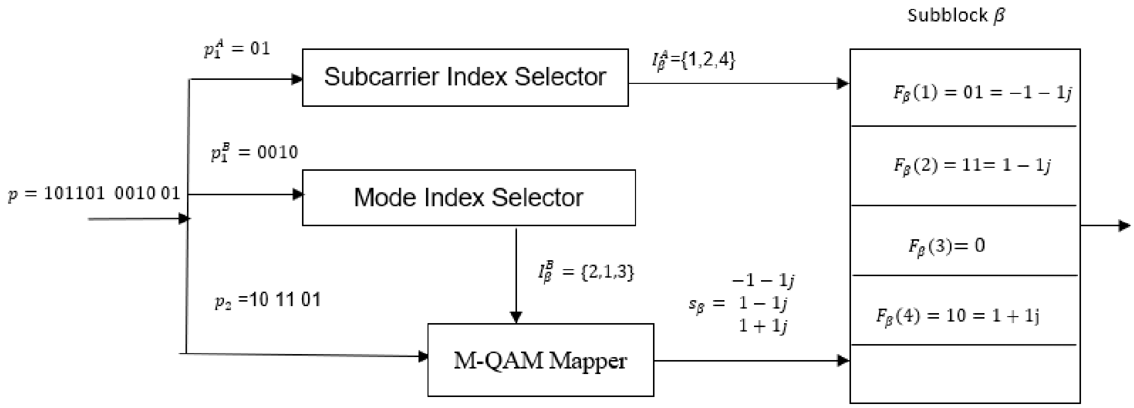


FIGURE 3.6: NMM-OFDM-IM th subblock bit allocation and mapping

Subcarrier Index Selector (SIS)

Subcarrier Index Selector (SIS) uses the same concept of OFDM-IM and like any other indexing incorporated with OFDM for subcarriers for the activation of a portion of each subblock. Subcarrier activation can be done simply using look-up table or Combinatorial Method.

- **Look-up table Method:** Look-up table is usually created at the transmitter side. It gives information about subcarrier indices corresponding to the incoming index bits of a subblock. As for example, there are total n number of subcarriers in each subblock of total g subblocks and k out of n subcarriers are active.

  Then, p_1^A bits are used for producing Subcarrier Activation Pattern (SAP) indices, I_β^A. SAP provides $\binom{n}{k}$ subcarriers combination, $F_\beta(\lambda)$ in the look up table for β^{th} subblock.

$$p_1^A = \lfloor log_2\binom{n}{k} \rfloor, \tag{3.4}$$

$$I_\beta^A = \{i_{\beta,1}^A, ..., i_{\beta,k}^A\} \tag{3.5}$$

where, $i_{\beta,\tau}^A = [1, 2, ..., n]$ for $\beta = 1, 2, ..., g$ and $\tau = 1, 2, ..., k$.

$$F_\beta(\lambda) = [F_1(\lambda), ..., F_g(\lambda)] \tag{3.6}$$

where, $\lambda = 1, 2, ..., k$.

If there are $n = 4$ subcarriers in a subblock and $k = 3$ of them are active, then the look-up table will look like Table 3.1:

Index Bits	Indices, I_{β}^{A}	SAP, $F_{\beta}(\lambda)$
0 0	1,2,3	$[F_{\beta}(1), F_{\beta}(2), F_{\beta}(3), 0]$
0 1	2,1,4	$[F_{\beta}(1), F_{\beta}(2), 0, F_{\beta}(4)]$
1 0	3,1,4	$[F_{\beta}(1), 0, F_{\beta}(3), F_{\beta}(4)]$
1 1	3,2,4	$[0, F_{\beta}(2), F_{\beta}(3), F_{\beta}(4)]$

Table 3.1: Look-up table of Subcarrier Activation Pattern for Subcarrier Index Selector (SIS) of NMM-OFDM-IM (Here, $g = 1, n = 4, k = 3$)

The look-up table must be present in the receiver side also. This is important for ML detection since all the possible realizations should be known at the ML decoding. This becomes hard for higher modulation scheme since there will be many combinations and some of them are discarded because of the floor value and bit calculation. For this reason, Combinatorial Method comes to calculate it faster with logical approach.

- **Combinatorial Method:** The combinatorial method provides one to one mapping of k-combinations for all n and k in a decreasing manner. This is not highlighted in this literature but very much appreciated to deal in case of higher modulation subcarrier indexing realization.

Mode Index Selector (MIS)

NMM-OFDM-IM's most highlighted part is the Mode Index Selector (MIS). This is the distinguishable part from all other IM variants. Though MM-OFDM-IM [28], also uses indexing regarding different modes by permutation, the proposed system also uses permutation method of active subcarriers. NMM-OFDM-IM permits subcarrier inactivation which cannot be done in MM-OFDM-IM since their indexing depends on keeping all the subcarriers active. So, the throughput of NMM-OFDM-IM shows similarities with OFDM-IQ-IM which is enough to compensate the disadvantages of OFDM-IM [24].

the Mode Index Selector maps p_1^B bits into Q number of modes by combination with order from a lookup table. Each subcarrier of k must take different modes, Q_{β} where $Mode_1 \cap Mode_2 \cap Mode_3 \cap Mode_4 = \emptyset$.

The MIS index bits,

$$
\begin{aligned}
p_1^B &= \lfloor log_2 \frac{Q!}{(Q-k)!} \rfloor \\
&= \lfloor log_2 \frac{n!}{(n-k)!} \rfloor
\end{aligned}
\tag{3.7}
$$

Since, $Q \geq n$; assuming, $Q = n$ here.

For, the proposed NMM-OFDM-IM uses only a portion of active subcarriers, k out of n subcarriers. Within this n number of subcarriers, Q number of M-QAM modes are mapped. Usually number of modes,Q_β should be taken equal to n, number of subcarriers in a subblock. So, $Q = n$. The number M-symbols in each mode determined by $R = \frac{M}{n}$.

So, Different type of modes,

$$
Q_\beta(\rho) = \{q_{\beta,i}(1), ...q_{\beta,i}(n)\}
\tag{3.8}
$$

where, $\rho = 1, 2, ... n; i = 1, 2, ... R; M \geq n$

p_1^B bits	p_1^B decimal	Mode sequence indices, I_β^B	Index MAP for $k = 3$ active subcarrier
0000	0	1,2,3	$[q_\beta(1), q_\beta(2), q_\beta(3)]$
0001	1	1,3,2	$[q_\beta(1), q_\beta(3), q_\beta(2)]$
0010	2	2,1,3	$[q_\beta(2), q_\beta(1), q_\beta(3)]$
0011	3	2,3,1	$[q_\beta(2), q_\beta(3), q_\beta(1)]$
0100	4	1,2,4	$[q_\beta(1), q_\beta(2), q_\beta(4)]$
0101	5	1,4,2	$[q_\beta(1), q_\beta(4), q_\beta(2)]$
0110	6	2,1,4	$[q_\beta(2), q_\beta(1), q_\beta(4)]$
0111	7	2,4,1	$[q_\beta(2), q_\beta(4), q_\beta(1)]$
1000	8	1,3,4	$[q_\beta(1), q_\beta(3), q_\beta(4)]$
1001	9	1,4,3	$[q_\beta(1), q_\beta(4), q_\beta(3)]$
1010	10	3,1,4	$[q_\beta(3), q_\beta(4), q_\beta(1)]$
1011	11	3,4,1	$[q_\beta(3), q_\beta(4), q_\beta(1)]$
1100	12	2,3,4	$[q_\beta(2), q_\beta(3), q_\beta(4)]$
1101	13	2,4,3	$[q_\beta(2), q_\beta(4), q_\beta(3)]$
1110	14	3,2,4	$[q_\beta(3), q_\beta(2), q_\beta(4)]$
1111	15	3,4,2	$[q_\beta(3), q_\beta(4), q_\beta(2)]$

TABLE 3.2: Look-up table for MIS

In this system, four modes, $Q_\beta = n = 4$ have been taken for $M = 4$ QAM and k=3 subcarriers are active out of n=4 size of subblocks. So, Symbols per mode are, $R = \frac{M}{n} = 4$.

In MM-OFDM-IM, n number of $2\lfloor log_2 \sqrt{Mn} \rfloor$ PAM constellations are used to form each mode for M-QAM mode constellations. Then, $\lfloor log_2 n! \rfloor$ Bits are mapped by it. Joint nM-QAM constellation is shown in figure 3.7.

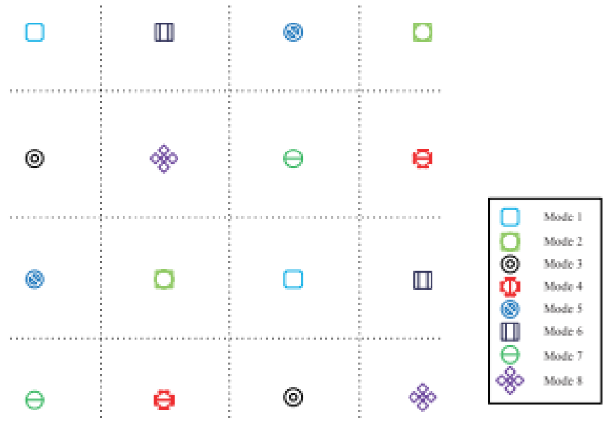


FIGURE 3.7: MM-OFDM-IM 16 QAM constellation diagram for eight modes where, n=8 [1]

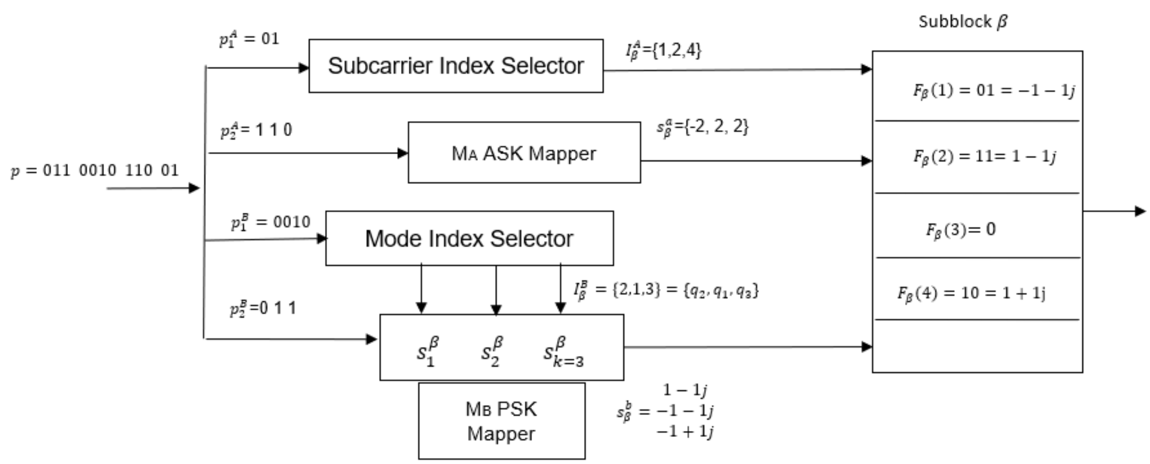


FIGURE 3.8: NMM-OFDM-IM th subblock bit allocation and mapping

It is upon us how we design modes, Q_β for M-Quadrature Amplitude Modulation. MIS can be used to simply take the permutation order of Q number of modes from which they are selected and in what order. This is a very generalized form. It can also be used to use in one of the two mappers and create mode M-QAM by itself and then follow the rest procedures. An elaborate design was also used to obtain different square M-QAM modes by coinciding with Amplitude Shift Keying (ASK) and Q modes Phase Shift Keying (PSK) at the transmitter side. These two modulation symbols are taken in such a way that it makes a square QAM with maximum inter and intra symbol distance with $d_{inter}^{QAM} = \frac{\sqrt{6}}{\sqrt{(Mn-1)}}$ like paper [1].

Modes for MAP, $Q_\beta(\rho)$	Symbols from Joint M QAM comprising Different Modes
$Mode_1, q_{\beta,i}(1)$	$\{M_A(1) + M_B(1)\}, \{M_A(1) + M_B(2)\}, \{M_A(1) + M_B(3)\}, \{M_A(1) + M_B(4)\}$
$Mode_2, q_{\beta,i}(2)$	$\{M_A(2) + M_B(1)\}, \{M_A(2) + M_B(2)\}, \{M_A(2) + M_B(3)\}, \{M_A(2) + M_B(4)\}$
$Mode_2, q_{\beta,i}(2)$	$\{M_A(3) + M_B(1)\}, \{M_A(3) + M_B(2)\}, \{M_A(3) + M_B(3)\}, \{M_A(3) + M_B(4)\}$
$Mode_2, q_{\beta,i}(2)$	$\{M_A(4) + M_B(1)\}, \{M_A(4) + M_B(2)\}, \{M_A(4) + M_B(3)\}, \{M_A(4) + M_B(4)\}$

TABLE 3.3: Mode Creation for MIS according to M_A and M_B mapper.

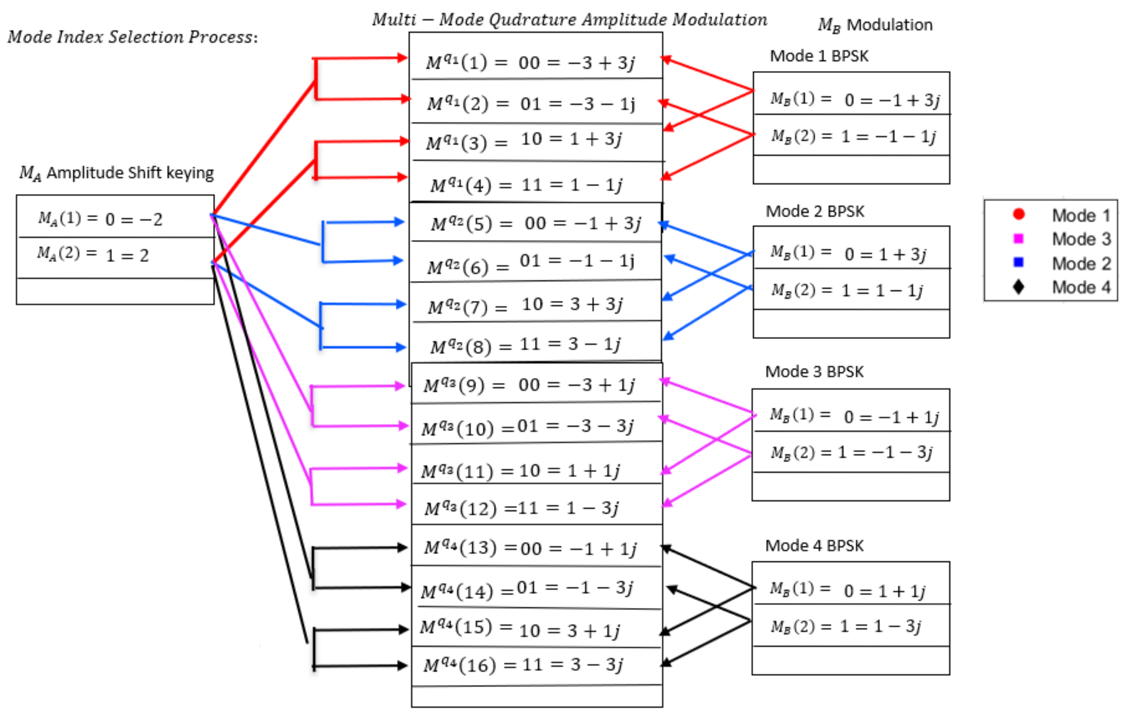


FIGURE 3.9: NMM-OFDM-IM 16 QAM Mode Selection Process, where n=4, $M = M_A \times M_B = 16$, $R = \frac{M}{n} = 4$

MIS look-up table is provided at both transmitter and receiver. A reverse operation is performed at the receiver. This is also easy to decode in receiver since MIS bits can be decoded the symbol of M. It does not need any extra step for decoding the MIS bits.

Modulation

In generalized system, p_2 bits are digitally modulated by Q number of separate M-ary QAM Mappers. Each Mode of M-QAM has been considered with their distinguished powers where $M_1 \cap M_2 ..... \cap M_{n=4} = \phi$ shown in figure 3.6. For the elaborate design of NMM-OFDM-IM, it can be seen that p_2 bits are digitally modulated by two separate M-ary mappers, M_A and M_B in the figure 3.8 of transmitter side. Generally, M_A carries M-ary ASK constellation and M_B contains PSK constellation points as shown in Figure 3.10. This design has been considered for forming Q number of M-QAM Mode with the correct mode symbol distance.

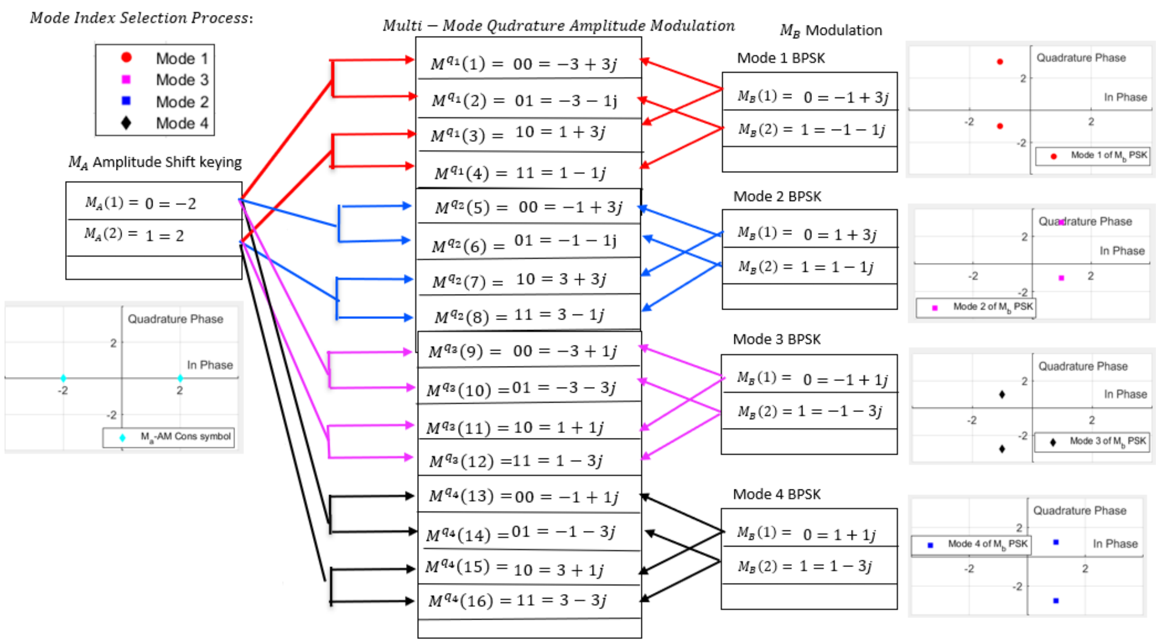


FIGURE 3.10: NMM-OFDM-IM Mode Selection Process Modulation

p_2^A number of information bits from designated modes goes into M_A mapper and modulated to s_β^1 symbols. On the other hand, p_2^B number of information bits are mapped in M_B mapper with the help of MIS and generate s_β^2 symbols. Eventually, Joint M QAM symbols, $L_\beta(\lambda)$ are formed by combining s_β^1 and s_β^2 according to the MIS; where, $\lambda = 1, 2, ..., k$.

The number of bits can be calculated independently,

$$p_2^A = klog_2 M_A \tag{3.9}$$

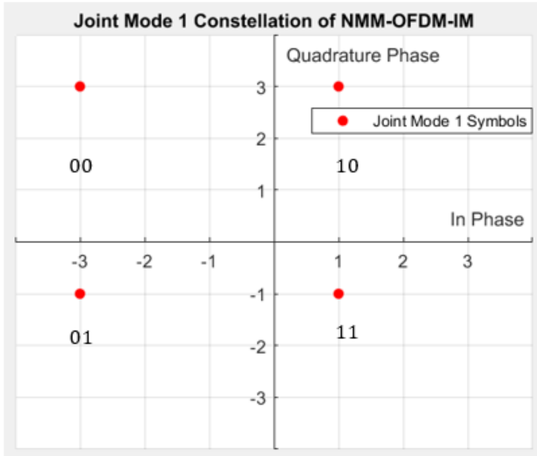
$$p_2^B = klog_2 M_B \tag{3.10}$$

$$s_\beta^1 = [s_\beta^1(1), ..., s_\beta^1(k)] \tag{3.11}$$

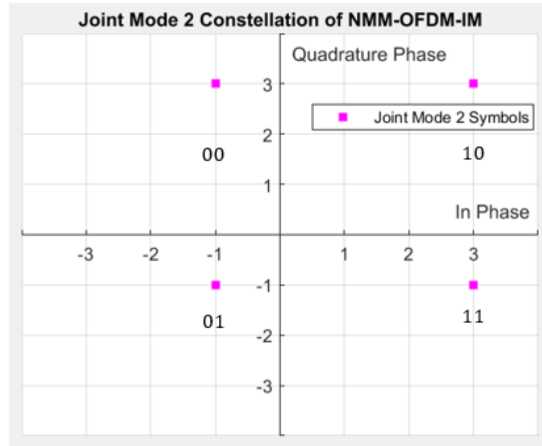
$$s_\beta^2 = [s_\beta^2(1), ..., s_\beta^2(k)] \tag{3.12}$$

or, It can be written in general for Q number of M-QAM modes,

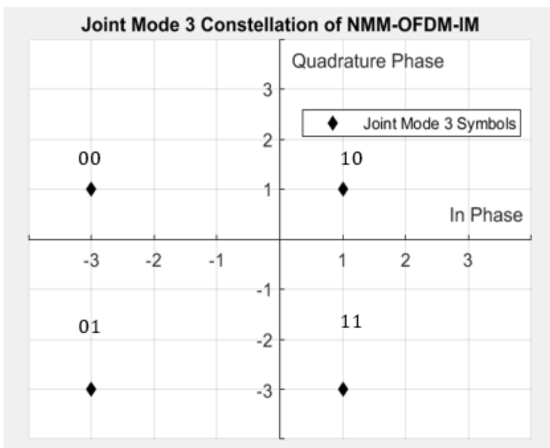
$$p_2 = klog_2 M \tag{3.13}$$



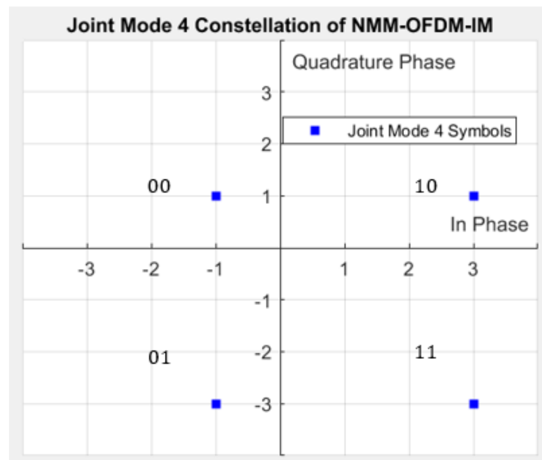
(A) fig: MODE 1 CONSTELLATION



(B) fig: MODE 2 CONSTELLATION



(C) fig: MODE 3 CONSTELLATION



(D) fig: MODE 4 CONSTELLATION

FIGURE 3.11: Q number of M-QAM mode constellation diagram of NMM-OFDM-IM

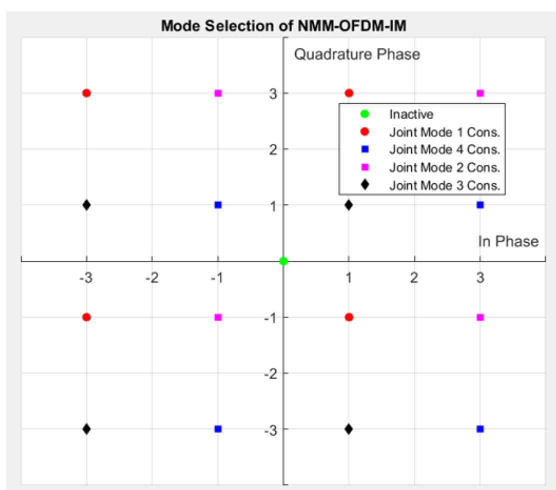


FIGURE 3.12: Joint nM QAM Constellation diagram of NMM-OFDM-IM with four different mode

$L_\beta(\lambda)$ symbol goes into g subblocks according to SAP as $F_\beta(\lambda)$ symbols and continues its journey towards OFDM block and IFFT process. This Joint M-QAM scheme with specific number of modes is the unique feature of NMM-OFDM-IM. . It creates very regular nM QAM constellation diagram though indexing mitigating all the problem regarding SE and EE of OFDM-IM, DM-OFDM and MM-OFDM-IM design structures. Figure 3.13 represents the last step nM-QAM constellation diagram. In this system, Q_β=4, M_A=4 QAM and n=4 QAM has been considered.

This constellation looks similar to DM-OFDM but NMM-OFDM-IM leads to greater symbol and indexing opportunity rather than DM-OFDM.

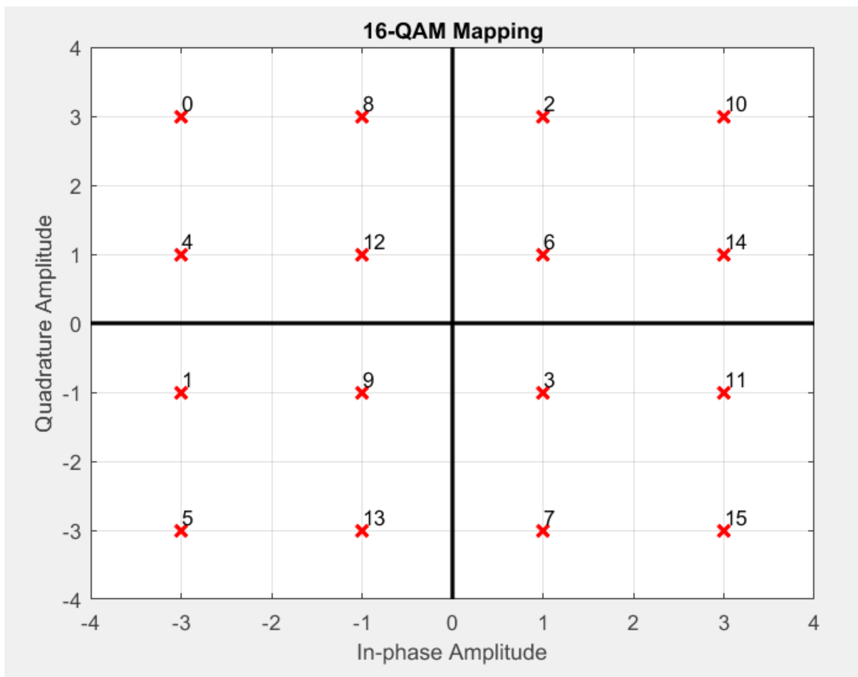


FIGURE 3.13: Joint Q mode nM QAM Constellation diagram with symbol mapping

OFDM Block creator and IFFT/FFT

$F_\beta(\lambda)$ signal constellations of each subblock are normalized to unit average power. Then, power is reallocated to active subcarrier symbols only according to Subcarrier Index Modulation (SIM) [ppr]. It is the benefit of activating a portion of subcarriers in each subblock which saves energy and improve BER. The OFDM block creator creates all the subblocks according to size of subblocks, SAP indexing and incoming $F_\beta(\lambda)$ signals and create a $N\times1$ OFDM symbol block which is

$$x = [x_1, x_2, ..., x_n]^T \tag{3.14}$$

$$x(F) = x_F = x = [x_1, x_2, ..., x_n]^T \tag{3.15}$$

After this procedure, all the steps are same as conventional OFDM. To indicate the index activation pattern, idle subcarriers are mentioned as $x = 0$ in OFDM symbol block. This was the only difference with OFDM. The OFDM symbol is needs to achieve orthogonality and convert from frequency domain to time domain which is done by N point Inverse Fast Fourier Transform (IFFT). Fourier transformation is done for the orthogonality and inverse action is applied to transform it into time domain signal so that it can pass in the real world transmission channel.

The time- domain OFDM signal,

$$\begin{aligned} X(t) =& [X_1, X_2, ..., X_N]^T \\ =& W_N^H x_F \end{aligned} \tag{3.16}$$

Here, W_N is the N-point Discrete Fourier Transform (DFT) matrix with $W_N^H W_N = NI_N$. IDFT is the efficient computational tool to perform orthogonality instead of using N number of Local oscillators. This OFDM signal then goes through parallel to serial (P/S) conversion and digital to analog (DAC) conversion before finally going into the channel. DAC is performed to shift the OFDM signal into high frequency in order to pass through the wireless channel.

3.2.2 NMM-OFDM-IM Receiver

Receiver's main task is to detect the received signal from wireless channel and decode it into the input bits. This step also contains the reverse operations of the transmitter and a precise detection process. This detection process is similar to OFDM-IM. There is only slight improvisation in the detection of index information. In simple words, the receiver has to detect the indices of active subcarriers among the OFDM symbol block and the corresponding information symbols in that each subcarrier in addition to the mode indices.

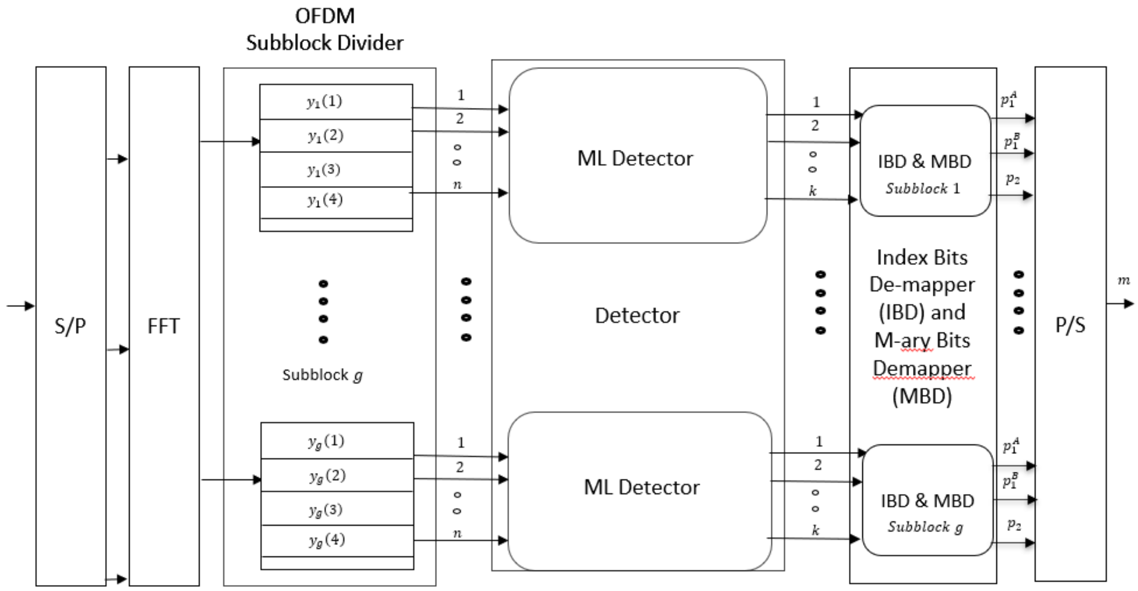


FIGURE 3.14: Receiver design of NMM-OFDM-IM

All reverse operation

The received signal after going through the Rayleigh Fading channel, $y_\alpha(t) = h_\alpha(t)X_\alpha(t) + w_\alpha(t)$ Here, $\alpha = 1, 2, ...N$; h is the channel impulse response (CIR) coefficient and w is the additive white gaussian noise (AWGN). In this system, the transmission was performed on Rayleigh Fading AWGN channel.

This received signal goes through Analog to Digital conversion (ADC), Serial to Parallel configuration and Fast Fourier transformation (FFT) respectively. FFT turns the time domain signal into frequency domain signal.

After going to ADC and P/S,

$$Y(t) = [Y_1, Y_2, ..., Y_N]^T \tag{3.17}$$

Received frequency domain signal after FFT,

$$y_{\alpha,F} = h_{\alpha,F}X_{\alpha,F} + w_{\alpha,F} \tag{3.18}$$

$$y(F) = y_F = y = [y_1, y_2, ..., y_N]^T \tag{3.19}$$

The proposed system's detection is more complex rather than the classical detection of OFDM. A simple decision of whether the received symbol is which one among the constellation points can not be used in this system. The detection lies on the decision of which constellation point it is coming from and what is the position of the symbol in the subcarriers to retrieve index information.

Maximum likelihood Detection Method have been considered in this system to retrieve the information data and indexing bits.

Mamimum Likelihood Detector

ML detector takes all the possible realization of each subblock into account. In this detection each signal constellations points of a subblock subcarrier are crosschecked with all of modulated symbols of the Joint M-ary Demapper. After getting the least Euclidean distance among them, that minimum distant point is selected. This way, each subcarrier modulated symbol is detected and then these symbols for all the combination of indices are checked simultaneously. The search option goes for all index combinations and signal constellation point to make joint decision on active indices and transmitted modulated symbols for each subblock. It tries to reduce the distance for both indices and symbols by

$$(\tilde{R}_\beta, \tilde{I}_\beta) = \sum_{\lambda=1}^{k} \sum_{\rho=1}^{M_A} |y_{F,\beta} - h_{F,\beta} x_{F,\beta}|^2 \tag{3.20}$$

This detection process is very precise since it considers all of the possible realization of everything by comparing with the Look-up table and Constellation diagram. This way is more complex as its computational complexity does not leave any comparison calculation left to confirm each symbol and indices.

Retrieving input bits in order

After detecting the symbols and indices of each subblocks, the index demapper seeks out the indices with symbols and retrieves SAP index bits, p_1^A. Parallelly, it also retrieves the M_A and M_B bits, p_2 bits from which MIS index bits, p_1^B are also collected. After all of these operations, the bits are arranged in parallel to sequencial order. This way, all the incoming bits of a NMM-OFDM-IM system are determined.

3.3 Methodology of NMM-OFDM-IM System

3.3.1 Derivation of Mode Index Selector, Throughput and Spectral Efficiency

NMM-OFDM-IM was designed keeping in mind three main elements and the performance. They are Spectral Efficiency, Energy Efficiency, Resultant Constellation Pattern and Bit error Rate (BER). The Mode Index Selector of the proposed NMM-OFDM-IM was designed considering these three factors.

The Mode Index Selector index bits,

$$\begin{aligned} p_1^B &= \lfloor log_2 \frac{Q!}{(Q-k)!} \rfloor \\ &= \lfloor log_2 \frac{n!}{(n-k)!} \rfloor \end{aligned} \tag{3.21}$$

Since, $Q \geq n$; assuming, $Q = n$ here.

Total bits transmitted by NMM-OFDM-IM for throughput calculation,

$$\begin{aligned} m_{NMM-OFDM-IM} &= (\lfloor log_2 \binom{n}{k} \rfloor + \lfloor log_2 \frac{Q!}{(Q-k)!} \rfloor + klog_2 M) \times g \\ &= (\lfloor log_2 \binom{n}{k} \rfloor + \lfloor log_2 \frac{n!}{(n-k)!} \rfloor + klog_2 M) \times g \end{aligned} \tag{3.22}$$

If Number of Modes of M modulation, Q is equal to n number of subcarriers; Q=n.

At last, The Spectral efficiency (SE) for NMM-OFDM-IM,

$$\begin{aligned} SE_{NMM-OFDM} &= \frac{(\lfloor log_2 \binom{n}{k} \rfloor + \lfloor log_2 \frac{Q!}{(Q-k)!} \rfloor + klog_2 M)}{N} \times g \\ &= \frac{(\lfloor log_2 \binom{n}{k} \rfloor + \lfloor log_2 \frac{n!}{(n-k)!} \rfloor + klog_2 M)}{N} \times g \end{aligned} \tag{3.23}$$

By using this equation 3.21, Look-up tables for Mode Index Selector can be designed for any subblock size and any modulation order. Besides, there is consistency for the resultant constellation pattern after the indexing only because of this, unlike OFDM-IQ-IM. This is important for the practical usage of the system in the industry as well as power consumption. By the use of both Subcarrier and Mode Index Selector in equation 3.23, Spectral Deficiency can be mitigated which is present in OFDM-Im for higher order modulation.

3.3.2 Observation of Key Characteristics

After the development of Mode Index Selection for NMM-OFDM-IM, Spectral Efficiency was observed to make the decision of whether it is capable to compete with conventional OFDM and other Index Modulation Variants. A table of varying subblock size and modulation order had been observed in table 4.16. This showed us that NMM-OFDM-IM is capable to beat the SE for other variants and OFDM. Even in higher modulation orders such as 256 QAM, it had very high SE in table 4.17. The comparison is clear in the bar diagram of figure 4.17 and figure 4.18.

Energy saving was also calculated and compared with other IM variants. It was seen that NMM-OFDM-IM is the only system that can give same SE activating only 6 subcarriers out of 16 subcarriers in a subblock for 16QAM. Thus it saved 8 subcarriers energy out of total of 128 subcarriers. This gives approximately 62.5% energy rather than other systems shown in the bar diagram of figure 4.19.

After Indexing, Resultant Constellation diagrams of proposed NMM-OFDM-IM and other systems were compared in figure 4.20. It showed a promising difference than other systems especially OFDM-IQ-IM.

3.3.3 Validation of the Performance of NMM-OFDM-IM System

The hypothesis of the proposed NMM-OFDM-IM indicated that performance would be better since most of the bits were transmitted as indices of active subcarriers and modes. The whole system was designed at MATLAB using 512 subblocks of 4 subcarrier resulting in total of 2048 subcarriers. Only 3 of the subcarriers were active among 4 subcarriers in each subblock. Random bits were generated to go through the Rayleigh Fading Channel with Additive White gaussian Noise

(AWGN) of 0.05 variance and zero mean with 2048 subcarriers, 4 constellation patterns of 4QAM and previously mentioned subblock settings at the transmitter. Maximum Likelihood detection was used in the receiver to retrieve the transmitted data. Both look-up tables were provided at the transmitter and receiver. Though these procedures can be mitigated by using the combinatorial methods with appropriate order on both sides. After an extensive search, the received data had been recovered by constellation demapper and selector demappers. The transmitted and received bits were compared and a BER performance for a range of 0 to 35 decibel(dB) Signal to Noise Ratio (SNR) was generated. It was seen that BER is better in higher SNR regions as stated in the hypothesis (figure 4.23). Though there is slight performance degradation than conventional MM-OFDM-IM due to null mode (figure 4.24). The BER performance was better from 5dB to higher SNR region (figure 4.25). By comparing it with reference paper performance (figure **??**), the performance was validated.

Chapter 4

RESULT AND DISCUSSION

4.1 Exploration of System Operation

Every OFDM with Index Modulation Variant including NMM-OFDM-IM is explained step by step by showing the data flow of bits, converting it into the symbols through their corresponding indexing and creation of their subblock symbols before IFFT. After and before this β^{th} subblock operation, everything is same as conventional OFDM So, the common steps are skipped for simplification and only one subblock operations is explained for each system.

4.1.1 OFDM-IM

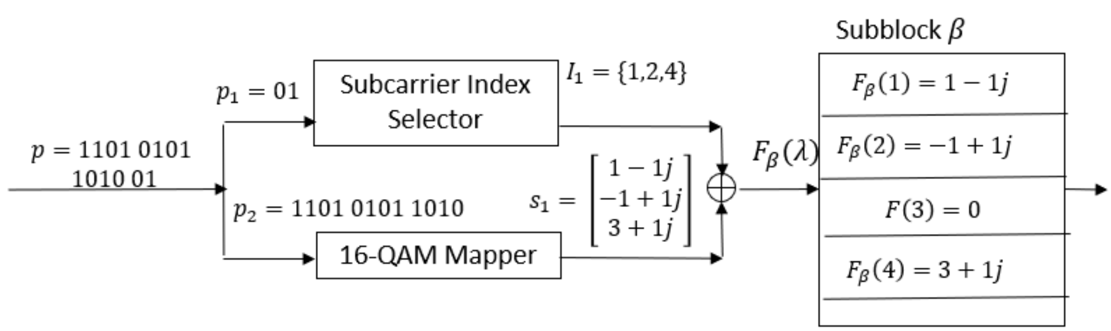


FIGURE 4.1: Operation of β^{th} subblock OFDM-IM

The total bits sent by OFDM-IM,

$$m_{OFDM-IM} = (\lfloor log_2\binom{n}{k} \rfloor + klog_2 M) \times g \quad (4.1)$$

Index bits	Subcarrier Activation Indices
00	1,2,3
01	1,2,4
10	1,3,4
11	2,3,4

TABLE 4.1: Look-Up table of OFDM-IM

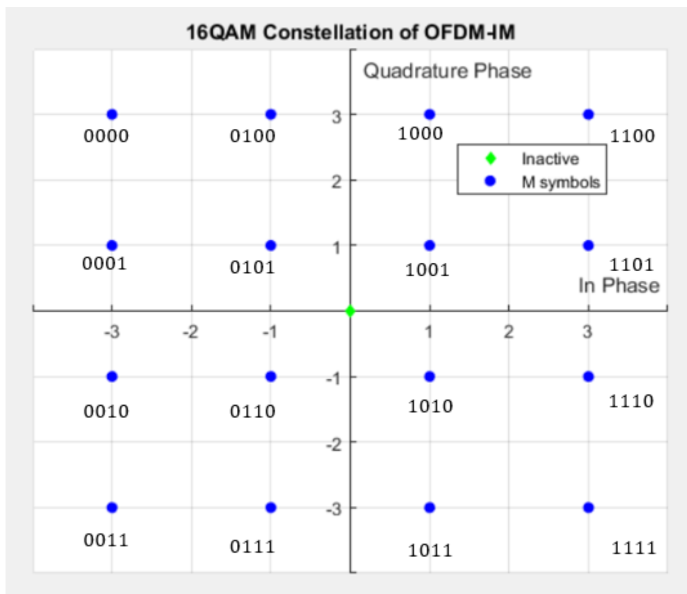


FIGURE 4.2: 16 QAM constellation used in OFDM-IM for symbol Modulation

4.1.2 DM-OFDM-IM

DM-OFDM-IM combines two individual modulation schemes in one system. The constellation symbol bits are labeled according to the order of 32 QAM constellation of binary mapping whereas reference constellation [44] are of gray coding.

Condition: Dual modulation scheme of the system must be distinguished from each other; $M_A \cap M_B = \emptyset$

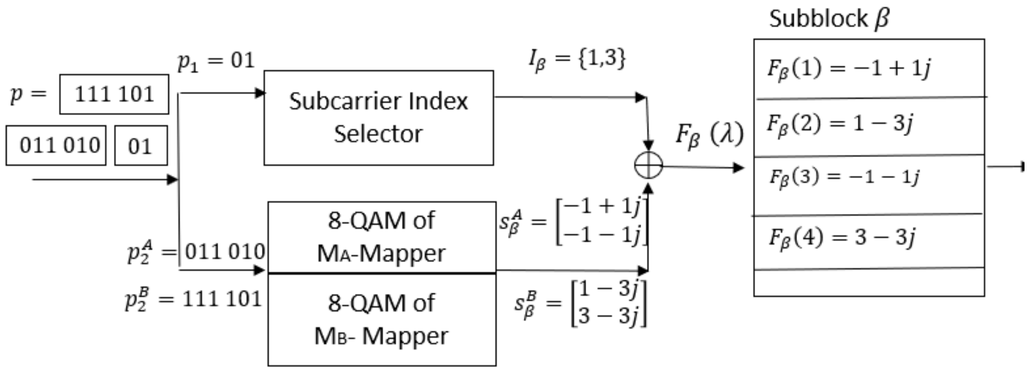
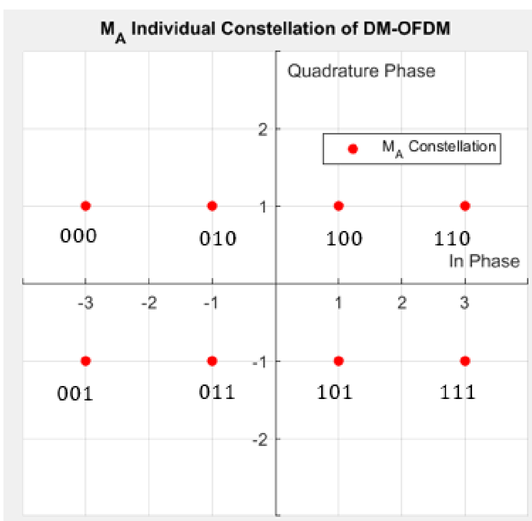


FIGURE 4.3: Operation of β^{th} subblock DM-OFDM

Index bits	Subcarrier Activation Indices, I_1	Subcarrier Activation Pattern
00	1,2	$[s_1^A, s_1^A, s_1^B, s_1^B]$
01	1,3	$[s_1^A, s_1^B, s_1^A, s_1^B]$
10	1,4	$[s_1^A, s_1^B, s_1^B, s_1^A]$
11	2,3	$[s_1^B, s_1^A, s_1^A, s_1^B]$

TABLE 4.2: Look-Up table of DM-OFDM



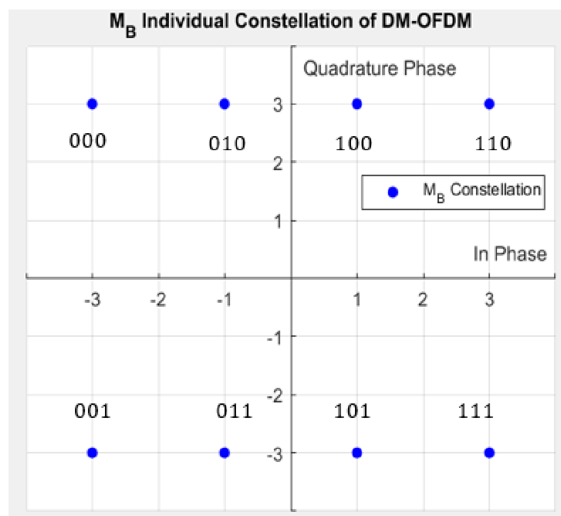


FIGURE 4.4: Individual constellation of DM-OFDM for symbol Modulation

Total bits transmitted by DM-OFDM-IM,

$$m_{DM-OFDM} = (\lfloor log_2\binom{n}{k}\rfloor + klog_2M_a \ + (n-k)log_2M_b) \times g \tag{4.2}$$

The constellation symbol bits are labeled according to the order of 32 QAM constellation of

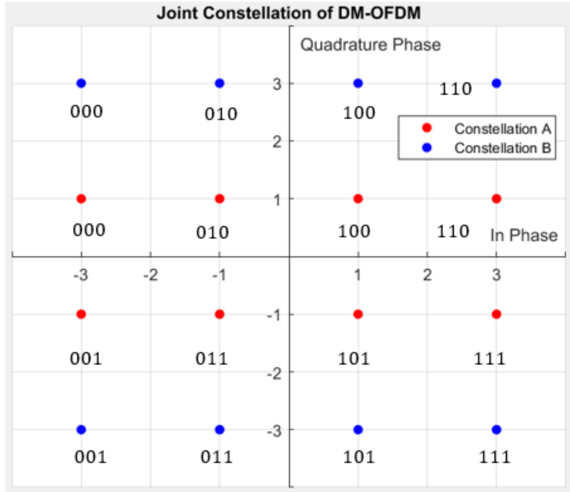


FIGURE 4.5: 16 QAM constellation used in DM-OFDM for symbol Modulation

binary mapping whereas reference constellation [27] are of gray coding.

4.1.3 OFDM-IQ-IM

OFDM-IQ-IM allows individual modulation of in phase and quadrature phase indexing independence.

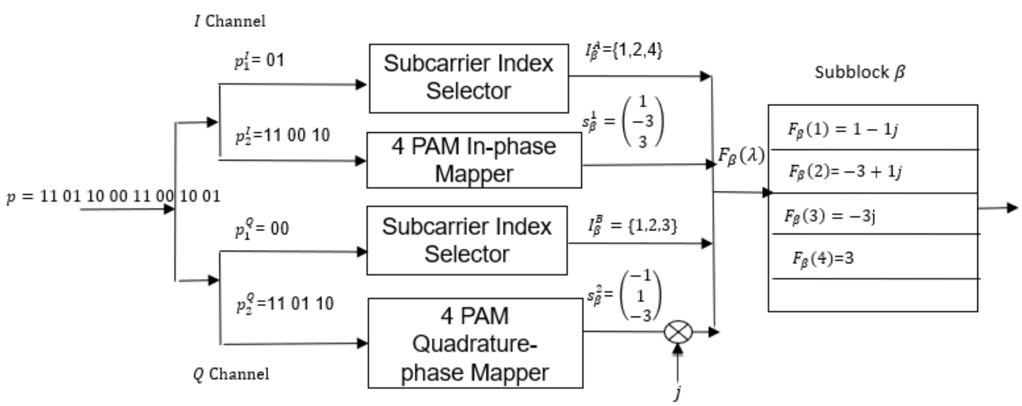


FIGURE 4.6: Operation of β^{th} subblock OFDM-IQ-IM

Total bits transmitted by OFDM-IQ-IM,

$$
\begin{aligned}
m_{OFDM-IQ-IM} &= (\lfloor log_2\binom{n}{k}\rfloor + klog_2M_I \ + \lfloor log_2\binom{n}{k}\rfloor + klog_2M_Q) \times g \\
&= (2\lfloor log_2\binom{n}{k}\rfloor + klog_2M \ ) \times g
\end{aligned}
\tag{4.3}
$$

Index bits	Subcarrier Activation Indices
00	1,2,3
01	1,2,4
10	1,3,4
11	2,3,4

TABLE 4.3: Look-Up table of OFDM-IQ-IM

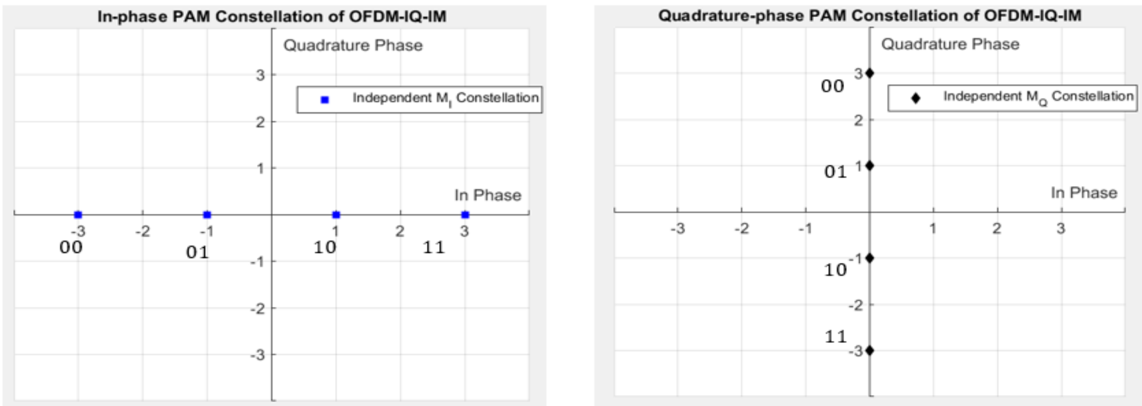


FIGURE 4.7: In-phase and Quadrature Phase Individual PAM constellation used in OFDM-IQ-IM

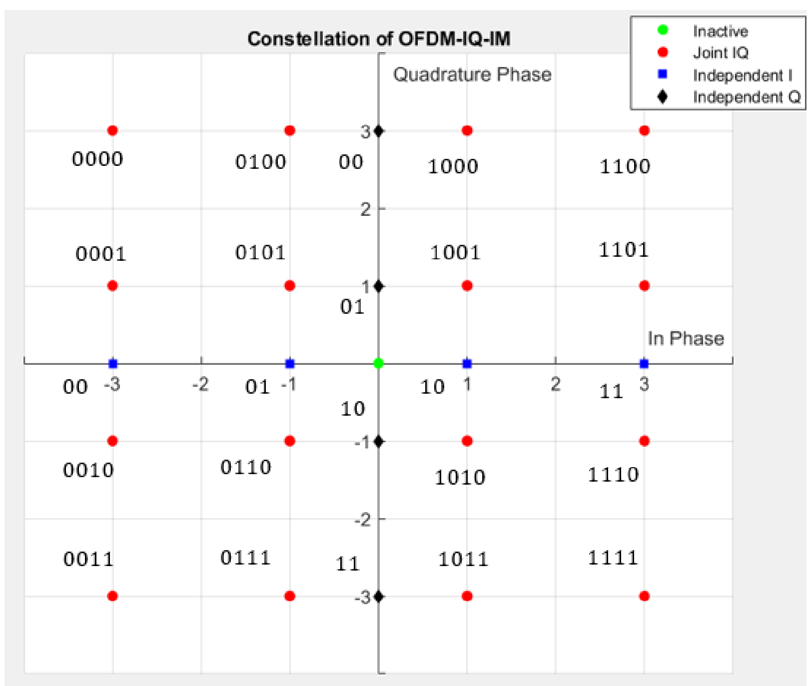


FIGURE 4.8: 16 QAM constellation used in OFDM-IQ-IM for symbol Modulation

4.1.4 MM-OFDM-IM

MM-OFDM-IM subcarriers indexing is different than all other IM variants. It uses permutation for indexing.

Total bits transmitted by MM-OFDM-IM,

$$m_{MM-OFDM-IM} = (\lfloor log_2(n!) \rfloor + nlog_2 M) \times g \tag{4.4}$$

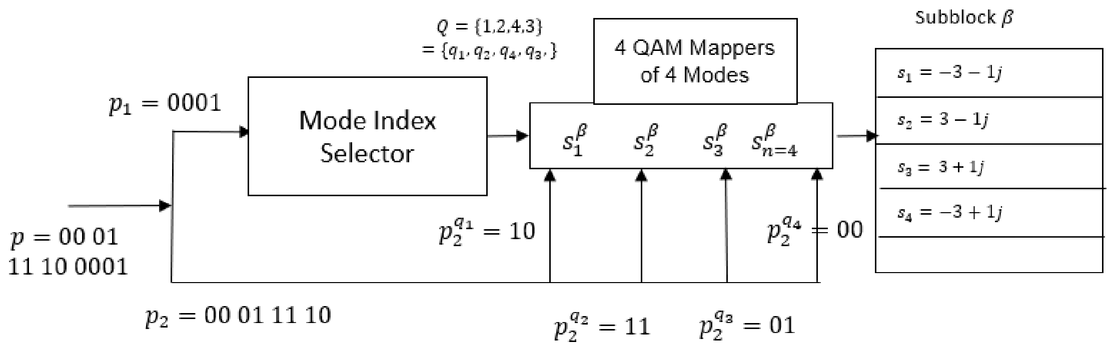
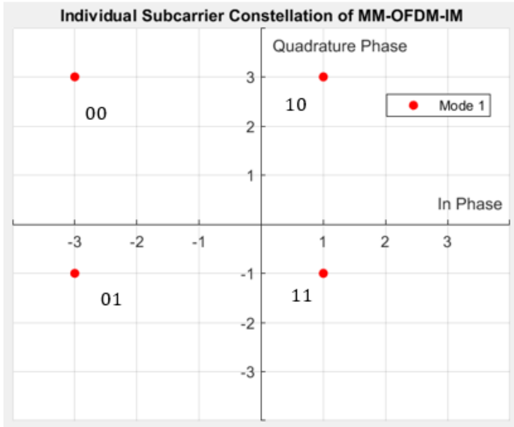


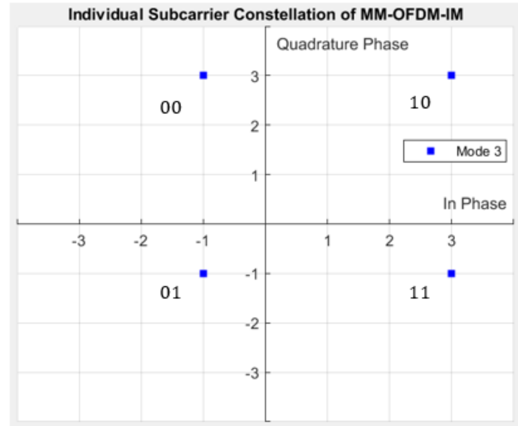
FIGURE 4.9: Operation of β^{th} subblock MM-OFDM-IM

Index bits	Subcarrier Activation Indices
0000	1,2,3,4
0001	1,2,4,3
0010	1,3,2,4
0011	1,3,4,2
0100	1,4,3,2
0101	1,4,2,3
0110	2,1,3,4
0111	2,1,4,3
1000	2,3,1,4
1001	2,3,4,1
1010	2,4,1,3
1011	2,4,3,1
1100	3,1,2,4
1101	3,1,4,2
1110	3,2,1,4
1111	3,2,4,1

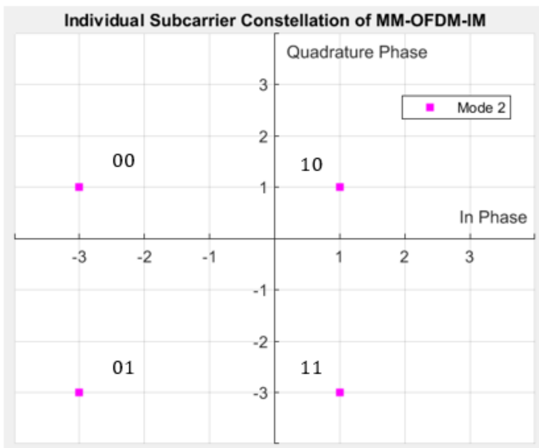
TABLE 4.4: Look-Up table of MM-OFDM-IM



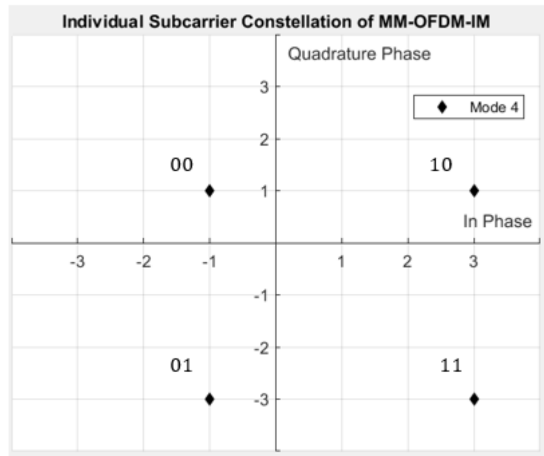
(A) fig: MODE 1 CONSTELLATION



(B) fig: MODE 2 CONSTELLATION



(C) fig: MODE 3 CONSTELLATION



(D) fig: MODE 4 CONSTELLATION

FIGURE 4.10: Individual Subcarrier Constellation for each mode of MM-OFDM-IM

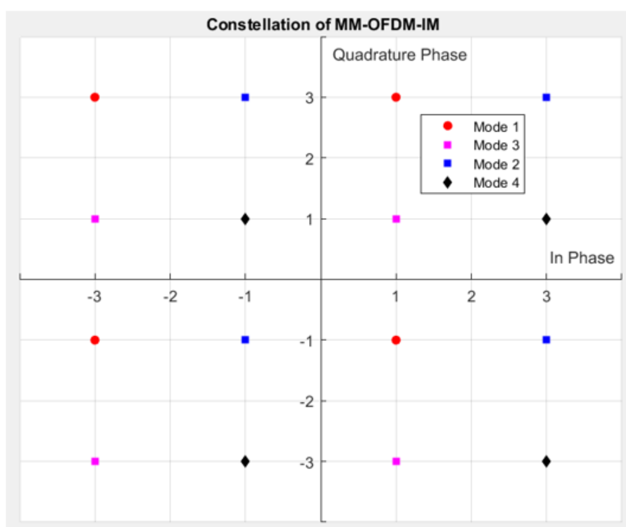


FIGURE 4.11: Combined constellation of MM-OFDM-IM for symbol Modulation

This system does not keep any subcarriers idle. Hence, Energy saving for the Next Generation Wireless Communication is not an option here.

4.1.5 NMM-OFDM-IM

NMM-OFDM-IM considers multiple Mappers with specifically two Index Selectors. Subcarrier Index Selector (SIS) and Mode Index Selector (MIS) of NMM-OFDM-IM achieved close to the attainable throughput of 16 QAM conventional OFDM-IM with 4 QAM of 4 Modes constellation here. Whilst, NMM-OFDM-IM is capable of achieving high throughput in higher Modulation order, OFDM-IM can not compete for the same throughput as conventional OFDM. For instance, in 16 QAM multiple constellations of NMM-OFDM-IM reached up to 1024 bits whereas 16QAM OFDM-IM reached 512 bits for the same subblock settings. NMM-OFDM-IM had no limits in 256 QAM or further Modulation order despite OFDM-IM failed to reach the same throughput as conventional OFDM after 64 QAM. The throughput and Spectral Efficiency of OFDM, OFDM-IM and NMM-OFDM-IM for different modulation orders for the same subblock settings are shown in table 4.8, 4.11 and 4.16. It is difficult to simplify the realizations in figures for higher modulation orders. Therefore, the system explanation has been done for the same subblock settings of 4 subcarriers with lower modulation order.

Total bits transmitted by NMM-OFDM-IM,

$$\begin{aligned} m_{NMM-OFDM-IM} &= (\lfloor log_2\binom{n}{k}\rfloor + \lfloor log_2\frac{Q!}{(Q-k)!}\rfloor + klog_2M) \times g \\ &= (\lfloor log_2\binom{n}{k}\rfloor + \lfloor log_2\frac{n!}{(n-k)!}\rfloor + klog_2M) \times g \end{aligned} \tag{4.5}$$

If Number of Modes of M modulation, Q is equal to n number of subcarriers; Q=n.

Since NMM-OFDM-IM has a null mode in the resultant constellation similar to OFDM-IM due to subcarrier deactivation through Subcarrier Index Selector (SIS). This null mode has lower inter-mode symbols in the constellation that resulted in a higher Bit Error Rate (BER) than OFDM-IM for the lower Signal to Noise Ratio (SNR) region shown in figure 4.23. Hence, this energy saving of inactive subcarriers could be used in expanding the constellation eventually to reach designated BER for specific applications. This is the trade-off for NMM-OFDM-IM.

Condition:

- The number of different M-QAM mode constellations, Q must be equal or greater than the size of subblock for the purpose of MIS, $Q \geq n$;
- Each active subcarrier must contain different mode, $Mode_1 \cap Mode_2 \cap Mode_3 \cap Mode_4 = \emptyset$

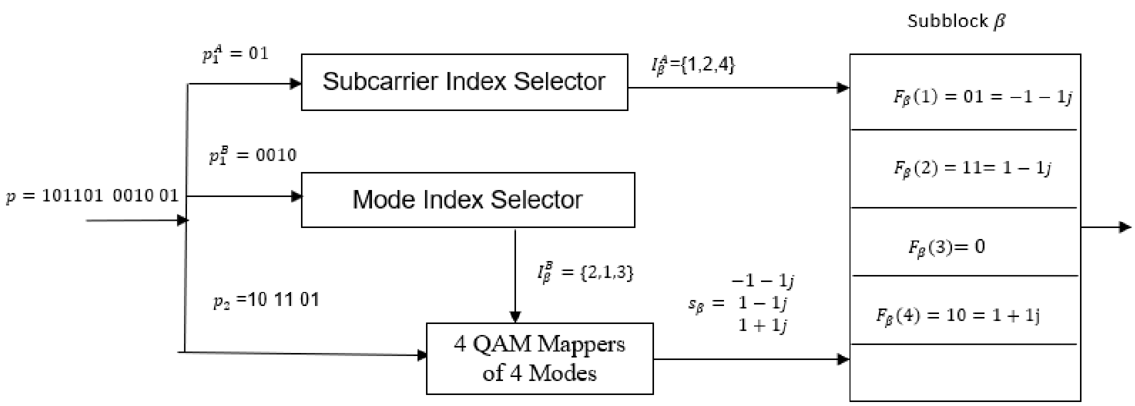


FIGURE 4.12: Operation of β^{th} subblock NMM-OFDM-IM of Generalized Version

Goal:

- Permutational rearrangement indexing with 2^{nd} constellation like OFDM-IQ-IM. To have the benefits of energy impact, the symbols of M_B constellations need to go into same subcarrier but still having index bits through order rearrangement.
- To achieve this additional rearrangement permutation indexing, another means of information passing are needed rather than SIS and symbol. Here, the idea of MM-OFDM-IM for its constellation indexing is used. M_A constellation is fixed and multiple mode constellations of $M_B$is going on each active subcarrier to introduce MIS bits. Hence, one combined constellation at the receiver is produced without the issues of OFDM-IQ-IM's congested constellation.

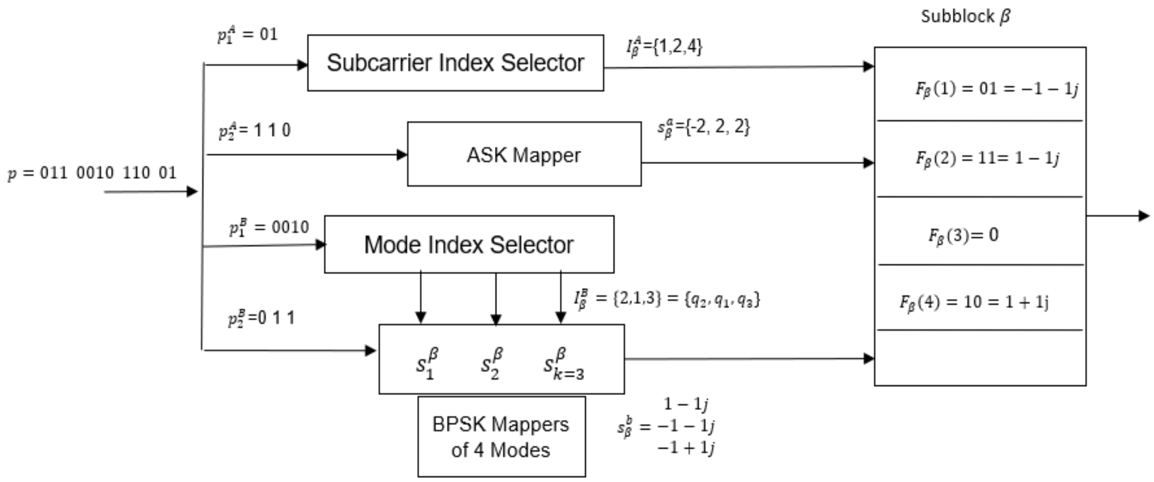


FIGURE 4.13: Operation of β^{th} subblock NMM-OFDM-IM

Index bits	Subcarrier Activation Pattern (SAP)
00	1,2,3
01	1,2,4
10	1,3,4
11	2,3,4

TABLE 4.5: SIS Look-Up table of NMM-OFDM-IM

Index bits	Mode Sequence indices, I_β^B	Index MIS for k=3 active subcarrier, $Q_\beta(\lambda)$
0000	1,2,3	$[q_\beta(1), q_\beta(2), q_\beta(3)]$
0001	1,3,2	$[q_\beta(1), q_\beta(3), q_\beta(2)]$
0010	2,1,3	$[q_\beta(2), q_\beta(1), q_\beta(3)]$
0011	2,3,1	$[q_\beta(2), q_\beta(3), q_\beta(1)]$
0100	1,2,4	$[q_\beta(1), q_\beta(2), q_\beta(4)]$
0101	1,4,2	$[q_\beta(1), q_\beta(4), q_\beta(2)]$
0110	2,1,4	$[q_\beta(2), q_\beta(1), q_\beta(4)]$
0111	2,4,1	$[q_\beta(2), q_\beta(4), q_\beta(1)]$
1000	1,3,4	$[q_\beta(1), q_\beta(3), q_\beta(4)]$
1001	1,4,3	$[q_\beta(1), q_\beta(4), q_\beta(3)]$
1010	3,1,4	$[q_\beta(3), q_\beta(4), q_\beta(1)]$
1011	3,4,1	$[q_\beta(3), q_\beta(4), q_\beta(1)]$
1100	2,3,4	$[q_\beta(2), q_\beta(3), q_\beta(4)]$
1101	2,4,3	$[q_\beta(2), q_\beta(4), q_\beta(3)]$
1110	3,2,4	$[q_\beta(3), q_\beta(2), q_\beta(4)]$
1111	3,4,2	$[q_\beta(3), q_\beta(4), q_\beta(2)]$

TABLE 4.6: MIS Look-Up table of NMM-OFDM-IM

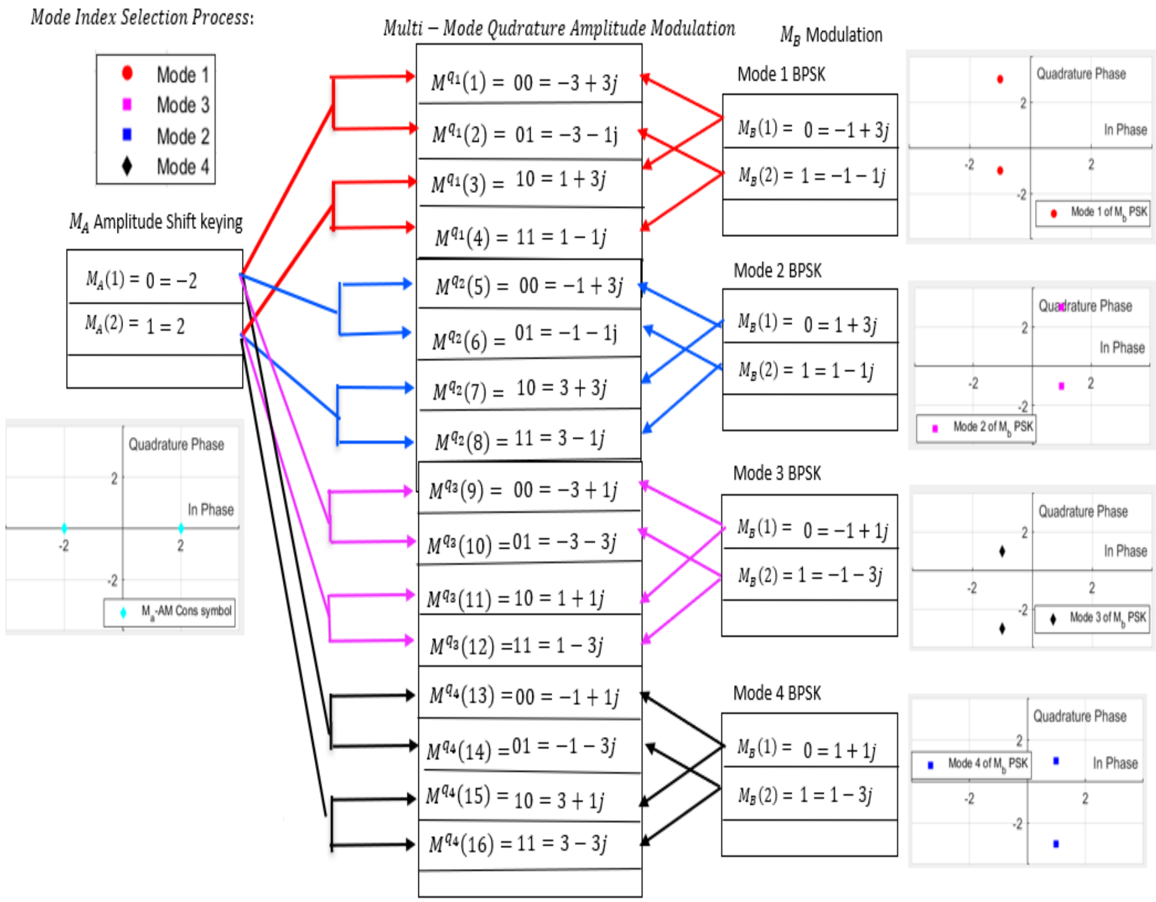
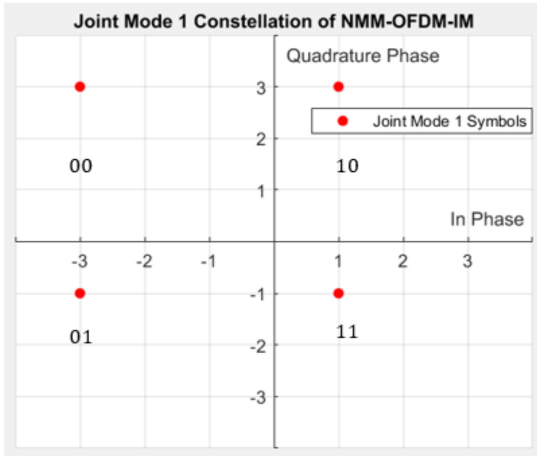


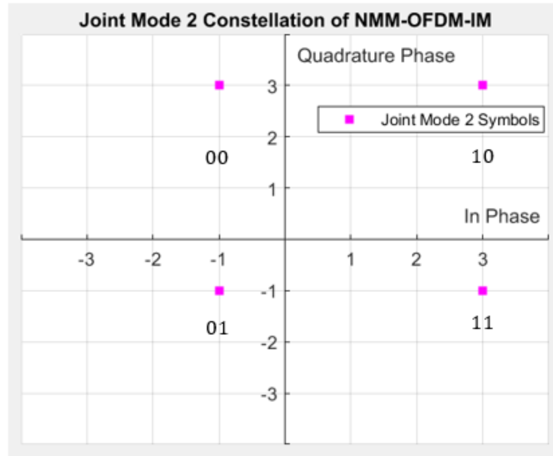
FIGURE 4.14: NMM-OFDM-IM Mode Selection Process

Modes formed by Mode Index Selector, q_{mode}	$\frac{M}{n}$ = 4 Symbols from Joint M= 16 QAM comprising Different Modes, $q_{\beta,i}(\rho)$
$Mode_1, q_1$	(-3+3j), (1+3j), (-3-1j), (1-1j)
$Mode_2, q_2$	(-1+3j), (3+3j), (-1-1j), (3-1j)
$Mode_3, q_3$	(-3+1j), (1+1j), (-3-3j), (1-3j)
$Mode_4, q_4$	(-1+1j), (3+1j), (-1-3j), (3-3j)

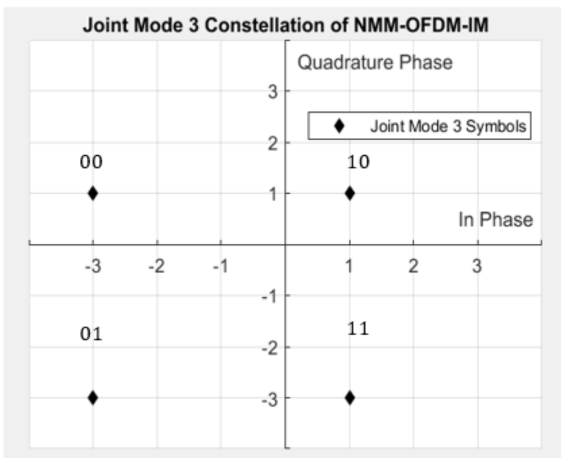
TABLE 4.7: Mode Classification and $q = \frac{M}{n}$-Symbols Comprising in each Mode



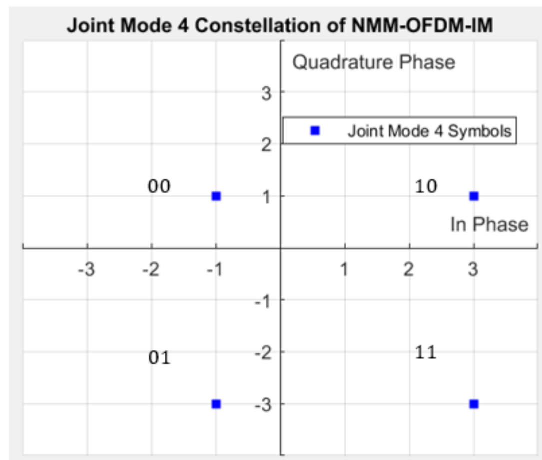
(A) fig: MODE 1 CONSTELLATION



(B) fig: MODE 2 CONSTELLATION



(C) fig: MODE 3 CONSTELLATION



(D) fig: MODE 4 CONSTELLATION

FIGURE 4.15: Individual Subcarrier Constellation for each mode of NMM-OFDM-IM

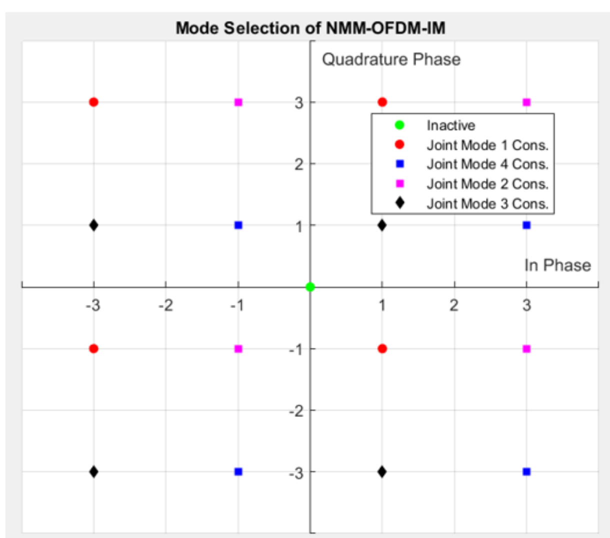


FIGURE 4.16: Combined constellation of NMM-OFDM-IM for symbol Modulation

4.2 THROUGHPUT

Throughput refers to the rate at which bits are successfully transmitted over a communication channel. Throughput is typically measured in bits per second (bit/s or bps). In this section, Total Transmitted Bits were measured in order to keep it simple and mentioned in later 4.3 section while comparing SE among all the systems.

4.3 SPECTRAL EFFICIENCY

Spectral Efficiency (SE) can be defined as the data transfer capacity over a particular bandwidth in a specific communication channel. It is the measurement of how proficiently a finite frequency spectrum is used. The number of bits transmitted per second per subcarrier (bps/subcarrier) is the measure of spectral efficiency. For simplicity, the effect of cyclic prefix on the SE performance was ignored.

Generally, Spectral Efficiency of OFDM depends only on the total subcarrier size and modulation order. Whilst, SE of OFDM-IM, DM-OFDM and OFDM-IQ-IM depends on subblock settings, Modulation order and subcarrier index selector activation pattern. On the other hand, SE of NMM-OFDM-IM has greater degree of freedom than any other system to attain its desirable SE since it is determined by subblock settings, modulation order, subcarrier activaton pattern of SIS and mode constellation selection of MIS. In this chapter 4, Spectral Efficiency of different systems are calculated and compared. This SE characteristics comparison is provided to meet the first and foremost goal of any communication system to introduce themselves into the practical world.

4.3.1 OFDM

Total number of subcarriers are N, Modulation order is M, then according to the definition, The Spectral efficiency, SE_{OFDM} would be,

$$SE_{OFDM} = \frac{N log_2 M}{N} \tag{4.6}$$

If total number of subcarriers are 128, then for 4-QAM modulation scheme, the spectral efficiency will be,

$$\begin{aligned} SE_{OFDM} &= \frac{Nlog_2M}{N} \\ &= \frac{128log_24}{128} \\ &= 2 \end{aligned}$$

By varying the modulation scheme, we can see the different transmitted bits and spectral efficiency where there are subtotal of 128 subcarriers throughout all the configurations.

Modulation Scheme	Total transmitted	Spectral Efficiency
4	256	2
8	384	3
16	512	4
32	640	5
64	768	6
256	1024	8

TABLE 4.8: SE of OFDM by varying modulation order for total 128 subcarriers, N=128

4.3.2 OFDM-IM

OFDM-IM has a number of parameters such as subblock number, subblock size apart from modulation scheme by controlling which we can achieve desired transmitted bits and Spectral efficiency. The benefits of OFDM-IM are that it can produce higher spectral efficiency than OFDM with the help of additional index bits. On the other hand, a reduced number of activated subcarriers can produce higher energy efficiency and lower BER in terms of the fair comparison with OFDM for same spectral efficiency. Now, the spectral efficiency of OFDM-IM [31] is,

$$SE_{OFDM-IM} = \frac{\lfloor log_2\binom{n}{k} \rfloor + klog_2M}{N} \times g \tag{4.7}$$

So, if total number of subcarriers is 128, they are divided into 8 subblocks each carrying 16 subcarriers. Then, for 4-QAM modulation scheme, if 10 out of 16 subcarriers are activated in each block, the spectral efficiency will be,

$$
\begin{aligned}
SE_{OFDM-IM} &= \frac{\lfloor log_2\binom{n}{k})\rfloor + klog_2M}{N} \times g \\
&= \frac{\lfloor log_2\binom{16}{10}\rfloor + 10log_2 4}{128} \times 8 \\
&= 2
\end{aligned}
$$

If 15 out of 16 subcarriers are activated in each block, the spectral efficiency will be,

$$
\begin{aligned}
SE_{OFDM-IM} &= \frac{\lfloor log_2\binom{n}{k}\rfloor + klog_2M}{N} \times g \\
&= \frac{\lfloor log_2\binom{16}{15}\rfloor + 10log_2 4}{128} \times 8 \\
&= 2.125
\end{aligned}
$$

Hence, first configuration yields the same spectral efficiency as OFDM with only 80 subcarriers out of 128 subcarriers. On the other hand, if maximum number of subcarriers such as 120 out of 128 subcarriers are activated, higher spectral efficiency than OFDM-IM will be activated with the same settings. In both cases, OFDM-IM are found to perform superior to conventional OFDM.

Now, SE in terms of modulation scheme and subblock number and size respectively in table 4.9 and table 4.10. In both of the cases, total number of subcarriers are 128. For table 4.9; there are 8 subblocks each containing 16 subcarriers. Same SE similar to OFDM and maximum SE for each modulation scheme were calculated for these settings.

Modulation Scheme	Number of Active Subcarriers, k	Total transmitted	Spectral Efficiency
4	10	256	2
	15	272	2.125
8	13	384	3
	15	392	3.0625
16	15	512	4
32	**15 [n<M]** [22]	**632**	**4.9375**
64	**15 [n<M]**	**752**	**5.875**
256	**15 [n<M]**	**992**	**7.75**

Table 4.9: SE of OFDM-IM by varying Modulation order for n=16, g=8 subblock settings

Here, in table 4.9, OFDM-IM was found to transmit the same or even increased number of bits for different settings of number of subcarriers. Despite of the degree of freedom of different subblock size; as the modulation order increases, it comes to a limit. It was found that for 8 subblocks containing 16 subcarriers, it can meet the desired SE up to 16 QAM modulation scheme. For higher modulation order such as 32, 256-QAM, it was found that it cannot produce as many bits as OFDM for this subblock size. It eventually rules out the main benefit of OFDM-IM.

In table 4.10, different subblock sizes were explored with 32 QAM modulation scheme to calculate the SE. It was seen that when subblock size is less than the modulation order which is up to 16 subcarriers, $SE_{OFDM-IM}$ is lower than SE_{OFDM}. It usually maintains this condition for the lower limit of subblock size for desired SE. The condition is given below:

If Subblock Size, n < Modulation Order, M; then $SE_{OFDM-IM} < SE_{OFDM}$

According to the paper [25]; If Subblock Size, n > Modulation Order, M; then $SE_{OFDM-IM} \geq SE_{OFDM}$ at maximum k for given n

Subblock Size, n and Subblock numbers, g	Number of Active Subcarriers, k	Total transmitted bits	Spectral Efficiency
n=2, g=64	**1**; **n<M** [22]	**384**	**3**
n=4, g=32	**3**; **n<M**	**544**	**4.25**
n=8, g=16	**7**, **n<M**	**608**	**4.75**
n=16, g=8	**15**; **n<M**	**632**	**4.9375**
n=32, g=4	31	640	5
n=64, g=2	61	640	5

TABLE 4.10: SE of OFDM-IM by varying subblock size for 32 QAM whereas $SE_{OFDM(32QAM)} = 5$

Whereas in table 4.9, OFDM-IM with 16 subcarriers of 8 subblocks only able to provide desired SE until 16 QAM, in table 4.10 with different size of subblock setting OFDM-IM provided the desired SE. That is how OFDM-IM has the degree of freedom by dividing the subcarriers into subblock.

At the end, all the different settings for 4,8,6,32, 64 and 256-QAM were arranged. For 256-QAM, it is impossible to achieve desired SE for any settings. This found to be the main limitation of OFDM-IM. OFDM-IM cannot compete OFDM in higher modulation scheme.

Modulation Scheme	Subblock Size, n and Subblock numbers, g	Number of Active Subcarriers, k	Total transmitted bits	Spectral Efficiencyy
4	n=4, g=32	3	256	2
	n=8, g=16	6	256	2
	n=16, g=8	10	256	2
	n=32, g=4	18	256	2
	n=64, g=2	34	256	2
8	n=4, g=32	3	352	2.75
	n=8, g=16	7	384	3
	n=16, g=8	13	384	3
	n=32, g=4	25	384	3
	n=64, g=2	48	384	3
16	n=4, g=32	3	448	3.5
	n=8, g=16	7	496	3.875
	n=16, g=8	15	512	4
	n=32, g=4	29	512	4
	n=64, g=2	56	512	4
32	n=4, g=32	3	544	4.25
	n=8, g=16	7	608	4.75
	n=16, g=8	15	632	4.9375
	n=32, g=4	31	640	5
	n=64, g=2	61	640	5
64	n=4, g=32	3	640	5
	n=8, g=16	7	720	5.625
	n=16, g=8	15	752	5.875
	n=32, g=4	31	764	5.96875
	n=64, g=2	63	768	6
256	n=4, g=32	3	832	2.5
	n=8, g=16	7	944	7.375
	n=16, g=8	15	992	7.75
	n=32, g=4	31	1012	7.90625
	n=64, g=2	63	1020	7.96875

TABLE 4.11: SE of OFDM-IM by varying Modulation order and number of subblock size

4.3.3 OFDM-IQ-IM

OFDM-IQ -IM was proposed by Fan eta al. [32] where Index Modulation were incorporated on the in-phase and quadrature (I/Q) components separately. In OFDM-IM, a portion of subcarriers in each subblock is modulated with symbols and others kept idle. On the other hand, I/Q part of OFDM-IQ-IM can travel in a fraction of same subcarriers of a subblock or they go in each separate subcarrier which results in activating all of them similar to classical OFDM.

So, there is generally a range rather than a specific value of how many subcarriers are active in a subblock and what is the Spectral Efficiency for that. If k_I and k_Q are the numbers of active subcarriers in a subblock for the I/Q components that are modulated by M_I and M_Q-PAM, respectively. Then,

The Spectral efficiency of OFDM-IQ-IM is,

$$SE_{OFDM-IQ-IM} = \frac{\lfloor log_2\binom{n}{k_I}\rfloor + k_I log_2 M_I + \lfloor log_2\binom{n}{k_Q}\rfloor + k_Q log_2 M_Q}{N} \times g \tag{4.8}$$

Both I/Q phase components activate equal number of k subcarriers in each subblock. It can go in same subcarrier or in different subcarrier according to its SAP sequence. So, SE of OFDM-IQ-IM for their ultimate joint M-QAM constellation can also be written as:

$$SE_{OFDM-IQ-IM} = \frac{\lfloor 2log_2\binom{n}{k}\rfloor + k log_2 M}{N} \times g \tag{4.9}$$

As presented in table 4.12, it can be seen that OFDM-IQ-IM achieves the same SE as OFDM and OFDM-IM activating a minimum portion of subcarriers of subblock. OFDM system transmits 512 information bits from 128 subcarriers of the system for 16 QAM. In OFDM-IQ-IM, 6 of the subcarriers out of 16 in each subblock comprising 8 subblocks produce same number of bits, 512 as OFDM for 16 QAM. It means that a total of 48 subcarriers out of 128 provides the same bits as OFDM. On the other hand, OFDM-IM must activate 15 subcarriers out of 16 which leads to total 120 active subcarriers out of 128 subcarriers to get same SE. Rest of the subcarriers must be inactive for the purpose of indexing. So, maximum subcarriers need to be active for the same bit transmission like OFDM in the OFDM-IM system.

Independent Modulation Scheme for I and Q branch	Subblock Size, n and Subblock numbers, g	Number of Active Subcarriers, k	Total transmitted bits	Spectral Efficiencyy
M_I=2, $M_Q = 2$	n=2,g=64	BPSK cannot be performed in OFDM-IQ-IM	N/A	N/A
	n=4, g=32	2	256	2
	n=8, g=16	3	256	2
	n=16, g=8	5	272	2.125
	n=32, g=4	9	264	2.0625
	n=64, g=2	16	256	2
$M_I = 4$,$M_Q = 4$	n=4, g=32	Out of the SE condition $n < M_I$ or $n < M_Q$	N/A	N/A
	n=8, g=16	3	512	4
	n=16, g=8	6	512	4
	n=32, g=4	10	512	4
	n=64, g=2	18	512	4
$M_I = 8$,$M_Q = 8$	n=4, g=32	Out of the SE condition $n < M_I$ or $n < M_Q$	N/A	N/A
	n=8, g=16	7	768	6
	n=16, g=8	14	768	6
	n=32, g=4	25	768	6
	n=64, g=2	48	768	6
$M_I = 16$,$M_Q = 16$	n=4, g=32	Out of the SE condition $n < M_I$ or $n < M_Q$	N/A	N/A
	n=8, g=16	"	N/A	N/A
	n=16, g=8	15	1024	8
	n=32, g=4	29	1024	8
	n=64, g=2	56	1024	8

TABLE 4.12: SE of OFDM-IQ-IM by varying Modulation order and number of subblock size

The challange begins when it is escalated to higher modulation, 64 QAM and beyond, yet same amount of bits in OFDM-IM is intended as classical OFDM. It was found that it cannot work further as there is no extra subcarrier to convey more information bits. Rest of the 8 subcarriers must remain idle for the purpose of sending index bits. Those inactive subcarriers lose more than 32 information bits that can not compensate index bits. On the other hand, OFDM-IQ-IM has 80 subcarriers left and at least 72 subcarriers can transmit more 288 bits where Spectral Efficiency is met even in higher modulation scheme.

4.3.4 DM-OFDM

DM-OFDM is a combination of OFDM and OFDM-IM. It has the similar system configuration as OFDM-IM. The only difference is that it indexes the subcarriers not by activating a fraction of subcarrier but by sending two distinguished modulation order by dividing them into two subsets of subcarriers. That means, ultimately, all the subcarriers are active similar to OFDM.

In DM-OFDM, considering there are two modulation order for two modes, M_A and M_B . If total number of subblocks is g and number of subcarriers within each subblock is n. then, the 1st subset of subcarriers in each subblock is $k_1 = k$ for M_A Mode and 2nd subset of subcarriers in that subblock will be $k_2 = (n - k)$ for M_B Mode.

Here, according to Tao et al. [32], the number of subcarriers in each subset was equally distributed and they had worked on square modulation order.

If total number of sub-blocks, g=32	If total number of sub-blocks, g=16	If total number of sub-blocks, g=64
Total number of subcarriers in each subblock, n=4	Total number of subcarriers in each subblock, n=8	Total number of subcarriers in each subblock, n=2
The 1st subset subcarriers for M_A Mode, $k_1 = 2$	The 1st subset subcarriers for M_A Mode, $k_1 = 4$	he 1st subset subcarriers for M_A Mode, $k_1 = 1$
The 2nd subset subcarriers for M_B Mode, $k_2 = 2$	The 2nd subset subcarriers for M_B Mode, $k_2 = 4$	The 2nd subset subcarriers for M_B Mode, $k_2 = 1$

TABLE 4.13: SE of DM-OFDM by varying modulation orderand number of activated subblocks

The Spectral efficiency of DM-OFDM is,

$$\begin{aligned} SE_{DM-OFDM} &= \frac{\lfloor log_2\binom{n}{k})\rfloor + klog_2M_A + (n-k)log_2M_B}{N} \times g \\ &= \frac{\lfloor log_2\binom{n}{k_1})\rfloor + k_1log_2M_A + k_2log_2M_B}{N} \times g \end{aligned} \tag{4.10}$$

As shown in table 4.14, the spectral efficiency was always greater than OFDM and OFDM-IM if each constellation mode used same modulation order as other systems. DM-OFDM worked fine in higher modulation such as in 256 QAM it could produce better SE than classical OFDM. However, they kept all the subcarriers active which is a drawback considering Energy Efficiency.

Independent Modulation Scheme for M_A and M_B Modes	Subblock Size, n and Subblock numbers, g	Number of two subset of Subcarriers in each subblock, k_1, k_2	Total transmitted bits	Spectral Efficiencyy
M_A=4, $M_B = 4$	n=2,g=64	$k_1 = 1, k_2 = 1$	320	2.5
	n=4, g=32	$k_1 = 2, k_2 = 2$	320	2.5
	n=8, g=16	$k_1 = 4, k_2 = 4$	352	2.75
	n=16, g=8	$k_1 = 8, k_2 = 8$	360	2.8125
	n=32, g=4	$k_1 = 16, k_2 = 16$	372	2.90625
	n=64, g=2	$k_1 = 32, k_2 = 32$	376	2.9375
M_A=8, $M_B = 8$	n=4, g=32	$k_1 = 2, k_2 = 2$	448	3.5
	n=8, g=16	$k_1 = 4, k_2 = 4$	480	3.75
	n=16, g=8	$k_1 = 8, k_2 = 8$	488	3.8125
	n=32, g=4	$k_1 = 16, k_2 = 16$	500	3.90625
	n=64, g=2	$k_1 = 32, k_2 = 32$	504	3.9375
M_A=16, $M_B = 16$	n=4, g=32	$k_1 = 2, k_2 = 2$	576	4.5
	n=8, g=16	$k_1 = 4, k_2 = 4$	608	4.75
	n=16, g=8	$k_1 = 8, k_2 = 8$	616	4.8125
	n=32, g=4	$k_1 = 16, k_2 = 16$	628	4.90625
	n=64, g=2	$k_1 = 32, k_2 = 32$	632	4.9375
M_A=32, $M_B = 32$	n=4, g=32	$k_1 = 2, k_2 = 2$	704	5.5
	n=8, g=16	$k_1 = 4, k_2 = 4$	736	5.75
	n=16, g=8	$k_1 = 8, k_2 = 8$	744	5.8125
	n=32, g=4	$k_1 = 16, k_2 = 16$	756	5.90625
	n=64, g=2	$k_1 = 32, k_2 = 32$	760	5.9375
M_A=128, $M_B = 128$	n=4, g=32	$k_1 = 2, k_2 = 2$	960	7.5
	n=8, g=16	$k_1 = 4, k_2 = 4$	992	7.75
	n=16, g=8	$k_1 = 8, k_2 = 8$	1000	7.8125
	n=32, g=4	$k_1 = 16, k_2 = 16$	1012	7.90625
	n=64, g=2	$k_1 = 32, k_2 = 32$	1016	7.9375

TABLE 4.14: SE of DM-OFDM by varying Modulation order and number of subblock size

4.3.5 MM-OFDM-IM

MM-OFDM-IM is similar to OFDM in nature as it transmits symbol though each subcarrier out of n subcarriers of g subblock. There is no inactive subcarrier for indexing rather it uses n number of distinguishable constellations. So, MM-OFDM-IM applies corresponding mode constellation symbols to specific subcarrier by permutation indexing mentioned in table4.4.

According to paper [1] The spectral efficiency of MM-OFDM-IM is,

$$\begin{aligned} SE_{MM-OFDM-IM} &= \frac{\lfloor log_2(n!) \rfloor + nlog_2 M}{N} \times g \\ &= \frac{1}{n} \times \lfloor log_2(n!) \rfloor + log_2 M \end{aligned} \tag{4.11}$$

Modulation Scheme for each subcarrier in subblock, M	Number of Subcarriers in each subblock, n	Total transmittedbits	Spectral Efficiencyy
2	4	256	2
	8	368	2.875
	16	480	3.75
	32	596	4.6563
	64	718	5.6094
	128	844	6.5938
4	4	384	3
	8	496	3.875
	16	608	4.75
	32	724	5.6563
	64	846	6.6094
	128	972	7.5938
8	4	512	4
	8	624	4.875
	16	736	5.75
	32	852	6.6563
	64	974	7.6094
	128	1100	8.5938
16	4	640	5
	8	752	5.875
	16	864	6.75
	32	979	7.6563
	64	1102	8.6094
	128	1228	9.5938
64	4	896	7
	8	1008	7.875
	16	1120	8.75
	32	1236	9.6563
	64	1280	10.6094
	128	1484	11.5938
256	4	1152	9
	8	1264	9.875
	16	1376	10.75
	32	1492	11.6563
	64	1614	12.6094
	128	1740	13.5938

Table 4.15: SE of MM-OFDM-IM by varying Modulation order and number of subblock size

As shown in this table, doubling each Modulation order, M for same subcarrier setting is causing the Spectral Efficiency to increase by 1bps/Hz. For ean instance, from BPSK to 4 PSK SE is increasing by 2 bps/Hz to 3bps/Hz for $n = 4$. MM-OFDM-IM works in both PSK and QAM system. From 4QAM to 8 QAM, SE increases by 1bps/HZ where each subblock carrying 4 subcarriers. On the other hand, doubling the subcarriers in each subblock, n for constant modulation order, M increases SE in a different way. The SE effect for doubling n is similar to doubling M when $n \geq 8$ where SE increases 1bps/Hz.

4.3.6 NMM-OFDM-IM

NMM-OFDM is the better reformation of OFDM incorporating Index Modulation Concept based on OFDM-IM and MM-OFDM-IM. It also uses the advantages of DM-OFDM and OFDM-IQ-IM in its brief operation system figure. It maintains the main principle of OFDM-IM by activating a portion of subcarriers creating Subcarrier Activation Pattern Sequence.

It also employs subcarrier sized distinguishable constellations like MM-OFDM-IM for additional indexing of which constellation is being used in each subcarrier of a subblock. The only difference is that it does not activate all the subcarriers but keeps some of the subcarriers deactivated in order to increase energy efficiency. Furthermore, it can produce same or even higher throughput than classical OFDM in higher modulation order.

$$\begin{aligned} SE_{NMM-OFDM} &= \frac{(\lfloor log_2\binom{n}{k}\rfloor + \lfloor log_2\frac{Q!}{(Q-k)!}\rfloor + klog_2M)}{N} \times g \\ &= \frac{(\lfloor log_2\binom{n}{k}\rfloor + \lfloor log_2\frac{n!}{(n-k)!}\rfloor + klog_2M)}{N} \times g \end{aligned} \tag{4.12}$$

Here, total number of active subcarriers of two subset must be equal since they follow same subcarrier activation pattern. By doing these, they activate a dedicated number of subcarriers and keeps deactivate other subcarriers to maintain a generic constellation diagram unlike OFDM-IQ-IM.

As shown in table 4.16, only 4-QAM modulation order of NMM-OFDM-IM can provide same transmitted bits as 16-QAM OFDM and OFDM-IM transmitted bits. This way, it can function in lower modulation order and yield the output of higher modulation scheme where OFDM-IM cannot even function. For an instance, OFDM-IM cannot operate in 256-QAM but the proposed system can provide the same SE of 256-QAM of OFDM by only using 16-QAM mode constellation of NMM-OFDM-IM. As shown in table, three settings of 16 QAM mode constellation of NMM-OFDM-IM provided same SE as 256 QAM of OFDM in addition to providing some inactive subcarriers for energy saving. Again, DM-OFDM can provide same SE_{OFDM} but it uses two 256-QAM modulation order which results in 512 symbol points in the constellation diagram whereas NMM-OFDM-IM 256 modulated symbols jointly.

Independent Modulation Scheme for M Modes	Subblock Size, n and Subblock numbers, g	Mode Size, Q and M symbols per mode, $q = \frac{M}{n}$	Number of Active Subcarriers in each sub-block, k	Total transmitted bits	Spectral Efficiency
M=4	n=4, g=32	Q=4, q=4	3	384	3
	n=8, g=16	Q=8, q=2	3	512	4
	n=16, g=8	Q=16, q=1	6	512	4
	n=32, g=4	n>M so Q can not be produced	N/A	N/A	N/A
	n=64, g=2	,,	N/A	N/A	N/A
M=8	n=4, g=32	Q=4, q=16	3	512	4
	n=8, g=16	Q=8,q=8	7	768	6
	n=16, g=8	Q=16,q=4	13	768	6
	n=32, g=4	Q=32,q=2	25	768	6
	n=64, g=2	Q=64,q=1	48	768	6
M=16	n=4, g=32	Q=4, q=16	3	704	5.5
	n=8, g=16	Q=8,q=8	7	768	6
	n=16, g=8	Q=16,q=16	15	1024	8
	n=32, g=4	Q=32,q=8	29	1024	8
	n=64, g=2	Q=64,q=4	56	1024	8
M=64	n=4, g=32	Q=4, q=16	3	768	6
	n=8, g=16	Q=8,q=8	7	960	7.5
	n=16, g=8	Q=16,q=16	15	1104	8.625
	n=32, g=4	Q=32,q=8	31	1232	9.625
	n=64, g=2	Q=64,q=4	63	1358	10.61
M=256	n=4, g=32	Q=4, q=16	3	960	7.5
	n=8, g=16	Q=8,q=8	7	1184	9.25
	n=16, g=8	Q=16,q=16	15	1344	10.5
	n=32, g=4	Q=32,q=8	31	1480	11.5625
	n=64, g=2	Q=64,q=4	63	1610	12.5

TABLE 4.16: Spectral Efficiency and Transmitted bits of NMM-OFDM-IM for different settings of subblock and modulation order

Subblock Size, n		4	8	16	32	64
$k_{OFDM-IM}$ and $k_{NMM-OFDM-IM}$		3	7	15	31	63
M=256; $SE_{OFDM} = 8$	$SE_{OFDM-IM}$	2.5	7.375	7.75	7.90625	7.96875
	$SE_{NMM-OFDM-IM}$	7.5	9.25	10.5	11.5625	12.5
	$SE_{MM-OFDM-IM}$	9	9.875	10.75	11.6563	12.6094

TABLE 4.17: Spectral Efficiency Comparison for 256 QAM with different settings of subblock

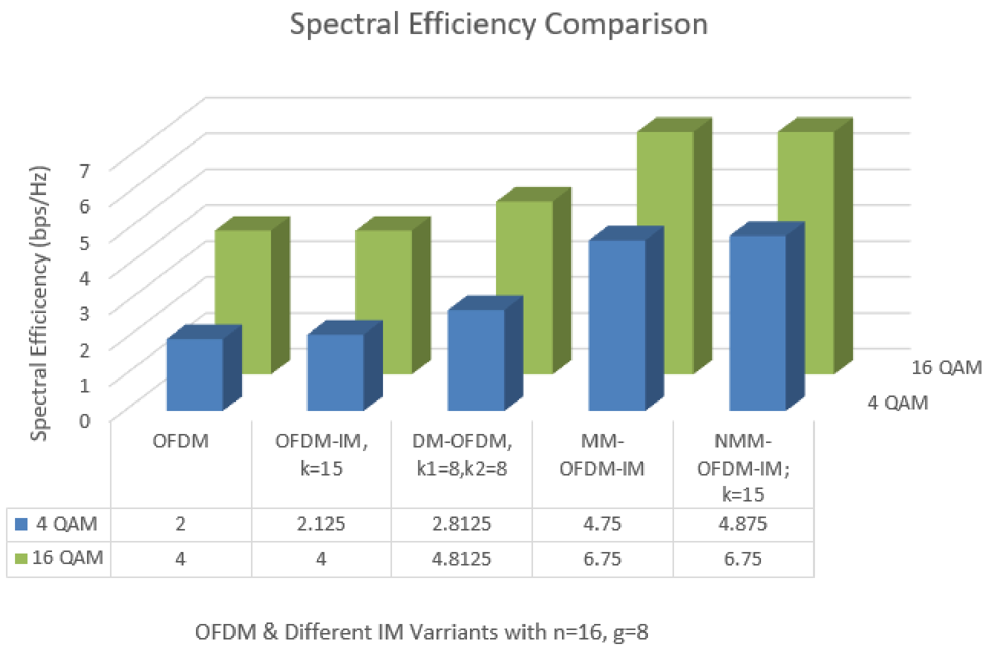


Figure 4.17: Maximum Achievable Spectral Efficiency Comparison for OFDM and Different IM Variant System for different Modulation Order

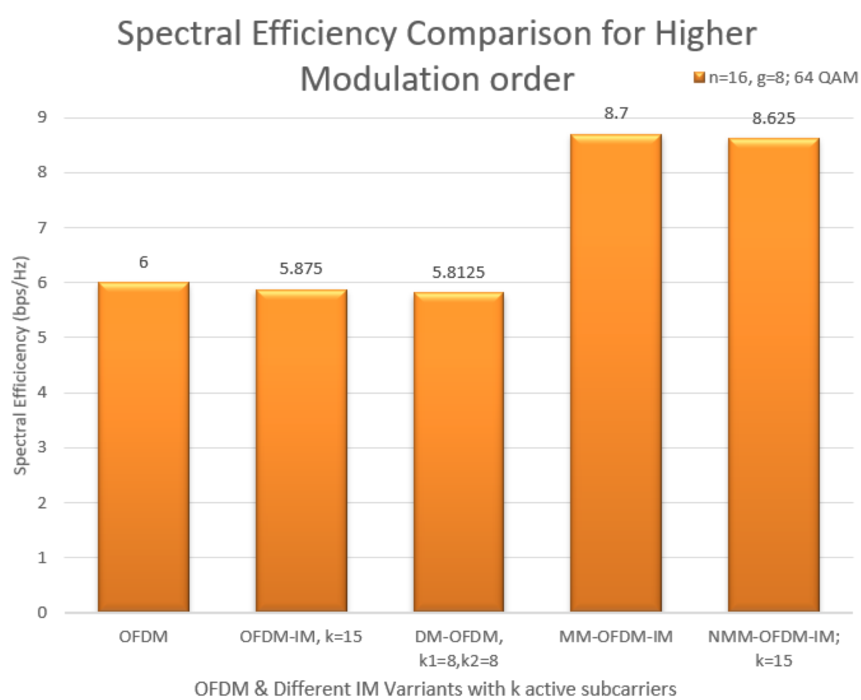


Figure 4.18: Spectral Efficiency Comparison for Higher Modulation Order, 64 QAM

From the results of table 4.17, it is clear that OFDM-IM can not meet the SE as OFDM in the higher modulation orders in any settings of subblock size or active subcarrier numbers. This happens due to the loss of huge symbol bits of the inactive subcarriers. Although NMM-OFDM-IM also keeps a part of subcarriers inactive, this system can keep up with greater SE than OFDM. The proposed system compensates the inactive subcarrier symbol bits with its SIS and MIS index bits. Only Mode Selection Index bits provides about 44 additional bits just for 64 QAM and n=16, g=8 settings. For this reason, NMM-OFDM-IM can provide 6.125bps/Hz with 72 active subcarriers only shown in which is still higher than SE_{OFDM} of 6bps/Hz. Furthermore, NMM-OFDM-IM can provide 8.65bps/Hz activating its 120 subcarriers which is the best utilization of Spectrum than OFDM. In this figure 4.18, OFDM-IM and DM-OFDM fails to provide same SE as OFDM.

4.4 ENERGY EFFICIENCY

The inspiration driving Index Modulation forger on OFDM is the endeavor to improve power utilization. This is a fundamental solicitation in applications to get green correspondence frameworks and battery powered gadgets in wireless communication system [38].

4.4.1 OFDM

In OFDM, all the subcarriers convey symbols and transmit it to the channel. Since all the subcarriers are operating, there is no energy saving in the classical OFDM system. OFDM-IM keeps a fraction of subcarriers inactive. These idle subcarriers save energy for the system. This is similar to Power Saving Policy (PSP) of SIM [22] . PSP vanquishes energy/ power allocated to the subcarriers who are active. This eventually results in energy saving that leads to a greater energy efficient system. Energy/ Power saving is also related to the battery of wireless communication. The more power results in consuming a large amount of battery quickly especially in the end user.

If there are n subcarriers in g subblocks in which only k subcarriers are active. Then, Energy savings per subcarrier, μ would be [51]:

$$\mu = \frac{(n-k)}{n} \times 100\% \tag{4.13}$$

Since, OFDM has zero power savings due to the activation of all subcarriers. All other systems will be considered how much they can save energy than OFDM.

4.4.2 OFDM-IM

The table shows that for a certain modulation, as subblock size increases, it saves more energy. The highest subblock size has the privilege of highest number of inactive subcarriers and greater energy saving possibility. For an instance, with 16-QAM modulation scheme,

Modulation Scheme	Subblock Size, n and Subblock numbers, g	Number of Active Subcarriers, k	Number of Inactive Subcarriers, k	Total transmitted Bits, m	Energy Saving, $\mu in\%$
4	n=2, g=64	N/A	N/A	N/A	N/A
	n=4, g=32	3	1	256	25%
	n=8, g=16	6	2	256	25%
	n=16, g=8	10	6	256	37.5%
	n=32, g=4	18	14	256	43.75%
	n=64, g=2	34	30	256	46.875%
8	n=4, g=32	N/A	N/A	N/A	N/A
	n=8, g=16	7	1	384	12.5%
	n=16, g=8	13	3	384	18.75%
	n=32, g=4	25	7	384	21.875%
	n=64, g=2	48	16	384	25%
16	n=4, g=32	N/A	N/A	N/A	N/A
	n=8, g=16	N/A	N/A	N/A	N/A
	n=16, g=8	15	1	512	6.25%
	n=32, g=4	29	3	512	9.375%
	n=64, g=2	56	8	512	12.5%
32	n=4, g=32	N/A	N/A	N/A	N/A
	n=8, g=16	N/A	N/A	N/A	N/A
	n=16, g=8	N/A	N/A	N/A	N/A
	n=32, g=4	31	1	640	3.125%
	n=64, g=2	61	3	640	4.6875%
64	n=4, g=32	Out of the SE condition as n<M	N/A	N/A	N/A
	n=8, g=16	,,	N/A	N/A	N/A
	n=16, g=8	,,	N/A	N/A	N/A
	n=32, g=4	,,	N/A	N/A	N/A
	n=64, g=2	63	1	768	1.5625%
256	n=4, g=32	N/A	N/A	N/A	N/A
	n=8, g=16	N/A	N/A	N/A	N/A
	n=16, g=8	N/A	N/A	N/A	N/A
	n=32, g=4	N/A	N/A	N/A	N/A
	n=64, g=2	N/A	N/A	N/A	N/A

TABLE 4.18: Energy Saving of OFDM-IM compared to OFDM

n=16, g=8 configuration	n=32, g=4 configuration	n=64, g=2 configuration
Total inactive subcarriers = 8	Total inactive subcarriers = 12	Total inactive subcarriers = 16
Energy Efficiency = 6.25%	Energy Efficiency = 9.375%	Energy Efficiency = 12.5%

TABLE 4.19: Energy Saving of OFDM-IM Compared to OFDM for 64QAM

According to Rami et al.[22], as the total number of inactive subcarriers increases in each subblock, power/energy saving increases. That is what happened in the table as we calculated. The inactive subcarriers were at the peak when the subblock size for a certain modulation order was in highest settings.

4.4.3 OFDM-IQ-IM

Energy saving of OFDM-IQ-IM is variable compared to OFDM due to the independency of subcarriers indexing. If all the subcarriers are used to produced expected Spectral Efficiency, then energy saving is zero. Indexing will serve the purpose of giving adequate bits for the sole purpose of highest transmission data rate. If booth I and Q branch bits goes into same subcarrier, energy saving will increase as subcarrier ratio increases. Such variable energy saving is not desirable for next generation wireless system.

4.4.4 DM-OFDM

DM-OFDM has the advantage of higher Spectral efficiency and it diminishes the limitation of OFDM-IM in higher modulation settings. Unfortunately, DM-OFDM uses all the subcarriers in each subblock in order to gain the SE advantage. This why, there is no energy saving in DM-ODM just like OFDM.

4.4.5 MM-OFDM-IM

MM-OFDM-IM uses the one to one permutation mapping regarding indexing of each sub-

Independent Modulation Scheme for I and Q branch	Subblock Size, n and Subblock numbers, g	Number of Active Subcarriers, k	Number of Inactive Subcarriers s,k	Total transmitted Bits, m	Energy Efficiency, $\mu in\%$
$M_I = 2, M_Q = 2$ Joint M=4	n=2, g=64	BPSK can't be performed in OFDM-IQ-IM	N/A	N/A	N/A
	n=4, g=32	2 ~ 4	0 ~ 2	256	0 ~ 25%
	n=8, g=16	3 ~ 6	2 ~ 5	256	25 ~ 62.5%
	n=16, g=8	5 ~ 10	5 ~ 11	272	31.25 ~ 68.75%
	n=32, g=4	9 ~ 18	14 ~ 23	264	43.75 ~ 71.875%
	n=64, g=2	16 ~ 32	32 ~ 48	256	50 ~ 46.875%
$M_I = 4, M_Q = 4$ Joint M=16	n=4, g=32	Out of the SE condition n<$M_I orn < M_Q$	N/A	N/A	N/A
	n=8, g=16	3 ~ 6	2 ~ 5	512	25 ~ 62.5%
	n=16, g=8	6 ~ 12	4 ~ 10	512	25 ~ 62.5%
	n=32, g=4	10 ~ 20	12 ~ 22	512	37.5 ~ 68.75%
	n=64, g=2	18 ~ 36	28 ~ 46	512	43.75 ~ 71.875%
$M_I = 8, M_Q = 8$ Joint M=64	n=4, g=32	Out of the SE condition n<$M_I orn < M_Q$	N/A	N/A	N/A
	n=8, g=16	7 ~ 8	0 ~ 1	768	0 ~ 12.5%
	n=16, g=8	14 ~ 16	0 ~ 2	768	0 ~ 12.5%
	n=32, g=4	25 ~ 32	0 ~ 7	768	0 ~ 21.875%
	n=64, g=2	48 ~ 64	0 ~ 16	768	0 ~ 25%
$M_I = 16, M_Q = 16$ Joint M=256	n=4, g=32	Out of the SE condition n<$M_I orn < M_Q$	N/A	N/A	N/A
	n=8, g=16	,,	N/A	N/A	N/A
	n=16, g=8	15 ~ 16	0 ~ 1	1024	0 ~ 6.25%
	n=32, g=4	29 ~ 32	0 ~ 3	1024	0 ~ 9.375%
	n=64, g=2	56 ~ 64	0 ~ 8	1024	0 ~ 12.5%

TABLE 4.20: Energy Saving of OFDM-IQ-IM compared to OFDM

carrier modulation. Since it increases SE by permutation indexing of each subcarrier symbol in a constellation, all of the subcarriers are active in this system. So, it does not have any energy saving due to all active subcarriers.

4.4.6 NMM-OFDM-IM

The proposed system, 4-QAM mode NMM-OFDM-IM is shown to generate bits for same Spectral Efficiency of 16-OAM OFDM and OFDM-IM. With that configuration, NMM-OFDM-IM keeps more inactive subcarriers that results into greater energy saving than any other system.

At the end, it can be concluded that NMM-OFDM-IM gives better SE with lower modula-

Independent Modulation Scheme for M Mode	Subblock Size, n and Subblock numbers, g	Mode Size, Q and M Symbols per mode q=M/n	Number of active Subcarriers in each sub-blocks,k	Numbers of inactive carriers in each subblock	Total transmitted Bits, m	Energy Efficiency, μ
M=4	n=4, g=32	Q=4,q=4	3	1	384	25%
	n=8, g=16	Q=8,q=2	3	5	512	62.5%
	n=16, g=8	Q=16,q=1	6	10	512	62.5%
	n=32, g=4	n>M so Q can not be produced	N/A	N/A	N/A	N/A
	n=64, g=2	,,	N/A	N/A	N/A	N/A
M=8	n=8, g=16	Q=8,q=8	7	1	768	12.5%
	n=16, g=8	Q=16,q=4	13	2	768	12.5%
	n=32, g=4	Q=32,q=2	25	7	768	21.875%
	n=64, g=2	Q=64,q=1	48	16	768	25%
M=16	n=16, g=8	Q=16,q=16	15	1	1024	6.25%
	n=32, g=4	Q=32,q=8	29	3	1024	9.375%
	n=64, g=2	Q=64,q=4	56	8	1024	12.5%

TABLE 4.21: Energy Saving of NMM-OFDM-IM compared to OFDM

tion order in each subset of subblock. It also leads to a huge inactive subcarriers that results in the greater Energy Efficiency.

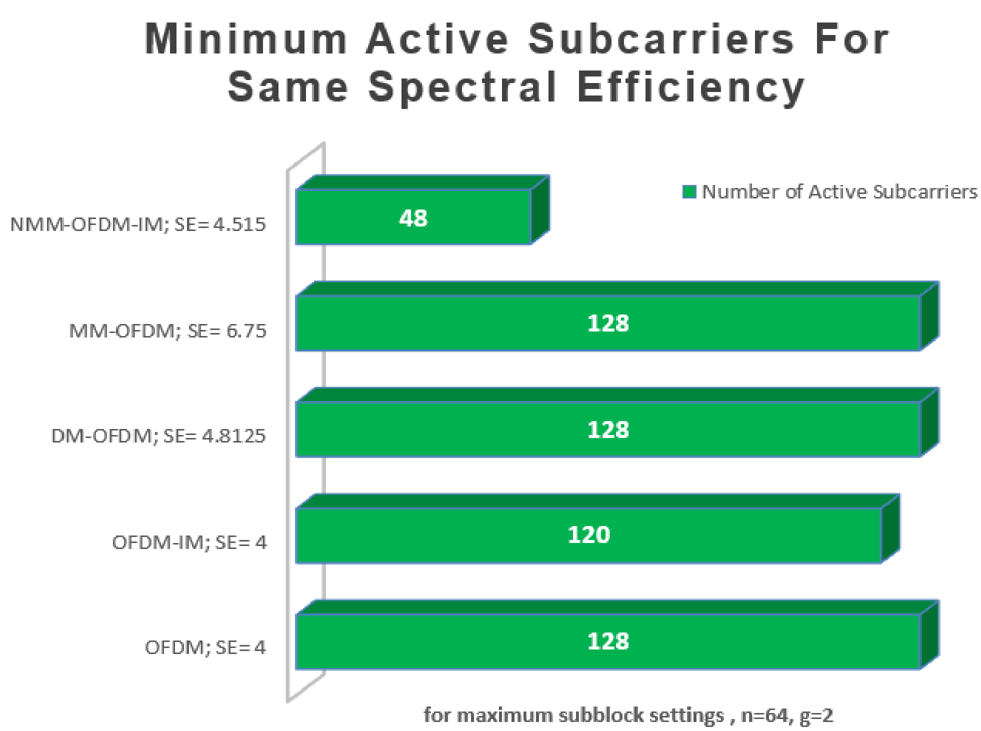


FIGURE 4.19: Minimum Active Subcarriers for Same Spectral Efficiency as OFDM for 16QAM

As shown in this figure, a desired Spectral efficiency was achieved with different IM systems.

Since, OFDM-IM and NMM-OFDM-IM has the flexibility of deactivating a portion of subcarriers in each subblock, it can achieve the same SE_{OFDM} by using fewer subcarriers. OFDM-IM needs to use 120 whereas NMM-OFDM-IM uses only 56 subcarriers out of 128 subcarriers. The remaining 72 subcarriers can save significant amount of energy and yields less crowded spectrum while other systems such as OFDM, DM-OFDM, MM-OFDM-IM must use all 128 subcarriers regardless of the desired SE.

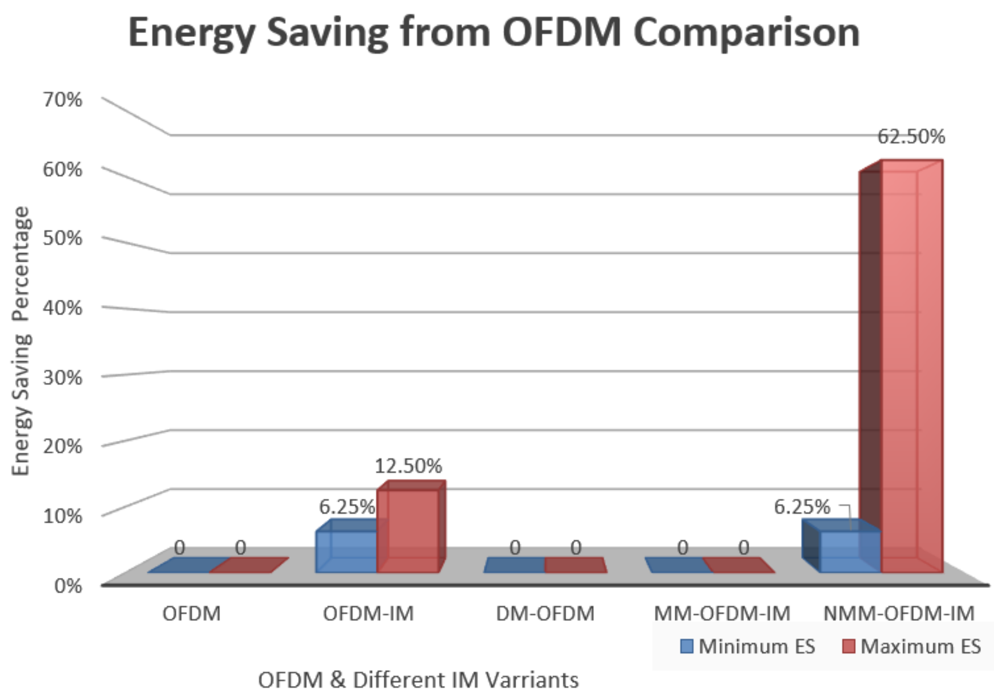
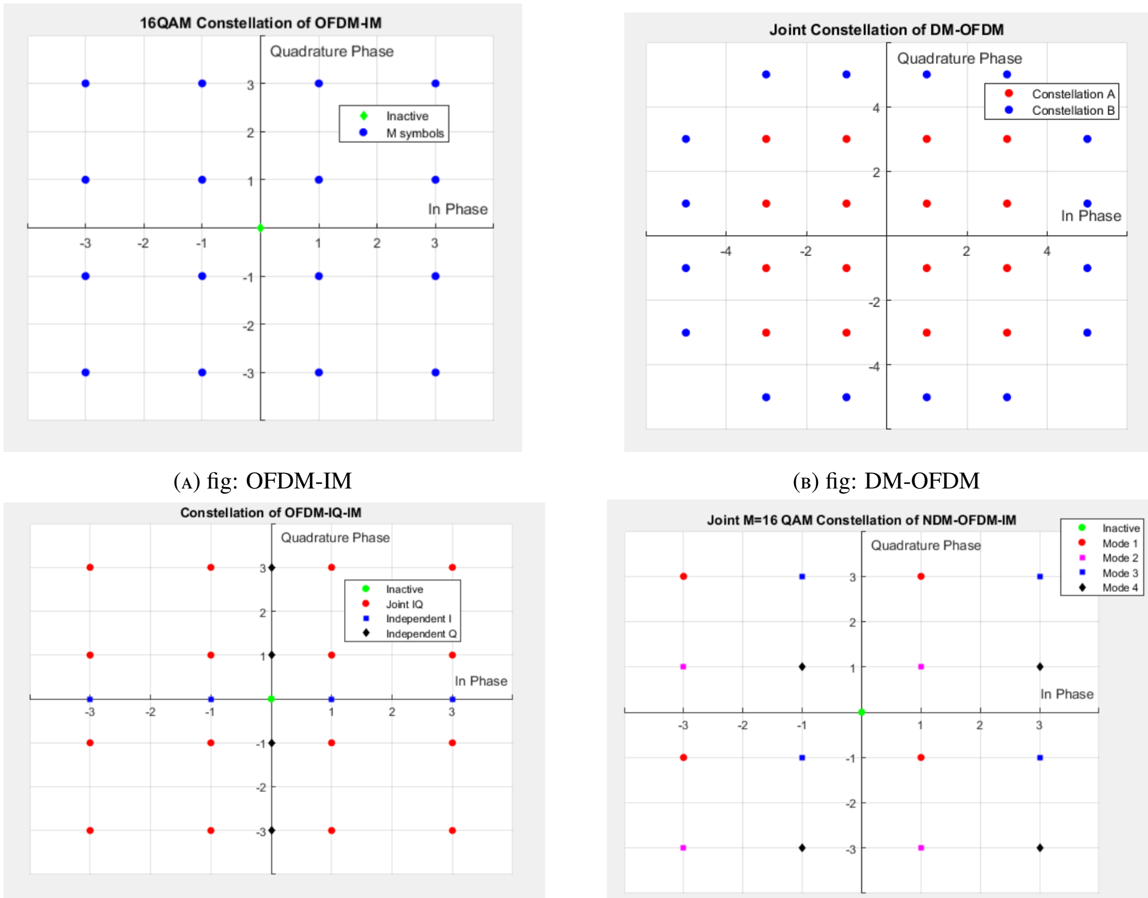


FIGURE 4.20: IM variant percentage of energy saving than conventional OFDM

4.5 Resultant Constellation Design Benefit

Based on all the results, it can be concluded that NMM-OFDM-IM will be better for some applications for its energy saving option than MM-OFDM-IM and DM-OFDM-IM. It also has no spectral efficiency limitation in higher modulation order like OFDM-IM. OFDM-IQ-IM also presents similar benefits though the energy saving policy depends on its independency of symbol indexing in different subcarriers in each subblock. Another factor is that OFDM-IQ-IM has irregular shape of constellation pattern (Figure (c)) because of separate and independent indexing of in phase and quadrature phase. Whereas DM-OFDM needs to have 16QAM in both A and B mapper to achieve same SE like other IM system. In the constellation, it has 32 points with higher amplitude that ultimately results in higher power consumption.



(A) fig: OFDM-IM

(B) fig: DM-OFDM

(C) fig: OFDM-IQ-IM

(D) fig: NMM-OFDM-IM

FIGURE 4.21: Constellation difference between IM variants

NMM-OFDM-IM was designed keeping all these factors in mind. It was designed in such a way that the constellation at receivers' point of view is similar to regular QAM constellation diagram. The multiple constellations should be designed considering their joint constellation. This would avoid the closer symbol distance while calculating BER. As a result, NMM-OFDM-IM with multiple constellations designed considering MM-OFDM-IM QAM constraint [1]. It also incorporated the idea of OFDM-IM for further benefits which does not interfere with the constellation pattern.

4.6 Bit Error Rate Simulation

Performance is a high-priority factor in evaluating a system. So, Bit Error Rate (BER) and Symbol Error Rate (SER) were simulated through MATLAB for the three main systems respectively, OFDM-IM, MM-OFDM-IM and NMM-OFDM-IM. OFDM-IM has been coded according to paper [31] with 16 QAM constellations where 3 subcarriers out of 4 are kept active in a subblock. Maximum likelihood detection process was carried out to find out the best performance. MM-OFDM-IM also showed a better performance in higher SNR regions like the paper[1] where all the subcarriers are active like conventional OFDM. Selecting different mode i.e., constellations for each subcarrier of a subblock is special indexing in this IM variants.

Proposed NMM-OFDM-IM consists of both indexing from OFDM-IM and MM-OFDM-IM. It used Subcarrier Activation Pattern Indexing for activating only a fraction of subcarriers in a subblock to introduce Energy Efficiency. Subcarrier Activation Indexing was done by combinatorial method. Then, Mode Selector used the second combinatorial method to select k-mode constellation symbol in a subblock out of n-mode constellation. For this reason, mode modulation, M must be greater than subblock size.

Random bits were generated to go through the M-Mappers and Index Selector. p_1^A bits generate the combination for active subcarriers for each block while p_1^B bits give the mode constellation combination with order for each active subcarrier. p_2 bits were coded according to the M-Mode Mappers which were fed by the constellation combination indexing. This created each subblock subcarrier symbol with MIS.

In the second part, all the symbols from different mode enters in each active subcarrier as per SAP. This way bit mapping was done. The symbols were then executed as the same manner as conventional OFDM. At last, it was sent to the Rayleigh fading channel with AWGN and was received by the receiver.

Maximum Likelihood detection was approached for the symbol decoding like OFDM-IM. Each symbol of a subblock was compared with all the symbols of M QAM and then each subblock symbol combination was determined. This whole process was done for all the possible SIS and MIS realization. The performance for 4 QAM MM-OFDM-IM (4,4) and 4 QAM NMM-OFDM-IM (4,3) for total 2048 subblocks were observed and recorded.

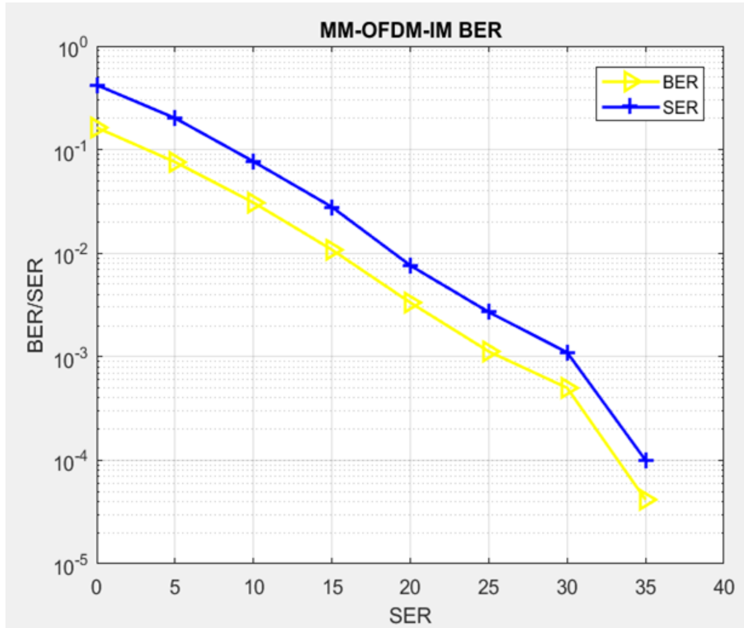


FIGURE 4.22: Bit Error Rate and Symbol Error Rate of MM-OFDM-IM

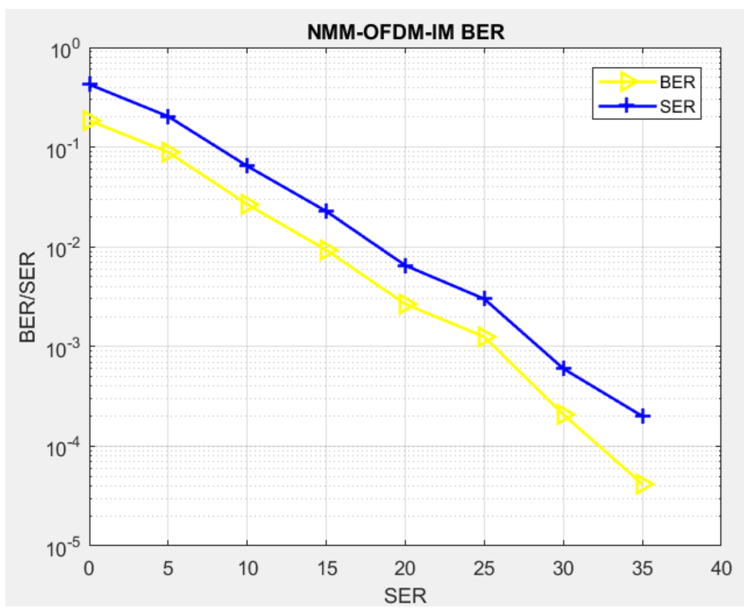


FIGURE 4.23: Bit Error Rate and Symbol Error Rate of NMM-OFDM-IM

As shown in the graph figure 4.22, 4.23, 4.24; BER at low Signal to Noise Ratio (SNR) area such as 5 decibels (dB) MM-OOFDM-IM shows better BER than proposed NMM-OFDM-IM BER. They are respectively 7×10^{-1} and 7.2×10^{-1}. This happens because of the null mode of NMM-OFDM-IM. It makes inter-symbol distance closer to the null mode which can reflect in an erroneous decision-making scenario. After 5 (dB), NMM-OFDM-IM has shown better performance than MM-OFDM-IM at high SNR region. As index bits are less affected by errors in the channel

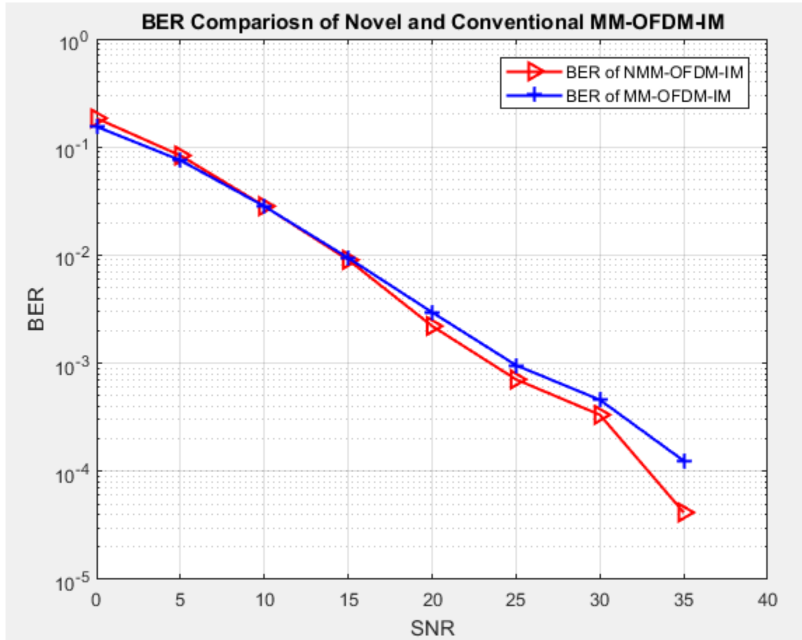


FIGURE 4.24: BER comparison between MM-OFDM-IM and NMM-OFDM-IM

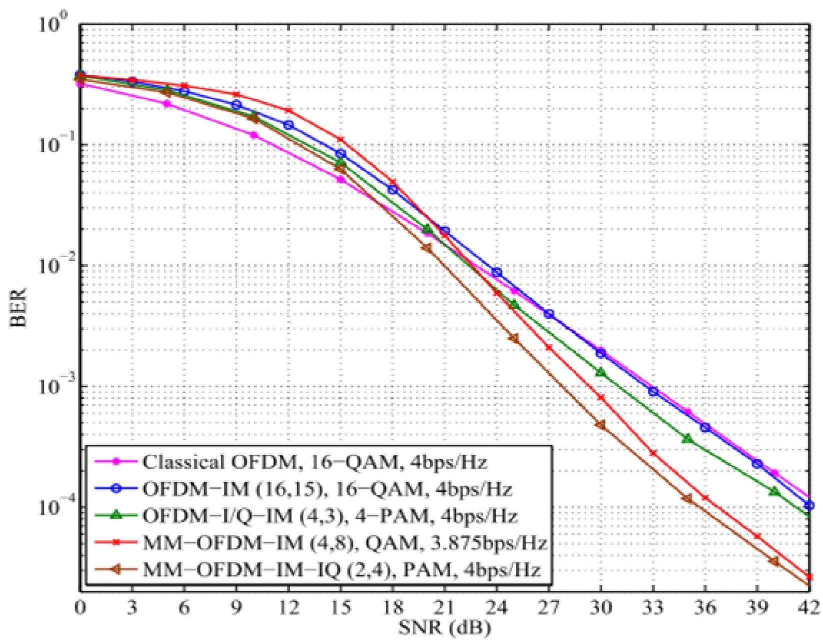


FIGURE 4.25: BER comparison between OFDM-IM and MM-OFDM-IM[1]

rather than conventional modulated symbols. BER from figure 4.12 of MM-OFDM-IM [1] shows similar pattern as figure 4.14. Though MM-OFDM-IM used 4 subcarriers and 8 modes but the generated MM-OFDM-IM used 4 subcarriers and 4 modes.

Chapter 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The proposed Novel MM-OFDM-IM (NMM-OFDM-IM) is a combination of two methods: OFDM-IM and MM-OFDM-IM. In this NMM-OFDM-IM design, there are two types of Selectors; one for selecting Active Subcarriers and one for selecting Modes. There is no Spectral Deficiency in the proposed method for higher-order modulation whereas classical OFDM-IM has this kind of deficiency. The proposed method outperforms other IM Variants including conventional MM-OFDM-IM in terms of Energy Efficiency. NMM-OFDM-IM has a better Bit Error Performance compared to classical MM-OFDM-IM in high SNR region. One of the advantages of the proposed method is that it is suitable for application-based design by trading off Energy Efficiency and BER. for instance, mobile health care applications. Replacing the whole existing modulation technique, OFDM can be more costly and troublesome for industries. Hence, a software change similar to Index modulation (IM) techniques can upgrade the system in terms of Spectral Efficiency, Energy Efficiency and Performance.

Orthogonal Frequency Division Multiplexing (OFDM) is the most common modulation scheme in existing Wireless Communication Systems. However, the conventional OFDM cannot meet the requirements of high demand of throughput, Spectral Efficiency (SE) and lower energy consumption for the Next Generation of Wireless Communication systems. Therefore, OFDM with an index Modulation (OFDM-IM) introduces the unique design of Index Modulation (IM) in addition to the conventional OFDM design. OFDM-IM can maximize the throughput, SE and Energy Efficiency (EE) by sending additional index bits of IM with classical OFDM symbols. These index bits activate a part of subcarriers through on-off key mechanism. This activation pattern is detected in the receiver and decoded into the transmitted index bits. Unfortunately, OFDM-IM cannot meet the minimum requirement of throughput and Spectral Efficiency (SE) as conventional OFDM in higher modulation order.

The objective of this study was to review different OFDM-IM variants to resolve the SE issue first. Then, a suitable system, Novel Multi-Mode OFDM with Index Modulation (NMM-OFDM-IM) was developed considering high SE, minimum energy consumption and better performance. The proposed Novel MM-OFDM-IM has similar multiple, distinguishable M-ary modulation constellation similar to MM-OFDM-IM[1].

5.2 Advantages

In the proposed Novel MM-OFDM-IM information is sent with conventional M Mode modulated symbols like MM-OFDM-IM and two types of indexing. One of the indexing is Subcarrier Activation Indexing (SAI) and the other part is Mode Selection Indexing (MSI). MSI and M-Mode Mapping is based on MM-OFDM-IM which is why it is called Novel MM-OFDM-IM (NMM-OFDM-IM). Although the concept is similar, however, they are done in different ways. The MSI indexing is done by permutation, but it keeps the option to choose k modes from Q number of modes to carry out the energy efficiency.

5.2.1 Spectral Efficiency

MSI and SAI, these two indexing meet the requirements of Spectral Efficiency in higher modulation similar to OFDM. This diminishes OFDM-IM inactive subcarrier's symbol transmission inadequacy shown in Table 4.16. Hence, it can be escalated to higher modulation order and still can generate as much throughput as OFDM, unlike OFDM-IM.

5.2.2 Energy Efficiency

The proposed system has the additional Mode Selection Indexing and inactivation of a subset of subcarriers. These two concepts were laid in the design for the purpose of SE and EE correction. Inactivation of a chunk subcarrier in a subblock bring down power consumption as shown in Figure 4.19. Meanwhile dividing the modulation scheme in several modes and indexing the symbols accordingly increases the transmission of data bits i.e., SE to be able to meet up the demand even in higher modulation.

5.2.3 Resultant Constellation Pattern

In elaborate design of NMM-OFDM-IM 4.13, two Mapper of AM and PSK were used to create n-Mode Constellation with the help of MSI indexing. This design was inspired by DM-OFDM and OFDM-IQ-IM design benefits. OFDM-IQ-IM is the most expected system because of the independent phase Subcarrier Activation Indexing. It gives the highest throughput at lowest Modulation order. However, their separate Indexing of Subcarrier at in-phase and quadrature phase brings two challenges. One of them is that the random placement of symbol in subcarriers results in minimum energy saving in OFDM-IQ-IM according to 4.20. The other one is that the irregular pattern of constellation which is also vulnerable to erroneous symbol detection in receiver 4.8.

Proposed NMM-OFDM-IM gives input to two simple Mappers like DM-OFDM and OFDM-IQ-IM in-phase and quadrature phase mappers to recreate the simple constellation design. Eventually it forms n-Modes with the help of MSI by itself. This system saves maximum energy by opting out the independent phase symbol travel with MS Index bits which are also less affected by errors and creates simple, regular, multiple constellations.

5.2.4 Performance

Proposed NMM-OFDM-IM have better performance than conventional MM-OFDM-IM in high Signal to Noise Ratio (SNR). It is possible beacuse most of the bits are transmitted as index bits which are less affected by errors in the channel as modulated symbols.

Hence, the Energy Saving feature of the proposed system mostly beat other systems with the adequate SE requirements of OFDM. It also follows classical constellation pattern. The BER of NDM-OFDM-IM is better than BER of OFDM-IM and similar to MM-OFDM-IM.

5.3 Disadvantages

Novel Multi-Mode OFDM with Index Modulation (NMM-OFDM-IM) yields a lot of advantages over conventional OFDM. However, it has few disadvantages too.

The condition for mode selection, $Q \geq n$ interferes with the degree of freedom of the subcarrier ratio combination. Though it restricts some of the subblock settings in lower modulation, it eventually has no limit as the modulation order increases. The goal of high data rate transmission is eventually achieved.

MSI also brings the possibility of getting more bit error in case of decoding wrong symbol. On the other hand, SAI does not have any dependency on symbol detection rather than their position. It has less chance of getting erroneous MSI bits since each subcarrier contains different mode with the provided lookup table at receiver.

Since NMM-OFDM-IM has a null mode in the resultant constellation similar to OFDM- IM due to subcarrier deactivation through Subcarrier Index Selector (SIS). This null mode has lower inter-mode symbols in the constellation that resulted in a higher Bit Error Rate (BER) than OFDM-IM for the lower Signal to Noise Ratio (SNR) region shown in figure 4.25. Hence, this energy saving of inactive subcarriers could be used in expanding the constellation eventually to reach designated BER for specific applications. This is the trade-off for NMM-OFDM-IM.

In short, NMM-OFDM-IM uses multi-mode modulation scheme with less active subcarriers for the OFDM framework. This design not only allows Subcarrier Indexing for symbol positioning but also creates Mode Indexing for each subcarrier. Hence, information bits are accompanied by the index bits that results in maximum throughput, significant spectrum usage, significant energy saving and better BER performance.

5.4 Future work

The proposed NMM-OFDM-IM was developed and designed considering better system characteristics and performance than conventional OFDM and other prominent Index Modulation Variants of OFDM. There are several parts where future works can be done to improve the performance and reduce the complexity.

Subblock Mode Constellation Design

Constellation design for independent mode modulation schemes in NMM-OFDM-IM is the portion where most of the work can be done further. Though it is preferred to follow the traditional constellation pattern, two separate mappers in later brief design of NMM-OFDM-IM were introduced in chapter4 to act like OFDM-IQ-IM with different media of additional index boosting. This design can be done as per application, highlighting its targeted performance. Another work can be done on these modulation schemes for better inter and intra Euclidean distance between the constellation points corresponding to their modes.

MSI Design

Mode Selection Indexing on M-QAM constellation is the most unique feature in the proposed system. This is also done in MM-OFDM-IM and Super-Mode OFDM with Index Modulation (SuM-OFDM-IM) [52]. Each subcarrier has a different constellation mode for that system. In the proposed system, different kinds of modes were created by having two different types of AM and PSK Modulation similar to in phase and quadrature phase modulation of OFDM-IQ -IM in a specific way described in chapter 3. It yields maximum index bits from OFDM-IM and DM-OFDM. This mode design can be a focus of improvement to enhance performance and reduce the complexity of detection at the receiver-end.

Detection Process

Maximum likelihood Detection is one of the best detection processes to get error free symbol detection which was used in the proposed NMM-OFDM-IM. It considers all the possible realization for both symbols and positions of the symbol in subcarrier to detect the incoming bits. So, it raises computational and detection complexity with longer processing time but the performance is much better. This becomes a problem for very high modulation scheme. The computational complexity becomes concern for latency.

Thus, Log-Likelihood Ratio (LLR) detection process can be implemented in this system to resolve these matters. It first detects the index and then goes for symbol detection in the subblock subcarriers which reduces the combined search complexity and time.

Subcarrier activation ratio optimization according to SE, EE, throughput

NMM-OFDM-IM can achieve maximum throughput, noteworthy SE , EE and BER performance. Subcarrier activation Ratio (r=k/n) is the concept of activating subset of available subcarriers [51].

$$r = \frac{k}{n} \tag{5.1}$$

where r=Subcarrier activation Ratio, k=number of active subcarriersand n= subblock size

The design of subblock size and subcarrier activation ratio are crucial for this reason. It can provide different throughput in different settings. This design can be optimized for expected efficiency and performance for different applications as required in future.

BER

The system was designed based on all the papers in literature review and the performance was crosschecked with the simulation of the system in MATLAB. It was compared with other reference papers for the confirmation of its efficiency and BER. Detection process is the most difficult part of the proposed system. The focus of this work was system design and its key characteristics as well as performance. In future, further research can be conducted on mathematical derivation of BER and better BER performance by working on Mode Selection Design.

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