# Performance of Sub-carrier Index Modulation in OFDM

A Dissertation
Submitted in partial fulfillment of
the requirements for the award of the degree of
Master of Technology
in
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By

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I would like to take this opportunity to express my profound gratitude to my guide not only for his academic guidance but also for his interest in my project. Finally, I am very grateful to my Institution and colleagues whose constant encouragement served to renew my spirit. I wish to avail myself of this opportunity to express a sense of gratitude and love to my friends and my beloved parents for their support and strength.

(Tanu Joshi)

# Candidate's Declaration

I hereby declare that the work, which is presented in this dissertation report titled, **"PERFORMANCE OF SUB-CARRIER INDEX MODULATION IN OFDM"** towards the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** with specialization in **Communication Systems**, submitted in the Department of Electronics and Communication Engineering, Indian Institute of Technology Roorkee, Roorkee (India) is an authentic record of my own work carried out during the period from May 2017 to November 2018, under the guidance of **Dr. ANSHUL TYAGI, Assistant Professor, Department of Electronics and Communications Engineering, Indian Institute of Technology Roorkee**.

I have not submitted the matter embodied in this dissertation for the award of any other Degree or Diploma.

Date:
Place: Roorkee Tanu Joshi

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**CERTIFICATE**

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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Place: Roorkee

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# Abstract

Orthogonal Frequency Division Multiplexing with sub-carrier Index modulation (OFDM-SIM) is a recently developed scheme which has certain advantages over the existing OFDM scheme. In this scheme information is sent not only through the sub-carriers but also through their indices.

The performance of OFDM-SIM has been analyzed in comparison to classical OFDM. The energy efficiency of this technique is always more than OFDM because all subcarriers are not active. The Bit Error Rate of OFDM-SIM is less than OFDM for the same spectral efficiency at high signal to noise ratio values. Also there is an enhancement in spectral efficiency for lower order of modulation and certain sub-carrier activation ratio. Simulation results show the superiority of the OFDM-SIM over OFDM.

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# Abbreviations

| | |
|---|---|
| **AM** | **A**mplitude **M**odulation |
| **BER** | **B**it **E**rror **R**ate |
| **BPSK** | **B**inary **P**hase **S**hift **K**eying |
| **CP** | **C**yclic **P**refix |
| **DFT** | **D**iscrete **F**ourier **T**ransform |
| **FFT** | **F**ast **F**ourier **T**ransform |
| **FM** | **F**requency **M**odulation |
| **IDFT** | **I**nverse **D**iscrete **F**ourier **T**ransform |
| **IEEE** | **I**nstitute **O**f **E**lectrical and **E**lectronics **E**ngineers |
| **IFFT** | **I**nverse **F**ast **F**ourier **T**ransform |
| **ICI** | **I**nter **C**arrier **I**nterference |
| **ISI** | **I**nter **S**ymbol **I**nterference |
| **LAN** | **L**ocal **A**rea **N**etwork |
| **LLR** | **L**og **L**ikelihood **R**atio |
| **LTE** | **L**ong **T**erm **E**volution |
| **MIMO** | **M**ultiple **I**nput **M**ultiple **O**utput |
| **ML** | **M**aximum **L**ikelihood |
| **MMSE** | **M**inimum **M**ean **S**quare **E**rror |
| **OFDM** | **O**rthogonal **F**requency **D**ivision **M**ultiplexing |
| **OFDMA** | **O**rthogonal **F**requency **D**ivision **M**ultiple **A**ccess |
| **PAPR** | **P**eak to **A**verage **P**ower **R**atio |
| **PM** | **P**hase **M**odulation |
| **QAM** | **Q**uadrature **A**mplitude **M**odulation |
| **QPSK** | **Q**uadrature **P**hase **S**hift **K**eying |

| | |
|---|---|
| **SE** | **S**pectral **E**fficiency |
| **SIM** | **S**ub-carrier **I**ndex **M**odulation |
| **SNR** | **S**ignal to **N**oise **R**atio |
| **ZFE** | **Z**ero **F**orcing **E**qualizer |

# Symbols

| | |
|---|---|
| $E_b$ | Average energy per bit |
| $G$ | Number of sub groups |
| $k$ | Number of active sub-carriers per sub-block |
| $L$ | Cyclic Prefix Length |
| $M$ | Order of Modulation |
| $n$ | Number of sub-carriers per sub-block |
| $N$ | Total number of sub-carriers |
| $N_o$ | Noise Power |
| $p_1$ | Number of index selecting bits |
| $P_b$ | Average Bit Error Probability |
| $r$ | Sub-carrier activation ratio |
| $\nu$ | Channel multipaths |
| $T$ | Number of Transmit Antennas |
| $R$ | Number of Receive Antennas |

# Chapter 1

# Introduction

## 1.1 Introduction to OFDM

Modulation involves mapping of information on different parameters( amplitude, phase or frequency) of a high frequency signal. In multiplexing, available bandwidth is shared among the different users. OFDM combines both- modulation and multiplexing. In OFDM, the whole bandwidth is distributed among multiple data carriers. It is different from other modulation techniques because information is carried by multiple carriers and any digital modulation technique can be used by individual carrier. OFDM is useful when information is sent via frequency selective channels. In a frequency selective channel, different fading is experienced by different frequencies of the signal. The complexity of receiver increases for this frequency selective faded signal. Hence in spite of transmitting data over a large bandwidth channel(which is frequency selective in nature), it is transmitted over multiple narrow bandwidth channels which behave as flat fading channels. Flat fading can be easily handled in comparison to frequency selective fading by using various equalization methods. In OFDM, various sub-carriers that have narrow spacing are orthogonal with respect to one another and data is transmitted simultaneously over these sub-carriers without any interference.

### 1.1.1 Basic Principle of OFDM

In single carrier transmission technique, single carrier frequency carries the information in the form of bits whereas in OFDM, the bit stream is sent over multiple carriers, all having the different frequency. OFDM is different from frequency division multiplexing in the sense that in OFDM, all the sub carriers transmit data from a single data source. In OFDM, IDFT is used at the transmitter to transmit the data over multiple sub-carriers.
Baseband OFDM signal

$$A(t) = \sum_{k=0}^{N-1} b_k e^{i2\pi k\Delta f t}, 0 \leq t \leq T_s$$

Pass-band OFDM signal

$$A(t) = Re \sum_{k=0}^{N-1} b_k e^{i2\pi(f_c + k\Delta f)t}, 0 \leq t \leq T_s$$

$b_k$ =modulated symbols
$f_c$ = frequency of the carrier signal
$N$ = size of IDFT
$T_s$ = sampling duration,
$\Delta f$ = sub-carrier spacing; $\Delta f = 1/T_s$

### 1.1.2 Modulation and Demodulation in OFDM System

At the transmitter, bits in the input data stream are modulated (BPSK/4-QAM/etc). Different sub-carriers may use different modulation schemes. An IDFT is taken on the $N_{FFT}$ complex numbers. Afterwards some redundant bits are inserted between the consecutive symbols to overcome ISI. These bits are called as cyclic prefix(CP). The output data is then sent to a parallel data to serial data converter which gives output signal as a sequence of symbols with each symbol having $N_{FFT}$ samples.
At the receiver, the signal is applied to a serial data to parallel data converter. A

DFT is taken on the $N_{FFT}$ complex numbers to get the symbol. CP associated with each symbol is removed. Each symbol is demodulated to get the data bits. These bits are again converted from parallel to serial form and input data stream is retrieved.

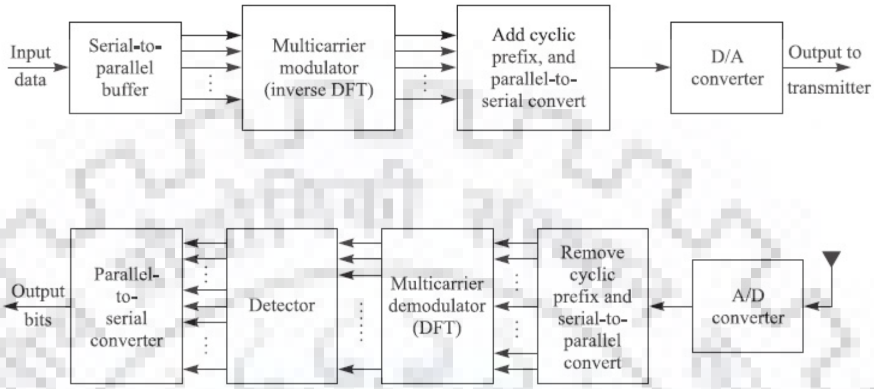


FIGURE 1.1: Block Diagram of OFDM System [8]

### 1.1.3 Cyclic Prefix

In OFDM system, cyclic prefix is used to remove ISI effects. It copies the end portion of an IDFT block to the starting of an OFDM symbol. The duration of cyclic prefix is chosen greater than the impulse response duration of the channel to remove ISI completely.

Figure 1.2 shows two OFDM symbols, each with duration $T_{sub}$ and CP length as $T_G$

Figure 1.3 illustrates the OFDM symbols with CP in time/frequency domain.

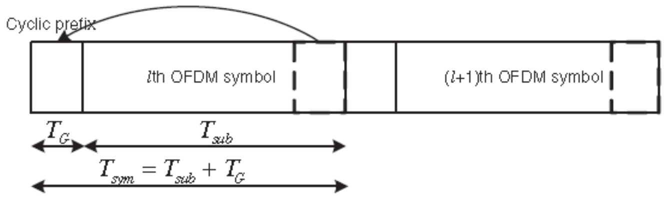


FIGURE 1.2: OFDM symbols with Cyclic Prefix [9]

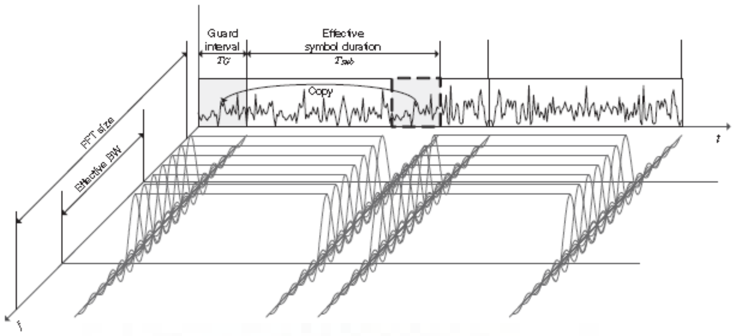


FIGURE 1.3: Time/Frequency domain description of OFDM symbols with CP [9]

### 1.1.4 Applications of OFDM

OFDM is used in numerous wireless communication applications. It is used in digital audio broadcasting, digital video broadcasting and wireless LAN networks like IEEE 802.11a/g/n
The applications include use in wireless networks like personal area and local area networks.
OFDMA has application in LTE i.e. in 4G communication standard.

### 1.1.5 Drawbacks of OFDM

OFDM performance gets affected because of synchronization errors and it results in interference and loss of orthogonality.
High peak values in OFDM results in high PAPR. The higher values of PAPR decreases the efficiency of circuits like power amplifiers and A/D converters. Power amplifiers generate non linear effects which results in ICI and thus orthogonality is destroyed.

## 1.2 Introduction to OFDM-SIM

SIM OFDM is a new scheme that has better spectral efficiency than OFDM. It involves the use of subcarrier-index to transmit information by keeping the certain

carriers on or off depending upon the input bits. SIM OFDM aims at providing either BER performance enhancement or power-efficiency improvement over conventional OFDM by incorporating different power allocation policies.
SIM OFDM along with MIMO system can be used in 5G wireless networks. MIMO-OFDM SIM scheme provides improvement in spectral efficiency and it gives superior bit error performance than MIMO-OFDM using certain detectors and for realistic conditions.

## 1.3 Introduction to MIMO-OFDM

MIMO when combined with OFDM is suitable for applications that demand high data rate. MIMO helps to achieve higher data rate by transmitting data over multiple antennas. OFDM provides reliable communication over fading channels by dividing a broadband channel into narrow bandwidth flat fading channels. In this way MIMO OFDM provides good quality and higher data rate communication which is the demand of the modern communication.

### 1.3.1 Performance Gain in MIMO System

The multiple antennas are deployed either at transmitter or receiver to get reliable transmission over multi-path fading channels and improves capacity of the system. In MIMO, multiple transmitting and receive antennas are used to get the spatial multiplexing gain which increases the spectral efficiency.

#### 1.3.1.1 Diversity Gain

To get the diversity gain, same data is sent on independent fading channels. When same data is sent multiple times over different fading channels, the fading suffered by same data over different channels is different. This assures that data through one of the channels will get less faded as compared to other copies of same data.

Thus, there is more probability of receiving the correct data. Hence reliability of the communication system improves. Also co-channel interference reduces significantly. The gain introduced by above technique is called spatial diversity gain.

$$\text{Diversity Gain} = T * R$$

where $T$ is the number of transmitting antennas and $R$ is the number of receiving antennas. In Figure 1.4 diversity gain for a 2X2 MIMO system is 4.

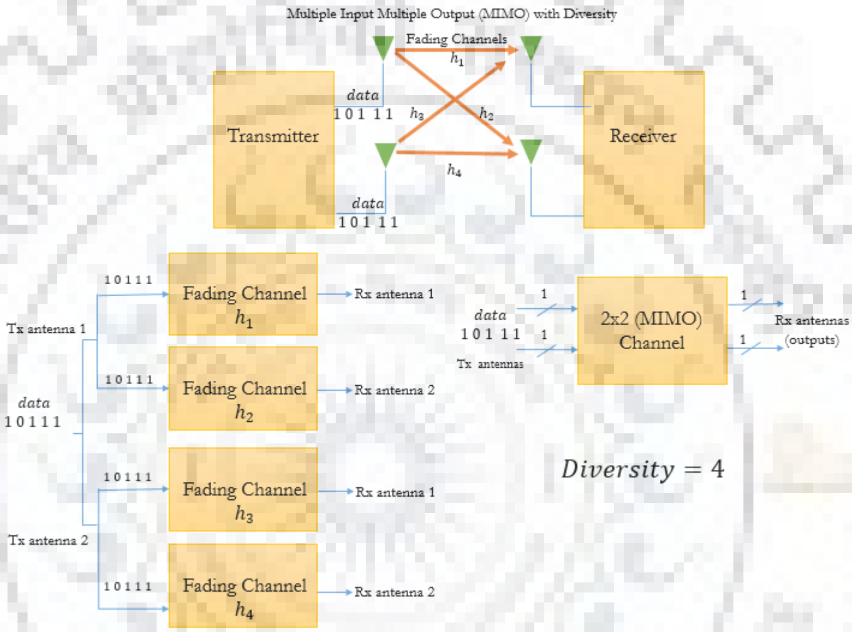


FIGURE 1.4: Diversity Gain in MIMO System [16]

#### 1.3.1.2 Spatial Multiplexing Gain

In comparison to single antenna system used at transmitting or receiving end, Spatial multiplexing results in linear capacity increase at no extra power or bandwidth requirement. In spatial multiplexing, every transmitting antenna transmits independent data. The multiplexing gain is obtained provided that the channel has abundant scattering and it allows the independent data to be transmitted simultaneously at the same frequency. As independent data transmitted through MIMO channel at same frequency experience different fading, thus the receiver is able to separate the different signals and capacity gain is obtained. This gain is also called as spatial multiplexing gain.

$$\text{Multiplexing Gain} = \min(T, R)$$

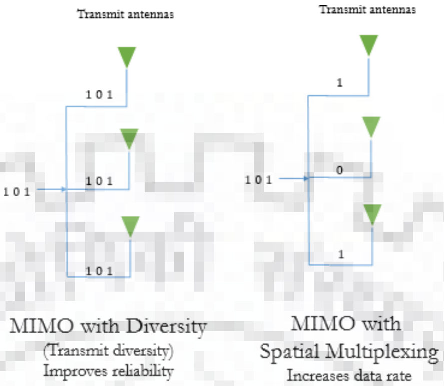


FIGURE 1.5: Diversity Gain vs Spatial Multiplexing Gain in MIMO System [16]

In figure 1.5 for a 3X3 MIMO with spatial multiplexing, multiplexing gain is 3. For the same 3X3 MIMO with diversity, diversity gain is 9.

#### 1.3.1.3 Array gain

Array gain is achieved by using coherent combining at the transmitting and the receiving end. It increases the average SNR at the receiver and thus coverage is improved.

Multiple antennas at transmitter and receiver can eliminate co-channel interference that causes an increase in cellular system capacity.

# Chapter 2

# Literature Survey

## 2.1 System Model of OFDM-SIM

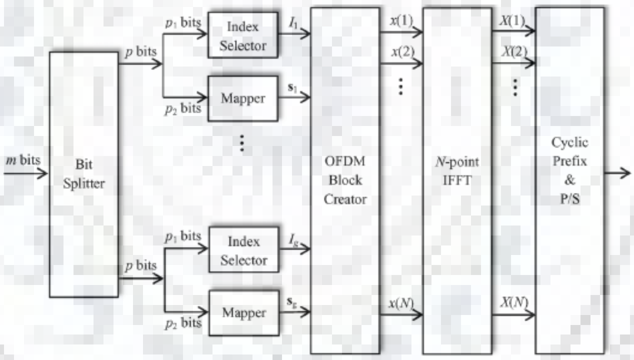


FIGURE 2.1: Block diagram of the OFDM-SIM transmitter [1]

There are $m$ information bits for each OFDM block that enter the OFDM-SIM transmitter. The $m$ bits are divided in $G$ groups, every group has $p$ bits, such that $m = pG$. Every $p$-bits are used to create an OFDM sub-block with length $n$, where $n = N/G$ and $N$ is the number of OFDM sub-carriers, i.e.,the size of the FFT.

In every OFDM sub-block, $k$ sub-carriers are activated out of $n$ sub-carriers. The indices of the carriers to be activated is decided by the first $p_1$ bits of the incoming $p$ bits. A simple look-up table is utilized for lower value of $n$. The remaining $p_2$

bits, where $p_2 = k\log_2 M$ are $M$-ary modulated. So information is carried by both the modulated symbols as well as the indices of active sub-carriers.

## 2.2 Implementation of OFDM-SIM

The OFDM-SIM can be implemented with a look-up table. This table is required both at the transmitter and the receiver side. A look-up table example is given in Table 2.1. Here $s_\chi$ and $s_\zeta$ are modulated symbols using $M$-ary modulator. This look-up table can be used with ML detector at the receiver but this method is not feasible for large value of $n$ and $k$ because of the size of the table.

| Bits | Indices | sub-blocks |
|---|---|---|
| [0 0] | {1,2} | $[s_\chi s_\zeta\ 0\ 0]$ |
| [0 1] | {2,3} | $[0\ s_\chi s_\zeta\ 0]$ |
| [1 0] | {3,4} | $[0\ 0\ s_\chi s_\zeta]$ |
| [1 1] | {1,4} | $[s_\chi 0\ 0\ s_\zeta]$ |

TABLE 2.1: A Look-up table for $n = 4$, $k = 2$ and $p_1 = 2$ [1]

## 2.3 Bit Error Probability of OFDM-SIM

Let $\{x(1), x(2), ....x(N)\}^T$ be the $N \times 1$ OFDM block before taking $N$ point IFFT and $\mathbf{h} = [h_F(1)......h_F(\nu)]^T$ is the set of channel fading coefficients in frequency domain. Let $\mathbf{X}$ is $N \times N$, diagonal matrix whose elements are given by $x(1)$, $x(2)$, ... $x(N)$. If $\mathbf{X}$ is transmitted and wrongly detected as $\widehat{\mathbf{X}}$. This can be due to the decision error on both active indices and constellation symbols. The bit error probability of the OFDM-SIM can be evaluated as:

$$P_b \approx \frac{1}{pn_{\mathbf{X}}} \sum_{\mathbf{X}} \sum_{\widehat{\mathbf{X}}} P(\mathbf{X} \to \widehat{\mathbf{X}})\, e(\mathbf{X}, \widehat{\mathbf{X}}) \quad [1]$$

where $n_{\mathbf{X}}$ denote the number of possible realizations of X. $e(\mathbf{X}, \widehat{\mathbf{X}})$ is the number of bit errors and $P(\mathbf{X} \to \widehat{\mathbf{X}})$ is the unconditional pairwise error probability and it is given as:

$$P(\mathbf{X} \to \widehat{\mathbf{X}}) = \frac{1/12}{\det(\mathbf{I}_n + q_1\mathbf{K}_n\mathbf{A})} + \frac{1/4}{\det(\mathbf{I}_n + q_2\mathbf{K}_n\mathbf{A})}$$

where $q_1 = \frac{1}{4N_{0,F}}$ and $q_2 = \frac{1}{3N_{0,F}}$. $N_{0,F}$ is the noise variance in frequency domain. Also $\mathbf{A} = (\mathbf{X} - \widehat{\mathbf{X}})^H(\mathbf{X} - \widehat{\mathbf{X}})$ and $\mathbf{K}_n = E\{\mathbf{hh^H}\}$

## 2.4 Space-Time-Frequency Coding in MIMO-OFDM

MIMO OFDM helps to acheive higher data rates. MIMO provides diversity gain and spatial multiplexing gain. There are mainly three types[17] of coding that are used in MIMO-OFDM for obtaining diversity:

1. Space Time Coding
2. Space Frequency Coding
3. Space Time Frequency Coding

### 2.4.1 Space Time Coded OFDM

This technique involves transmitting the same data by multiple antennas at different time. The same information transmitted multiple times is received at many receive antennas and it increases the probability of retrieving the information accurately because the fading is different in each case.

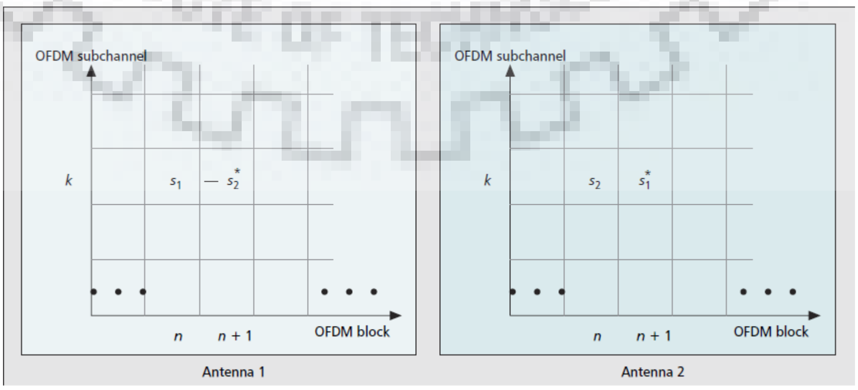


FIGURE 2.2: Space Time Coding in MIMO-OFDM [18]

Figure 2.3 shows a 2X2 MIMO-OFDM with Space Time Coding at transmitter. In this figure symbols $s_1$ and -$s_2^*$ are transmitted at the same frequency sub-carrier at different time at antenna 1. Similarly at antenna 2, symbols $s_2$ and $s_1^*$ are transmitted.

### 2.4.2 Space Frequency Coded OFDM

Space Time Coding is not helpful in case of fast fading. To remove this problem, same data is transmitted on the adjacent sub carriers at different antennas which is called Space Frequency Coding. Figure 2.4 shows a 2X2 MIMO-OFDM with Space Frequency Coding at the transmitter. In this at antenna 1, symbol $s_1$ and -$s_2^*$ are transmitted at two different subcarriers of OFDM. Simultaneously, at antenna 2, symbols $s_2$ and $s_1^*$ are transmitted at same set of respective OFDM sub-carriers.

This technique fails in case of frequency selective channels due to loss of orthogonality. If the channel frequency response is not constant over neighbouring subcarriers in space frequency coded OFDM then orthogonality is lost and it results in degradation of performance.

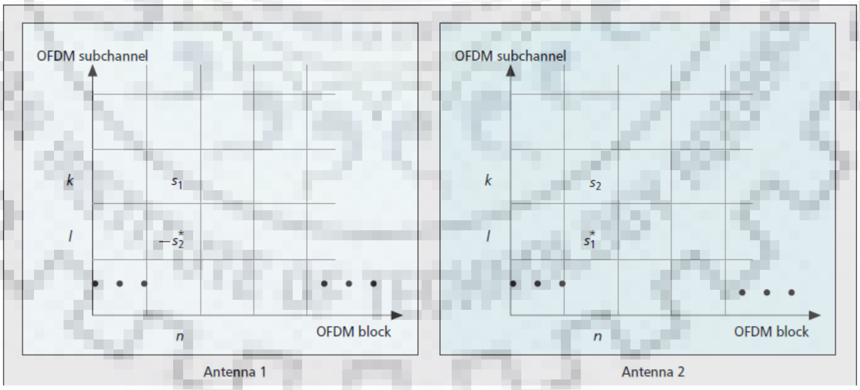


FIGURE 2.3: Space Frequency Coding in MIMO-OFDM [18]

### 2.4.3 Space Time Frequency Coded OFDM

As Space Time Coding suffers from fast fading and Space Frequency Coding suffers from frequency selectivity of channel so Space Time Frequency Coded OFDM can

be used. In this technique, symbols are transmitted at different time and at different frequency simultaneously to get the better performance irrespective of channel limitations.
Figure 2.5 shows Space time frequency coded 2X2 MIMO OFDM. In this symbols are transmitted in time, frequency and space domain to get the best results.

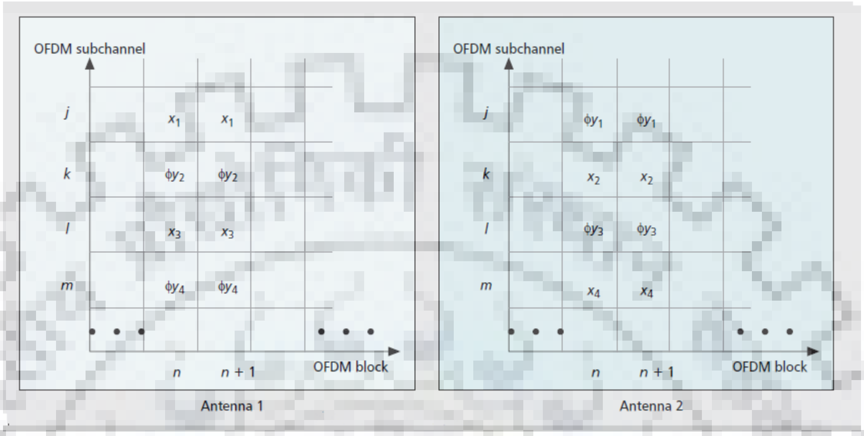


Figure 2.4: Space Time Frequency Coding in MIMO-OFDM [18]

## 2.5 System Model of MIMO OFDM-SIM

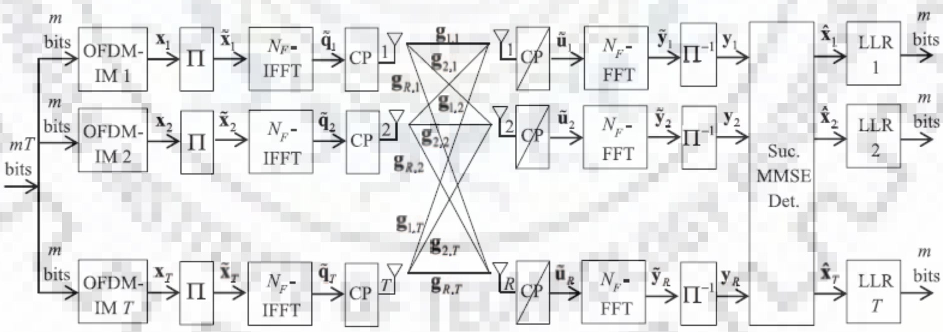


Figure 2.5: Block diagram of the MIMO OFDM-SIM transmitter [6]

Figure 2.3 shows a MIMO OFDM-SIM transceiver structure for a $TXR$ MIMO System i.e. $T$-trasmit antennas and $R$-receive antennas are considered. Input $mT$ bits are divided into $T$ branches with each branch processing the $m$ bits by OFDM SIM transmitter as shown in figure 2.1 The signal model for MIMO OFDM-SIM for subcarrier $n$ of subblock $g$ is given as:

$$\begin{bmatrix} y_1^g(n) \\ y_2^g(n) \\ \vdots \\ y_R^g(n) \end{bmatrix} = \begin{bmatrix} h_{1,1}^g(n) & \dots & h_{1,T}^g(n) \\ h_{2,1}^g(n) & \dots & h_{2,T}^g(n) \\ \vdots & \ddots & \vdots \\ h_{R,1}^g(n) & \dots & h_{R,T}^g(n) \end{bmatrix} \begin{bmatrix} x_1^g(n) \\ x_2^g(n) \\ \vdots \\ x_T^g(n) \end{bmatrix} + \begin{bmatrix} w_1^g(n) \\ w_2^g(n) \\ \vdots \\ w_R^g(n) \end{bmatrix}$$

$$\mathbf{Y}_n^g = \mathbf{H}_n^g \mathbf{X}_n^g + \mathbf{W}_n^g$$

Here $n = 1, 2, ..., N$ and $g = 1, 2, ..., G$,

$\mathbf{Y}_n^g$ is the received signal vector,

$\mathbf{H}_n^g$ is the channel coefficients matrix between transmitter and receiver,

$\mathbf{X}_n^g$ is the input data vector containing simultaneously transmitted symbols from all transmitters,

$\mathbf{W}_n^g$ is the noise vector.

# Chapter 3

# BER Performance of OFDM-SIM

## 3.1 Different Detection methods

OFDM-SIM detection involves detection of active indices of sub-carriers. This can be done using different detection methods.

### 3.1.1 Maximum Likelihood Detector

The ML detector searches for all possible sub-carrier index combinations and select the combination close to the received symbol. Mathematically, For any sub-block $\beta$, it minimizes the below metric:

$$(\hat{I_\beta}, \hat{s_\beta}) = \arg\min_{I_\beta, s_\beta} \sum_{\gamma=1}^{k} \left| y_F^\beta(i_{\beta,\gamma}) - h_F^\beta(i_{\beta,\gamma}) s_\beta(\gamma) \right|^2$$

where $y_F^\beta(\zeta)$ for $\zeta = 1, ....n$ are the received signals. $h_F^\beta(\zeta)$ for $\zeta = 1, ....n$ are the corresponding fading coefficients. $\mathbf{I}_\beta = \{i_{\beta,1}, .....i_{\beta,k}\}$ is the set of k active indices out of $n$ carriers. $\mathbf{s}_\beta = [s_\beta(1).........s_\beta(k)]$ is the vector of modulated symbols from M-ary modulator and $(\hat{I_\beta}, \hat{s_\beta})$ is the estimated value of sub-block $\beta$.

### 3.1.2 Log Likelihood Ratio Detector

The LLR detector takes the logarithm of the ratio of a posteriori probabilities of symbols in frequency domain which can be either zero or non-zero. This ratio gives information on the active status of the corresponding index $\alpha$. For $k = n/2$ and BPSK modulation, this ratio is given as:

$$\lambda(\alpha) = max(a, b) + \ln(1 + \exp(-(|b - a|))) + \frac{|y_F(\alpha)|^2}{N_{o,F}}$$

where $a = -|y_F(\alpha) - h_F(\alpha)|^2 / N_{o,F}$ and $b = -|y_F(\alpha) + h_F(\alpha)|^2 / N_{o,F}$. A larger $\lambda(\alpha)$ value indicates the more probable index $\alpha$ which is selected by the index selector at the transmitter.

### 3.1.3 Zero forcing Equalizer

ZFE is a linear equalizer that multiplies the received signal in frequency domain with the inverse of frequency response of channel. Thus the signal is restored back after removing the channel effect on it. If the channel frequency response is matrix $\mathbf{H}$, filter coefficients matrix $\mathbf{C}$ is given by $\mathbf{C} = \mathbf{H}^{-1}$. So that channel combined with equalizer gives a flat frequency response.

### 3.1.4 Minimum Mean Square Error Estimation

The zero-forcing equalizer do not give the best error performance because it does not consider noises in the system. Another equalizer that considers noises is the minimum mean square error (MMSE) equalizer. It is based on the MSE criteria. It is a linear equalizer which try to minimize the Mean square error between the received information symbols $\mathbf{I}_k$ and the output of the equalizer $\hat{\mathbf{I}}_k$, where MSE is given as:

$$\text{MSE} = E[\mathbf{e}_k^2] = E[(\mathbf{I}_k - \hat{\mathbf{I}}_k)^2]$$

## 3.2 Simulation Results

### 3.2.1 Different detection methods

The simulation parameters used are given in table 3.1. In figure 3.1, simulation results for ML detector are shown. BPSK has been used as a modulation scheme. Theoretical and simulated bit error rate for classical OFDM have also been plotted for comparison. The theoretical BER for classical OFDM with BPSK is given by the expression:

$$\text{BER} = \frac{1}{2} \times \left(1 - \sqrt{\frac{E_b/N_o}{E_b/N_o + 1}}\right)$$

where $E_b/N_o$ = Signal to Noise Ratio in linear scale

| Parameters | Values |
|---|---|
| No. of Sub-carriers($N$) | 128 |
| No. of Occupied Sub-carriers | 116 |
| Cyclic Prefix Length($L$) | 16 |
| Channel Multipaths($\nu$) | 10 |
| No of Sub-carriers per OFDM sub-block($n$) | 4 |
| No of active Sub-carriers per OFDM sub-block($k$) | 2 |

Table 3.1: Simulation parameters

Figure 3.1 shows the bit error rate performance of OFDM-SIM using Maximum Likelihood detector. BER is little higher for OFDM-SIM at low values of SNR but it decreases at a higher rate as SNR increases. For high SNR, BER for OFDM-SIM reaches theoretical BER for OFDM. Spectral Efficiency of the system is 0.806 bits/s/Hz as cyclic prefix reduces the spectral efficiency by a factor of $N/(N+L)$. BER using Log Likelihood Ratio detector has been shown in figure. 3.2. It is comparatively better than ML detector. Also complexity of detector reduces in case of LLR detector in comparison to ML detector.

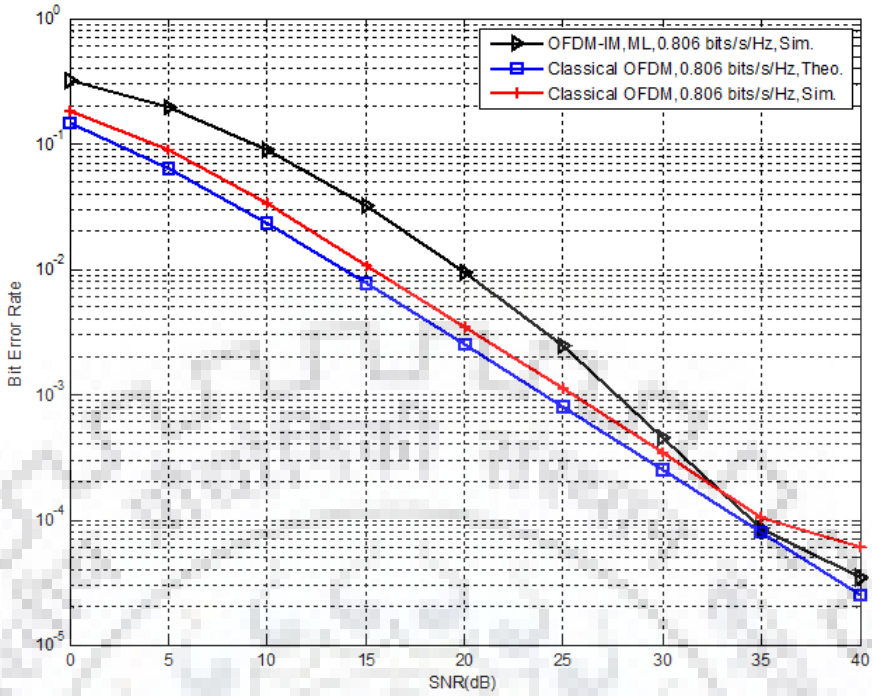


FIGURE 3.1: BER performance using ML detector

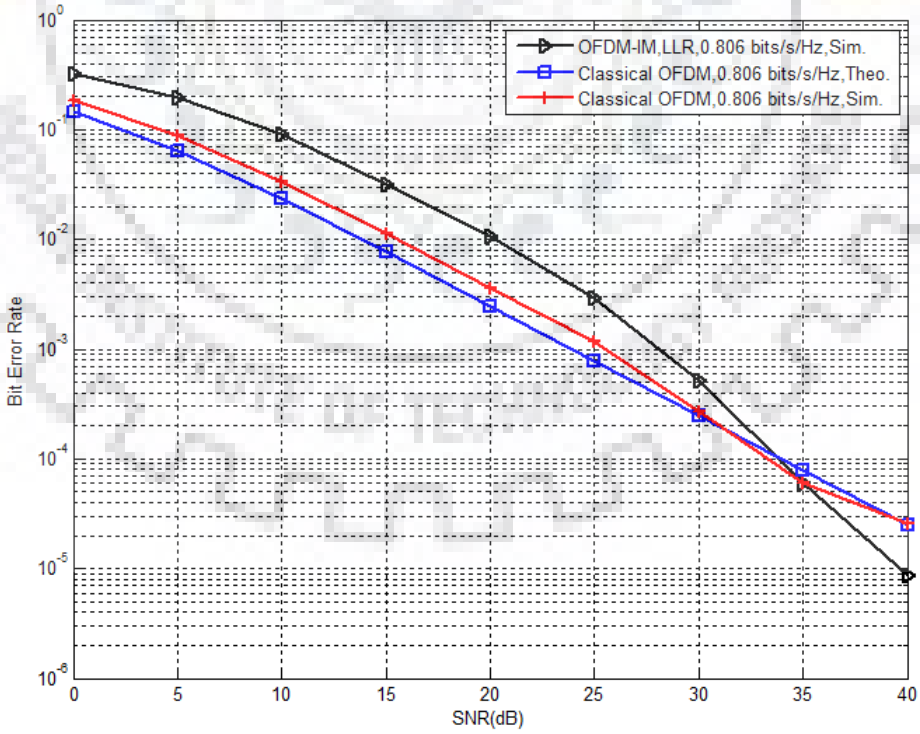


FIGURE 3.2: BER performance using LLR detector

Figure 3.3 shows BER performance using Zero forcing Equalization. Bit error rate is higher than ML detector at high SNR values. This is because zero forcing equalizer is useful when the channel is noiseless. Otherwise it may amplify the noise at certain frequencies.

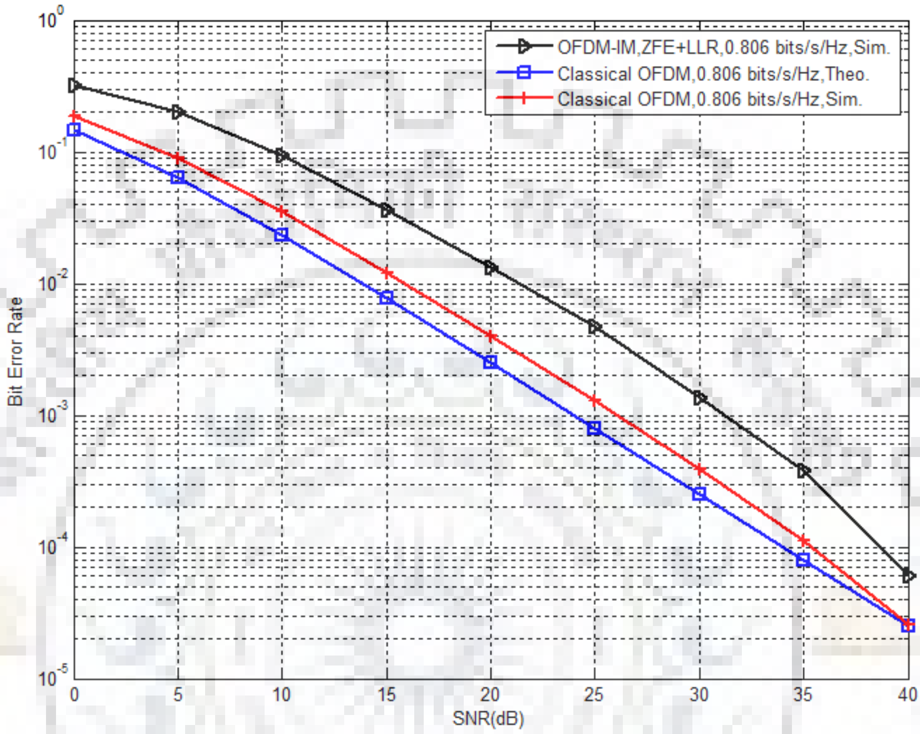


FIGURE 3.3: BER performance using ZFE+LLR detector

Figure 3.4 shows BER performance using Minimum Mean Square Error Equalization followed by LLR detector. There is no much improvement in performance because ISI is already avoided by cyclic prefix so equalization doesn't improve the performance further. At high SNR values BER is even higher with equalization than without using any equalizer.

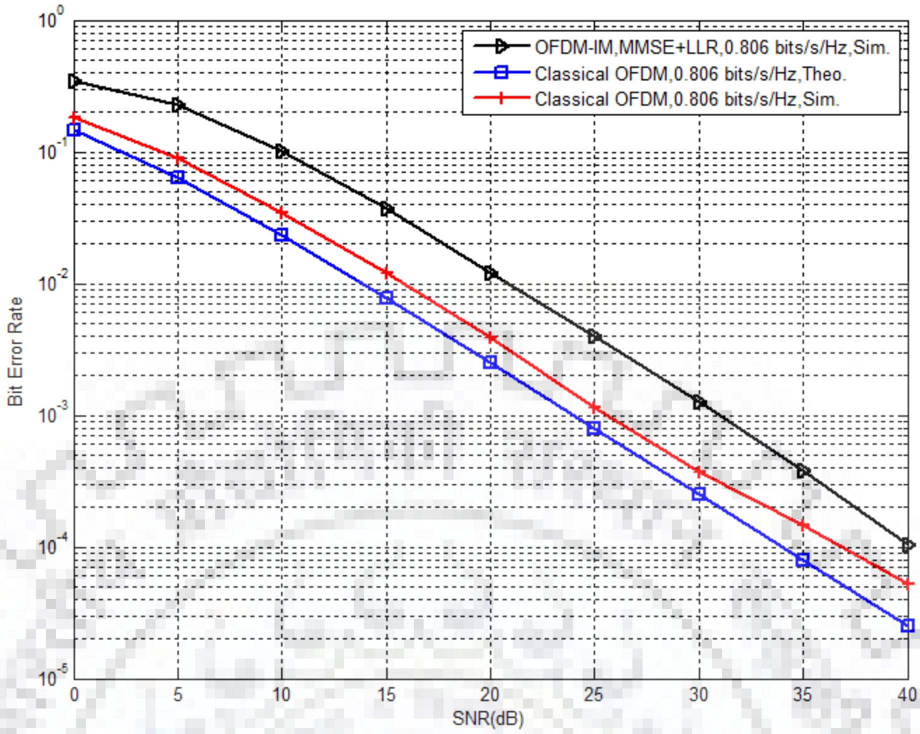


FIGURE 3.4: BER performance using MMSE+LLR detector

### 3.2.2 Variable Cyclic Prefix length

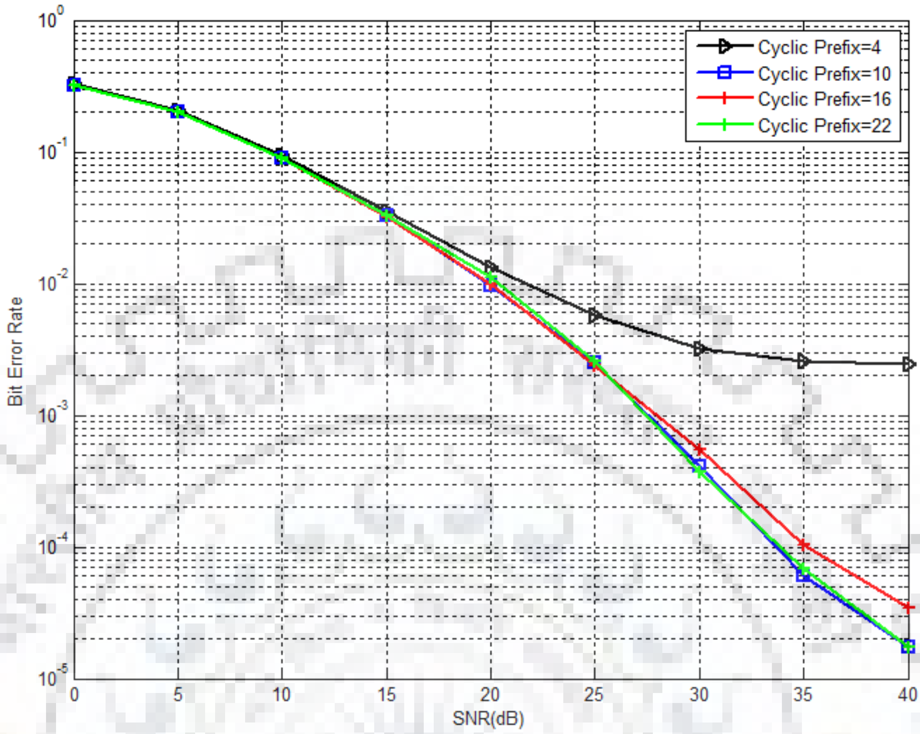


FIGURE 3.5: BER performance with variable cyclic prefix

Figure 3.5 shows the simulation results with 10 tap rayleigh channel by varying the length of cyclic prefix as 4, 10, 16 and 22. Other simulation parameters are same as given in table 3.1. If the chosen length of cyclic prefix is shorter than the multipath channel length then BER is high because of ISI. For Cyclic prefix length greater than or equal to channel taps, the BER performance is optimum. From results, it is evident that cyclic prefix length=4 with 10 tap rayleigh channel gives the worst performance.

### 3.2.3 Variable Channel Length

Figure 3.6 shows the simulation results for BER by varying multipath channel taps. Length of cyclic prefix is chosen as 16 whereas other simulation parameters are same as given in table 3.1. Channel taps have been varied as 5, 10, 15 and 20. BER is more in case of channel taps exceeding the length of cyclic prefix due to ISI i.e., for channel taps=20 which is greater than cyclic prefix length of 16. Otherwise for smaller number of taps, BER performance is optimum.

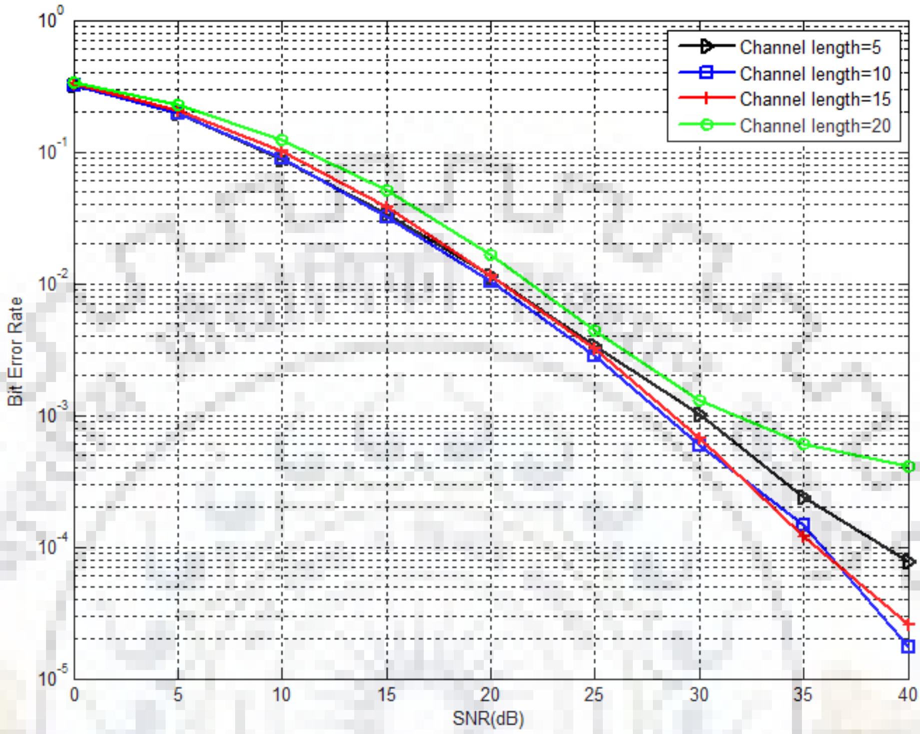


FIGURE 3.6: BER performance with variable channel length

### 3.2.4 Variable Sub-carrier activation ratio

| Parameters | Values |
|---|---|
| No. of Sub-carriers($N$) | 120 |
| No. of Occupied Sub-carriers | 108 |
| Cyclic Prefix Length($L$) | 16 |
| Channel Multipaths($\nu$) | 10 |
| No of Sub-carriers per OFDM sub-block($n$) | 5 |
| No of active Sub-carriers per OFDM sub-block($k$) | 3 |

TABLE 3.2: Simulation parameters

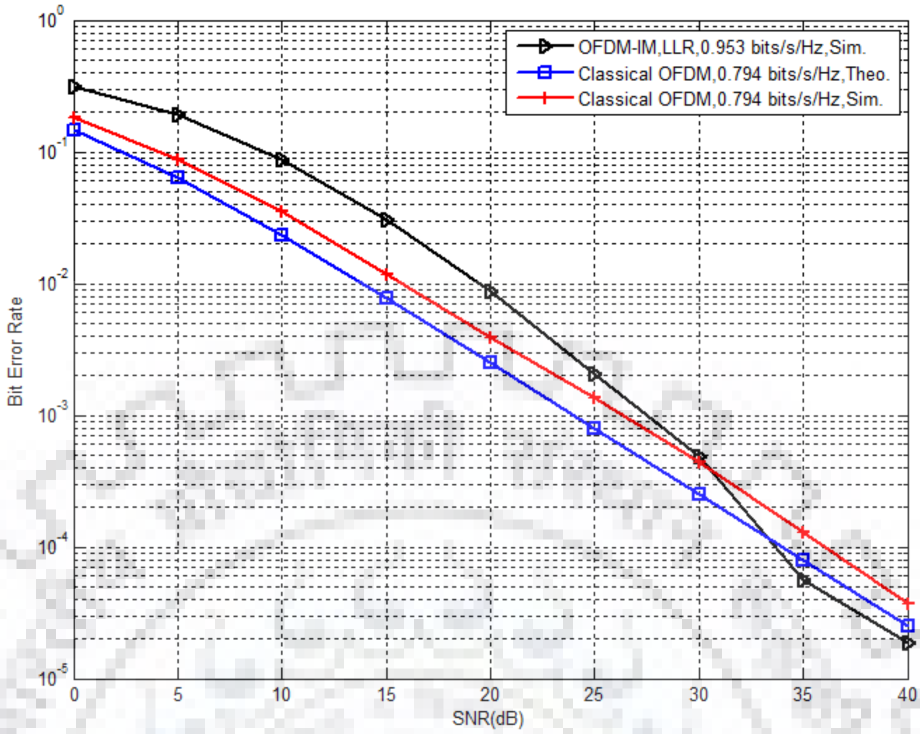


FIGURE 3.7: BER performance with $r$=0.6

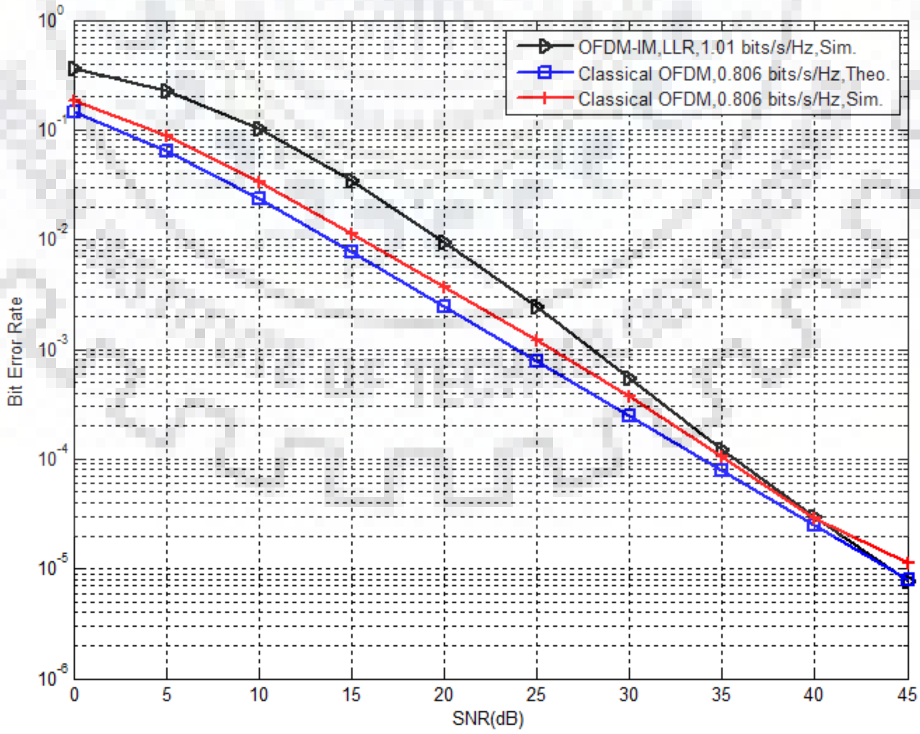


FIGURE 3.8: BER performance with $r$=0.75

By varying the number of active sub-carriers per sub-block i.e., by varying the sub-carrier activation ratio '$r$', spectral efficiency of the system is enhanced while maintaining the similar BER values. Table 3.2 shows simulation parameters for figure 3.7. The spectral efficiency for OFDM-SIM in this case is 0.953 bits/s/Hz in comparison to OFDM which is 0.794 bits/s/Hz.

Figure 3.8 shows results for $n = 4$ and $k = 3$ whereas other parameters are same as given in table 3.1. Here spectral efficiency for OFDM-SIM is 1.01 bits/s/Hz whereas it is 0.806 bits/s/Hz for classical OFDM.

# Chapter 4

# BER Performance of MIMO OFDM-SIM

A 2X2 MIMO system has been used for simulations. At a time, different symbols are transmitted from the two antennas to get the spatial multiplexing gain. If for each OFDM subblock $m$ and subcarrier $g$, $\mathbf{y}_m^g$ is a vector of the received symbols at the two receiving antennas then mathematically it is given as:

$$\mathbf{y}_m^g = \mathbf{H}_m^g \mathbf{x}_m^g + \mathbf{w}_m^g$$

Here $\mathbf{w}_m^g$ is the noise vector that gets added to transmitted vector $\mathbf{x}_m^g$ from two antennas. $\mathbf{H}_m^g$ is the corresponding channel matrix for 2X2 MIMO system. In matrix form it is given as:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}$$

Where $y1$ and $y2$ are the symbols received at antenna 1 and 2 respectively corresponding to OFDM subblock $m$ and subcarrier $g$. $x1$ and $x2$ are symbols transmitted from antenna 1 and 2 respectively. $w1$ and $w2$ are the noise components added while transmission through the channel. $h_{1,1}$, $h_{1,2}$, $h_{2,1}$ and $h_{2,2}$ are the coefficients of channel matrix $\mathbf{H}_m^g$.

## 4.1 Different Detection methods

OFDM-SIM detection involves detection of active indices of sub-carriers. A zero bit at the output of a detector indicates the inactive subcarrier whereas 1 or -1 indicates an active subcarrier. The detection can be done using different detection methods.

### 4.1.1 Maximum Likelihood Detector

For each subblock $g$ and subcarrier $m$ at the two receiving antennas, if vector $\mathbf{y}_m^g$ is received when vector $\mathbf{x}_m^g$ is transmitted and $\mathbf{H}_m^g$ is the channel matrix then ML detection of MIMO OFSM-SIM is done using the below expression:

$$(\mathbf{x}_m^g)_{ML} = \arg\min_{\widehat{\mathbf{x}}_m^g} ||\mathbf{y}_m^g - \mathbf{H}_m^g \widehat{\mathbf{x}}_m^g||^2$$

Where vector $\widehat{\mathbf{x}}_m^g$ has 9 possible realizations: $[0\ 0]$, $[0\ 1]$, $[0\ -1]$, $[1\ 0]$, $[1\ 1]$, $[1\ -1]$, $[-1\ 0]$, $[-1\ 1]$ and $[-1\ -1]$

### 4.1.2 Zero forcing Equalizer

The received vector $\mathbf{y}_m^g$ corresponding to subblock $g$ and subcarrier $m$ received at the two receiving antennas is multiplied with a pseudo inverse matrix $\mathbf{U}_m^g$ of the channel which is given as:

$$\mathbf{U}_m^g = [(\mathbf{H}_m^g)^H \mathbf{H}_m^g]^{-1} (\mathbf{H}_m^g)^H$$

$$\mathbf{z}_m^g = \mathbf{U}_m^g \mathbf{y}_m^g$$

Now the subcarrier $m$ of subblock $g$ for both the receiving antennas is approximated as per below expression:

$$\mathbf{x}_m^g = \arg\min_{\widehat{\mathbf{x}}_m^g} ||\mathbf{z}^g(m) - \widehat{\mathbf{x}}_m^g||^2$$

Where vector $\widehat{\mathbf{x}}_m^g$ has 9 possible realizations: [0 0], [0 1], [0 −1], [1 0], [1 1], [1 −1], [−1 0], [−1 1] and [−1 −1] .

### 4.1.3 Minimum Mean Square Error Estimation

The decoding complexity is reduced using MMSE detection of MIMO OFDM-SIM. For each subblock $g$ and subcarrier $m$ received at two antennas, a matrix $\mathbf{W}_m^g$ is calculated as given below:

$$\mathbf{W}_m^g = ((\mathbf{H}_m^g)^H \mathbf{H}_m^g + \frac{I_T}{\rho})^{-1} (\mathbf{H}_m^g)^H$$

The received symbol vector $\mathbf{y}_m^g$ corresponding to subblock $g$ and subcarrier $m$ for both the receiving antennas is multiplied by the matrix $\mathbf{W}_m^g$ to obtain another vector $\mathbf{z}_m^g$ which is given as:

$$\mathbf{z}_m^g = \mathbf{W}_m^g \mathbf{y}_m^g$$

Afterwards co-variance of $\mathbf{z}_m^g$ is calculated. It is given by $C_m$. Also a matrix $\mathbf{Q}_m$ is calculated as below:

$$\mathbf{Q}_m = (\mathbf{W}_m^g \mathbf{H}_m^g)$$

Now the subcarrier $m$ of subblock $g$ for both the receiving antennas is approximated as per below expression:

$$(\mathbf{x}_m^g)_{MMSE} = \arg\min_{\widehat{\mathbf{x}}_m^g} \frac{||\mathbf{z}_m^g - \mathbf{Q}_m \widehat{\mathbf{x}}_m^g||^2}{C_m}$$

Where vector $\widehat{\mathbf{x}}_m^g$ has 9 possible realizations: [0 0], [0 1], [0 −1], [1 0], [1 1], [1 −1], [−1 0], [−1 1] and [−1 −1]

After detecting the active subcarriers by any of the detector, look up table 4.2 which is used at the transmitter to perform the subcarrier modulation, same is used to retrieve the actual transmitted symbols.

## 4.2 Simulation Results

### 4.2.1 Maximum Likelihood Detector

The simulation parameters used are given in table 4.1. BPSK has been used as a modulation scheme. Simulated bit error rate for MIMO OFDM-SIM, MIMO OFDM and theoretical bit error rate for OFDM have been plotted for comparison. A 2X2 MIMO system has been used for the simulations.

| Parameters | Values |
|---|---|
| No. of Sub-carriers($N$) | 128 |
| No. of Occupied Sub-carriers | 116 |
| Cyclic Prefix Length($L$) | 16 |
| Channel Multipaths($\nu$) | 10 |
| No. of transmit antennas($T$) | 2 |
| No. of receive antennas($R$) | 2 |
| No. of Sub-carriers per OFDM sub-block($n$) | 4 |
| No. of active Sub-carriers per OFDM sub-block($k$) | 2 |

TABLE 4.1: Simulation parameters

In figure 4.1, simulation results using ML detector are shown. A look-up table has been used at the transmitter and same at the receiver to detect the symbols as shown in table 4.2.

| Bits | Indices | sub-blocks |
|---|---|---|
| [0 0] | {1,2} | $[s_\chi s_\zeta\ 0\ 0]$ |
| [0 1] | {2,3} | $[0\ s_\chi s_\zeta\ 0]$ |
| [1 0] | {3,4} | $[0\ 0\ s_\chi s_\zeta]$ |
| [1 1] | {1,4} | $[s_\chi 0\ 0\ s_\zeta]$ |

TABLE 4.2: A Look-up table for $n = 4$, $k = 2$ and $p_1 = 2$ [1]

For lower values of SNR, bit error rate is higher for MIMO OFDM-SIM than theoretical BER of OFDM but it is lower for higher SNR values. Sectral Efficiency for MIMO OFDM-SIM is 1.778 bits/s/Hz whereas for classical OFDM, spectral efficiency is 0.889 bits/s/Hz.

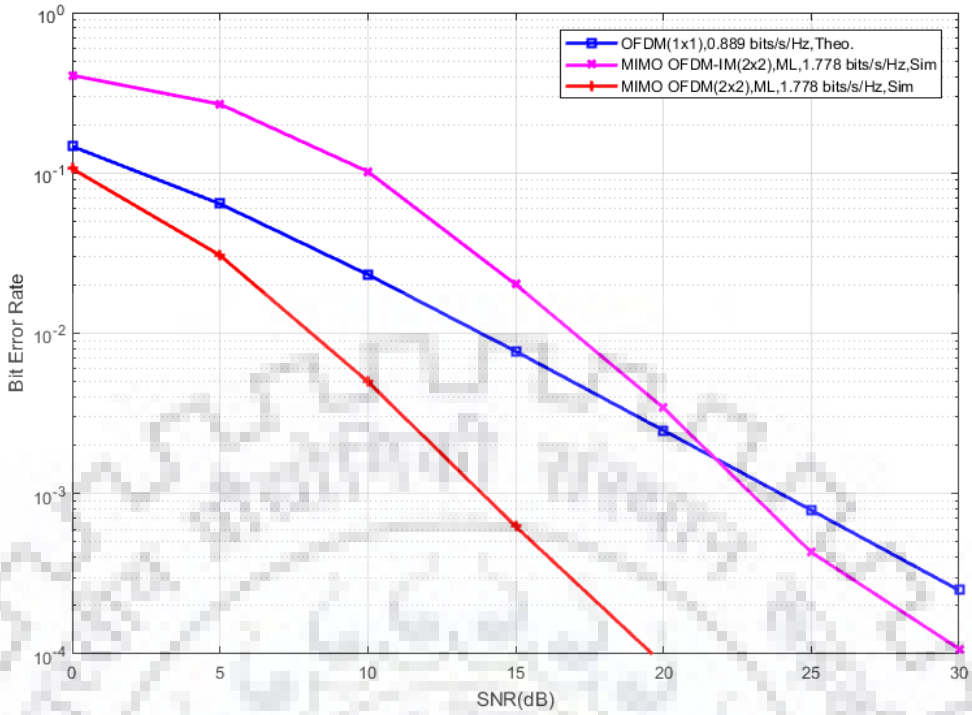


FIGURE 4.1: BER performance using ML detector

### 4.2.2 Zero Forcing Equalizer

In figure 4.2, simulation results using ZFE detector are shown. This type of detection is simple but it results into amplification of noise. So the BER performance is relatively poor with ZFE detector.Spectral Efficiency for MIMO OFDM-SIM is 1.778 bits/s/Hz whereas for classical OFDM, spectral efficiency is 0.889 bits/s/Hz.

### 4.2.3 Minimum Mean Square Error Estimation

In figure 4.3, simulation results using MMSE detector are shown. BER performance using MMSE detector is superior than ZFE detector. BER for MIMO OFDM-SIM approaches the theoretical BER of OFDM at high SNR values. Spectral Efficiency for MIMO OFDM-SIM is 1.778 bits/s/Hz whereas for classical OFDM, spectral efficiency is 0.889 bits/s/Hz.

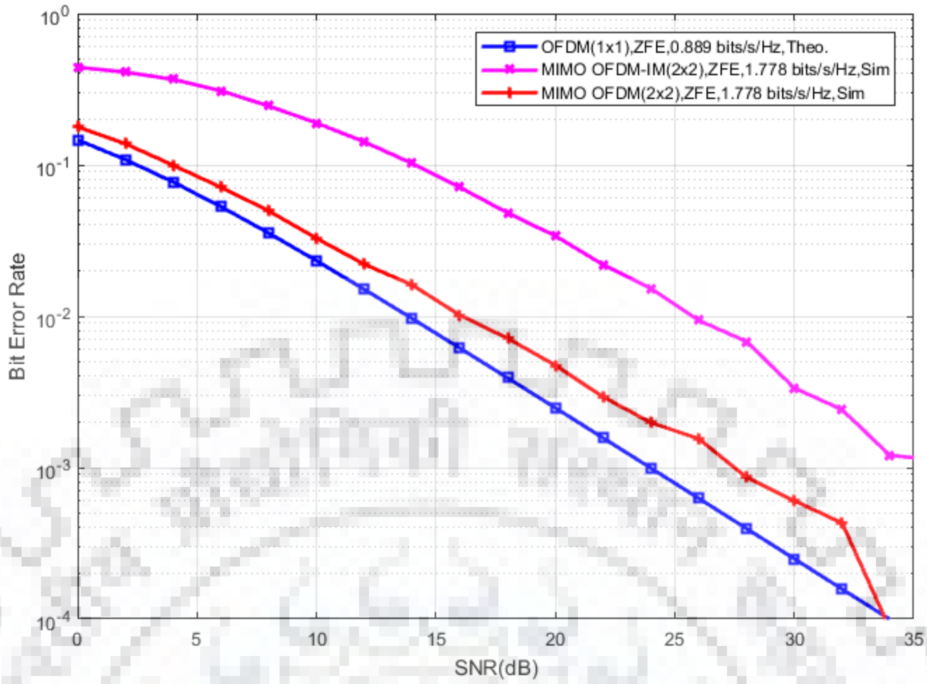


FIGURE 4.2: BER performance using ZFE detector

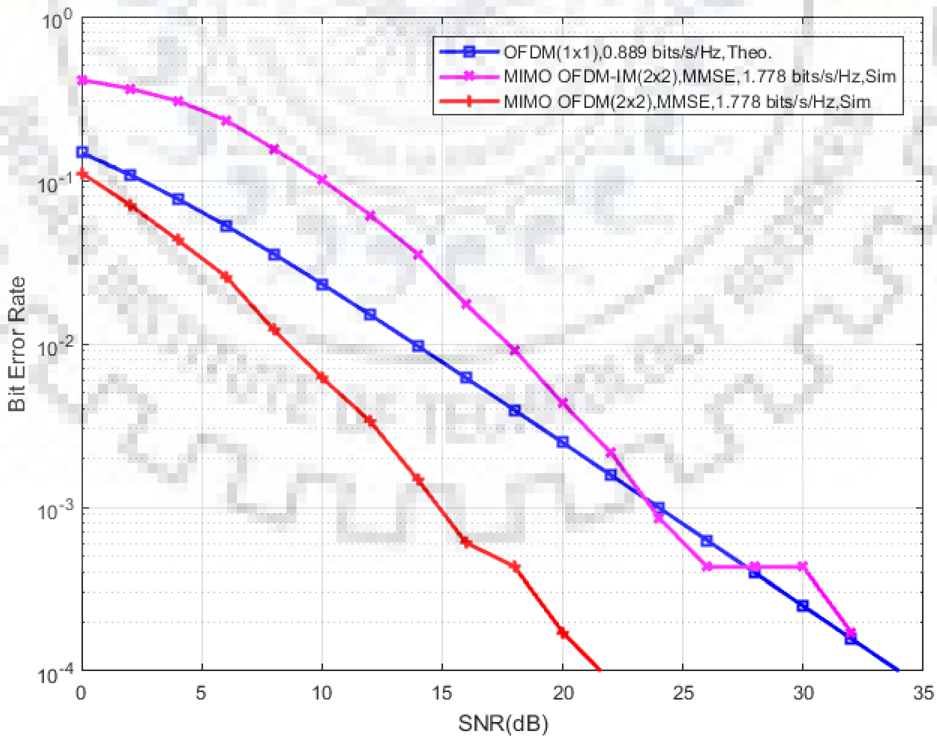


FIGURE 4.3: BER performance using MMSE detector

### 4.2.4 Variable Sub-carrier activation ratio

In figure 4.4, simulation results using ML detector are shown. The value of r used is 0.75 i.e out of 4 sub-carriers, three carriers are kept on and one carrier is kept off. It increases the spectral efficiency from 1.778 bits/s/Hz(with r=0.5) to 2.222 bits/s/Hz. Simulation parameters are shown in table 4.3.

| Parameters | Values |
|---|---|
| No. of Sub-carriers($N$) | 128 |
| No. of Occupied Sub-carriers | 116 |
| Cyclic Prefix Length($L$) | 16 |
| Channel Multipaths($\nu$) | 10 |
| No. of transmit antennas($T$) | 2 |
| No. of receive antennas($R$) | 2 |
| No of Sub-carriers per OFDM sub-block($n$) | 4 |
| No of active Sub-carriers per OFDM sub-block($k$) | 3 |

TABLE 4.3: Simulation parameters

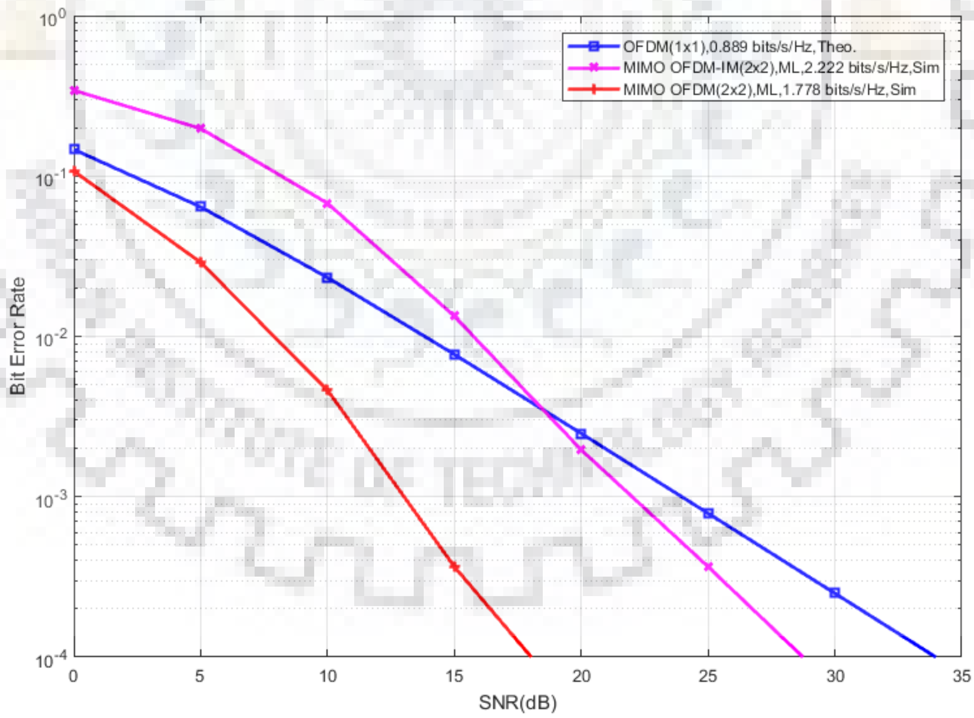


FIGURE 4.4: BER performance using ML detector, r=0.75

A look-up table has been used at the transmitter and same at the receiver to detect the symbols as shown in table 4.4.

| Bits | Indices | sub-blocks |
|---|---|---|
| [0] | {2,3,4} | [0 $s_\chi s_\zeta$ $s_\psi$] |
| [1] | {1,2,3} | [$s_\chi s_\zeta$ $s_\psi$ 0] |

TABLE 4.4: A Look-up table for $n = 4$, $k = 3$ and $p_1 = 1$

Depending upon the incoming bit at index selector, corresponding combination of sub-carriers is selected as per above table. At the receiver, same table is being used while detecting the symbols.

# Chapter 5

# Sub-carrier activation ratio for OFDM-SIM

## 5.1 Introduction

If $n$ is the number of sub-carriers per sub-block and $k$ is the number of active sub-carriers then sub-carrier activation ratio $r$ is given as:

$$r = k/n$$

### 5.1.1 Effect of Sub-carrier activation ratio on Energy Efficiency

For $M$-ary symbol constellation, Let $E_s$ be the average symbol energy. Then the total energy of a $N$ sub-carrier block in OFDM-SIM is $rNE_s$ which is $r$ times the energy of an OFDM block. Since r generally takes a value less than unity so there is always energy saving in OFDM-SIM over OFDM. At the extreme case when $r = 1$, energy of OFDM-SIM becomes equal to OFDM. That is, more energy is saved in OFDM-SIM at lower $M$ and $r$ values.

### 5.1.2 Effect of Sub-carrier activation ratio on Spectral Efficiency

Spectral Efficiency is the number of transmitted bits per sub-carrier measured in $b/s/Hz$. It is $\log_2 M$ for OFDM and for OFDM-SIM it is given by:

$$SE_{SIM} = \frac{1}{n} \lfloor \log_2 C_k^n \rfloor + r \log_2 M$$

Proper selection of $k, n$ and $M$ can maximize $SE_{SIM}$. Mathematically, for $SE_{SIM}$ to be greater or equal to $SE_{OFDM}$ then the following inequality should apply:

$$|\lfloor C_k^n \rfloor| \geq M^{n-k}$$

There are following cases:

- When $r$=1 ($k = n$),then $SE_{SIM}$=$SE_{OFDM}$=$\log_2 M$.
- When $r$ is minimum, i.e., $k = 1$ then for all $n$ and $M$, $SE_{SIM} < SE_{OFDM}$. In the limit, $SE_{SIM}$ vanishes as $n$ goes to infinity.
- When $r = 0.5$ ($k = n/2$) then for $M = 2$ and all $n$, $SE_{SIM} > SE_{OFDM}$ whereas for other values of $M$, it is always less than OFDM.
- When $r$ is maximum, i.e., $r = (n-1)/n$. Then for all $M$ and $n \geq M$, $SE_{SIM} \geq SE_{OFDM}$. In this case, $r$ approaches unity at large $n$ and hence $SE_{SIM}$ approaches $SE_{OFDM}$ at large $n$.

## 5.2 Simulation Results

In figures 5.1-5.4, $SE_{SIM}$ and $SE_{OFDM}$ are plotted with n for $M = 2$, $M = 4$, $M = 8$ and $M = 16$ and $r = 1/n$, 0.5 and $(n-1)/n$.Simulation results show that in case of BPSK, spectral efficiency for OFDM-SIM is greater than OFDM for $r$=0.5 and $r = (n-1)/n$. For r=0.5, As the number of sub-carriers increases spectral efficiency first increases and then it reaches a constant value.

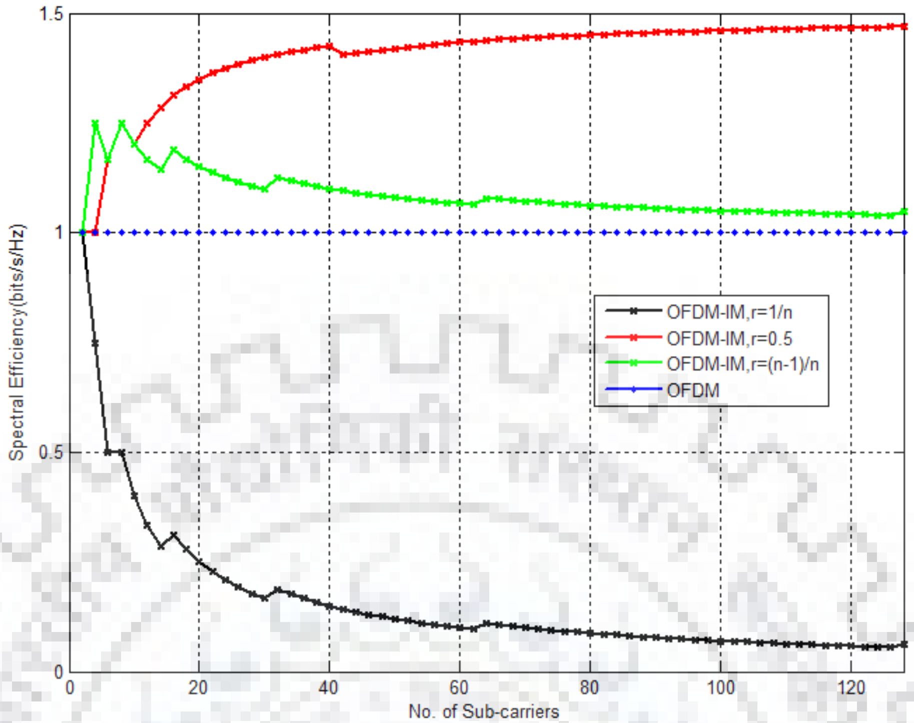


FIGURE 5.1: Plot of SE for $M$=2

Similarly for $r = (n-1)/n$, $SE_{SIM}$ is higher than $SE_{OFDM}$ at lower values of $n$ but it approaches to $SE_{OFDM}$ at higher values of $n$ as shown in figure 5.1. For $r = 1/n$ $SE_{SIM}$ is always lower than $SE_{OFDM}$ and it goes on decreasing with increase in $n$.

For $M > 2$, $SE_{SIM}$ is lower than $SE_{OFDM}$ for $r = 0.5$ and for $r = (n-1)/n$, it is little higher at low values of $n$ but approaches to $SE_{OFDM}$ at higher values of $n$ as shown in figure. 5.2. For $r = 1/n$, behaviour is same as that for BPSK.

Figure 5.3 shows that as $M$ increases Spectral efficiency of OFDM-SIM is almost equal to OFDM for $r = (n-1)/n$ and lower for other values of $r$. So as the order of modulation increases spectral efficiency improvement is almost negligible.

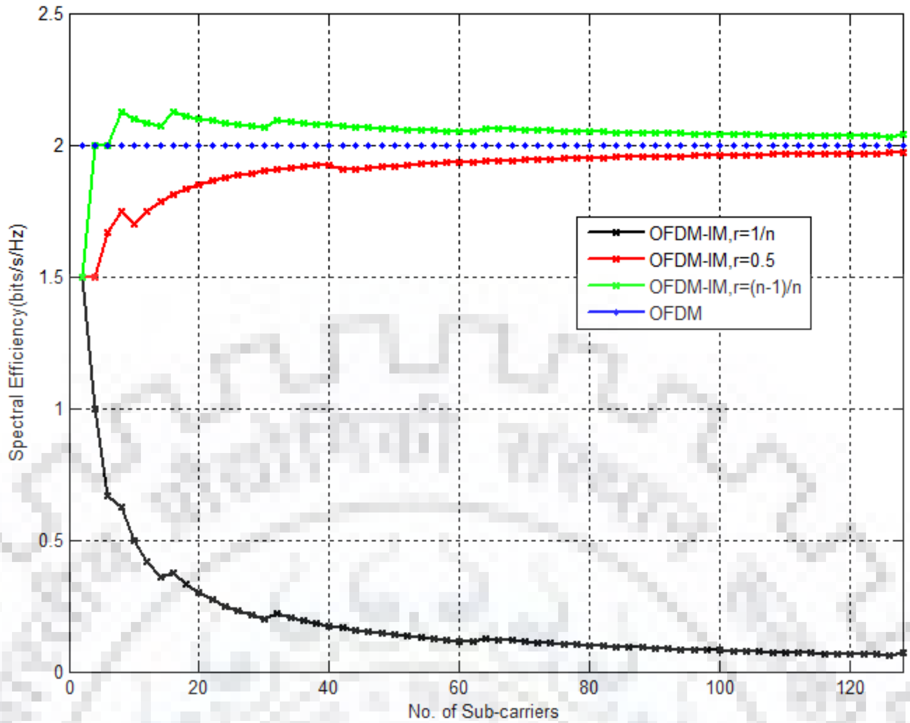


FIGURE 5.2: Plot of SE for $M$=4

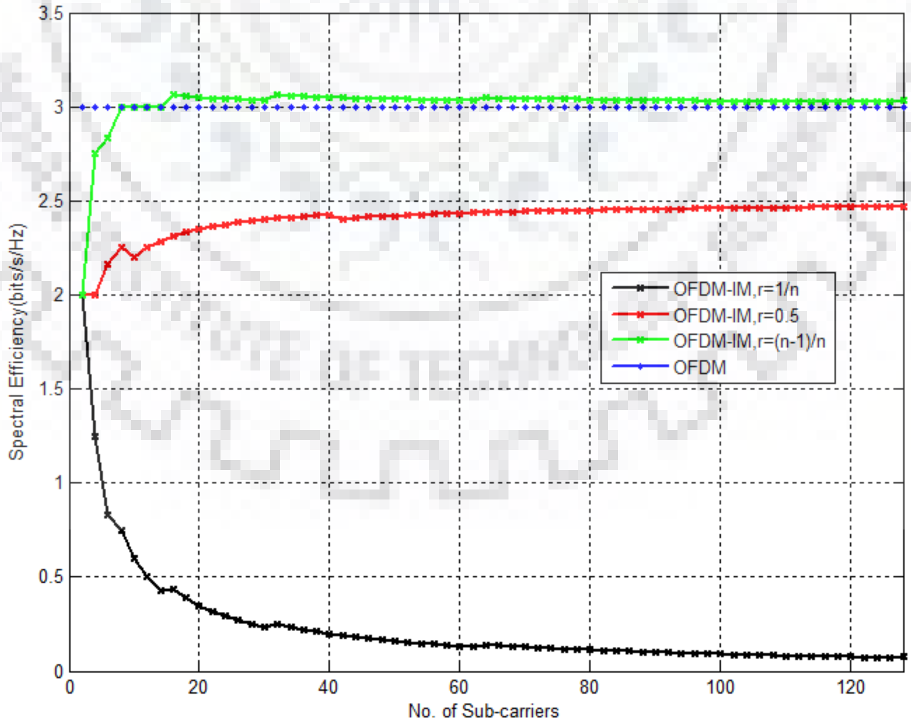


FIGURE 5.3: Plot of SE for $M$=8

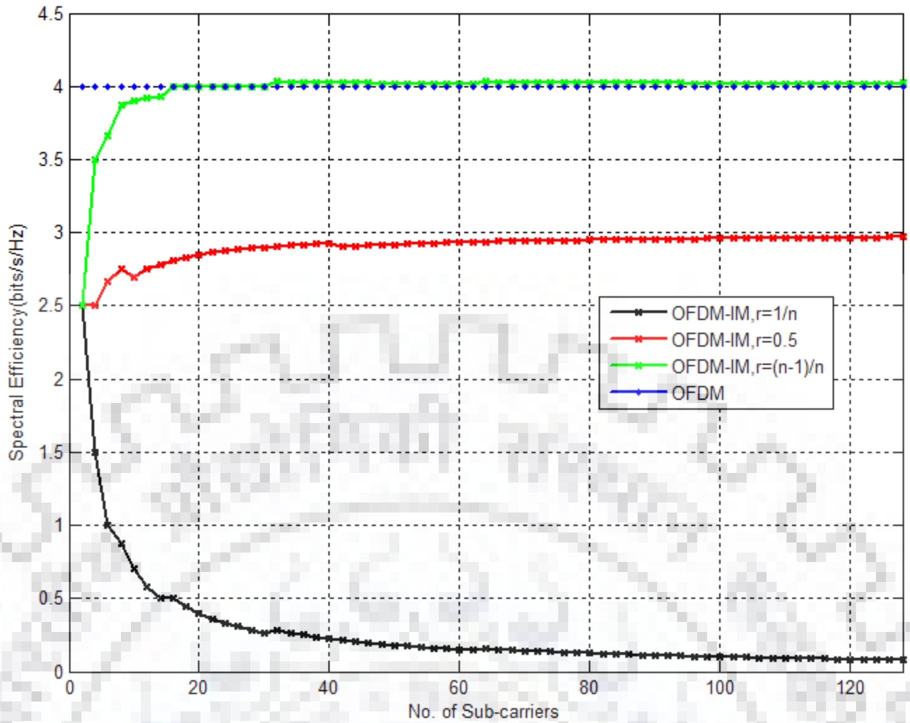


FIGURE 5.4: Plot of SE for $M$=16

Figure 5.4 further strengthens this conclusion as for no value of $n$ and $r$, $SE_{SIM}$ is higher than $SE_{OFDM}$.

# Chapter 6

# Sub-carrier activation ratio for MIMO OFDM-SIM

In MIMO-OFDM, different symbols are transmitted on multiple antennas simultaneously to get the higher data rate. The spatial multiplexing gain depends on number of transmitters as well as number of receivers. For MIMO-OFDM spectral efficiency is given as:

$$SE_{MIMO-OFDM} = \min(T, R) * (\log_2 M)$$

In case of MIMO OFDM-SIM spectral efficiency further increases due to less number of sub-carriers carrying the same amount of data as of MIMO-OFDM. Spectral Efficiency for MIMO OFDM-SIM is given by:

$$SE_{MIMO-SIM} = \min(T, R) * (\frac{1}{n}\lfloor \log_2 C_k^n \rfloor + r \log_2 M)$$

## 6.1 Simulation results

In figures 6.1-6.3, $SE_{SIM}$, $SE_{MIMO-SIM}$, $SE_{OFDM}$ and $SE_{MIMO-OFDM}$ are plotted for $M = 2$. In MIMO, 2X2 configuration has been assumed for simulations.

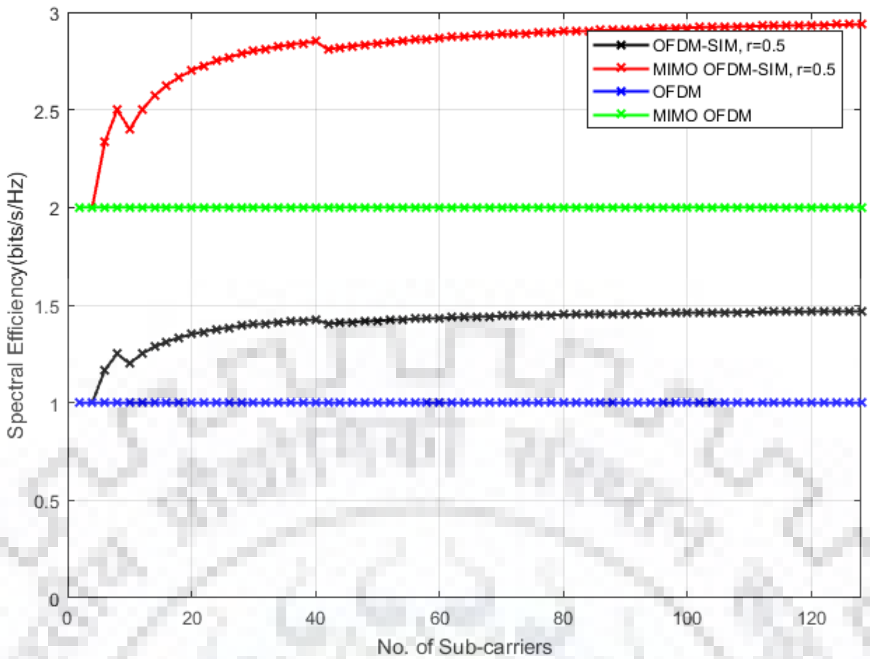


FIGURE 6.1: Plot of SE for $r$=0.5

Figure 6.1 shows spectral efficiency plots for $r$=0.5. From this figure, it can be seen that spectral efficiency of OFDM-SIM is higher than classical OFDM. Similarly spectral efficiency of MIMO OFDM-SIM is higher than MIMO-OFDM. At lower number of subcarriers, SE for SIM techniques is close to SE for classical modulation but at higher values of sub-carriers, SE for MIMO OFDM-SIM is almost thrice of classical OFDM. Hence MIMO OFDM-SIM achieves the best spectral efficiency among all the other variants.

Figure 6.2 shows spectral efficiency for $r = 1/n$. In this case, SE for OFDM-SIM and MIMO OFDM-SIM is lower than OFDM and MIMO-OFDM respectively. Also with increase in value of $n$, SE decreases to a very low value. Hence SIM techniques are not suitable to be used with lowest sub-carrier activation ratio.

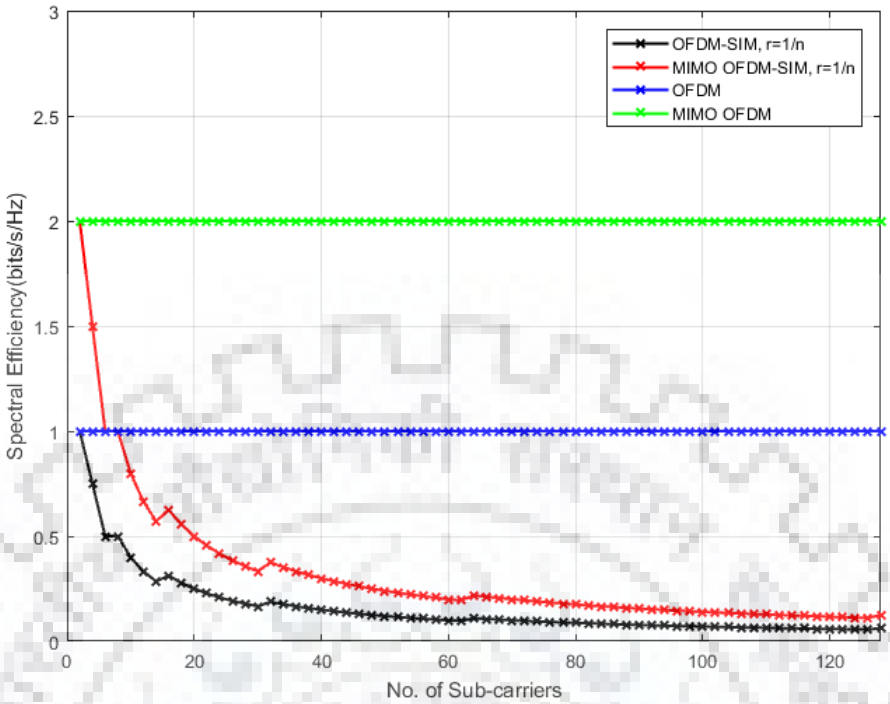


FIGURE 6.2: Plot of SE for $r = 1/n$

Figure 6.3 shows spectral efficiency plot for $r = (n-1)/n$ i.e. by keeping only one sub-carrier off from the given set. In this case, by using less number of sub-carriers better SE for MIMO OFDM-SIM and OFDM-SIM can be obtained in comparison to MIMO-OFDM and OFDM respectively. Even at higher values of $n$, SE for MIMO OFDM-SIM approaches close to MIMO OFDM and SE for OFDM-SIM approaches close to OFDM. Hence this choice of sub-carrier activation ratio is also suitable when using SIM over classical modulation.
From simulation results, it is concluded that proper choice of sub-carrier activation ratio in Sub-carrier index modulation is must for obtaining improved spectral efficiency and optimum BER performance.

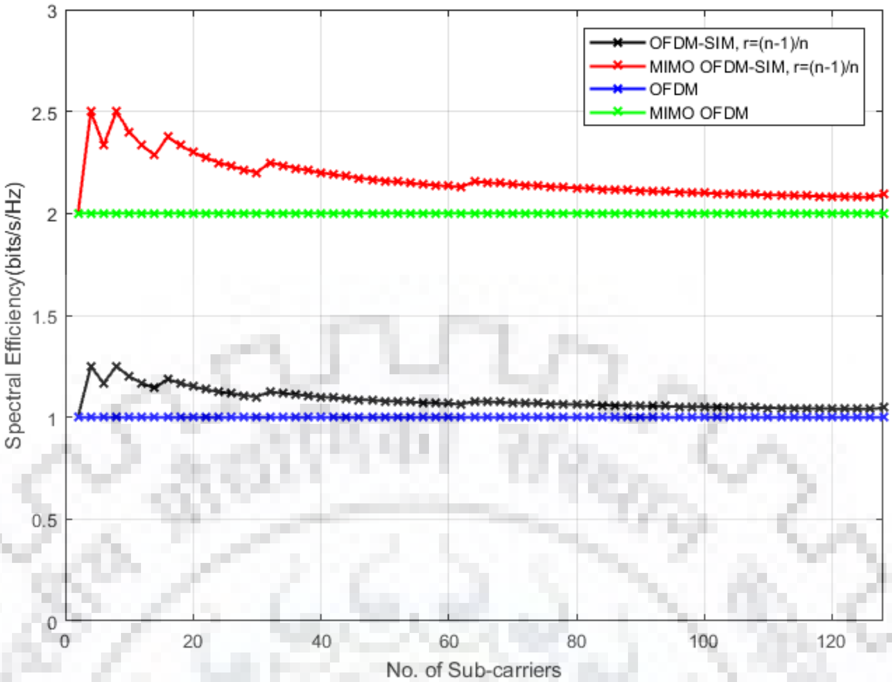


FIGURE 6.3: Plot of SE for $r = (n-1)/n$

# Chapter 7

# Conclusion and Future Work

Simulation results show that OFDM-SIM is superior over OFDM in terms of energy efficiency and spectral efficiency. The spectral efficiency improvement is important in terms of high data rate requirements of modern wireless system. By varying the sub-carrier activation ratio, we get an increase in spectral efficiency. Also bit error rate of OFDM-SIM is comparable to OFDM at low signal to noise ratio(SNR) values but it is superior at high SNR values.The BER performance by varying length of cyclic prefix and channel length has also been analyzed.

By using MIMO in combination with OFDM-SIM, data rate is further improved.To achieve the high demand for spectral and energy efficiency in 5G wireless networks, MIMO OFDM-SIM seems to be a promising technique.

The complexity of detector increases in SIM when used along with MIMO which is a major challenge for its practical feasibility. Hence for future work, low complexity detectors could be proposed for Sub-carrier index modulation. Also non coherent detection of OFDM-SIM could be analyzed in future.

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