

# Generalized Schemes of Orthogonal Frequency Division Multiplexing with Index Modulation

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**Abstract** - A newly developed scheme called orthogonal frequency division multiplexing with index modulation (OFDM-IM) which operates under frequency selective channels is proposed. The information is conveyed by selecting fixed number of subcarriers as active subcarriers which carries signal constellation symbols and their indices carry the additional information bits. In this paper three generalized schemes of OFDM-IM named as OFDM with generalized index modulation 1(OFDM GIM1), OFDM GIM2, OFDM GIM3 are proposed. In OFDM GIM1, the number of active subcarriers can be varied according to the input bit string. In OFDM GIM2, the index modulation is applied independently on in phase and quadrature per sub carrier. Through these ways the spectral efficiency can be higher than OFDM-IM. These schemes suffer from BER performance in lower SNR region. To overcome this problem the technique called interleaving is used in these generalization schemes as they are compatible with each other. The combination of these two schemes is named as OFDM GIM3. It is shown that from simulation results these schemes are superior in both spectral efficiency and BER performance than existing methods.

**Key Words** Bit error rate (BER), generalization, index modulation, interleaver, orthogonal frequency division multiplexing (OFDM), spectral efficiency.

## 1. INTRODUCTION

Multicarrier transmission is one of the key technology in wideband digital communication. It is included in many wireless standards to meet the increasing demands for high rate communication systems which operates on frequency selective fading channels. Orthogonal frequency division multiplexing (OFDM) is one of the most popular multicarrier technique that effectively combat with inter-symbol interference caused by frequency selective channels. The major advantage of OFDM over single-carrier schemes is its ability to work with frequency-selective fading channel with only one tap equalizer. Many attempts have been made to improve further classical OFDM system.

Spatial modulation (SM) [2] is a one of the most promising technique implemented in multiple input multiple output. In this scheme the information carried in amplitude/phase modulations and through antenna indices. The antenna indices are treated as sub carrier indices in MIMO systems. SM is applied successfully to SIM [4] and ESIM [3]. In SIM scheme, the number of active OFDM subcarriers varies for each OFDM block and perfect feed forward is to be assumed from the transmitter to the receiver in order to know the mapping method for the subcarrier index selecting bits. However, this scheme is impractical [4] and to feed forward requirement is removed in ESIM. ESIM needs higher order modulations to achieve same spectral efficiency as that of classical OFDM.

Recently, a transmission scheme OFDM-IM [1] is put forward. This scheme utilizes subcarrier indices as a source of information thereby error performance is better than that of classical OFDM in case of frequency selectivity channels when BPSK adopted. This improves the spectral efficiency without increasing the size of signal constellation because the indices of the active subcarriers carry information as well. Based on the technique in [1], an OFDM with generalized index modulation (OFDM-GIM) scheme is proposed in this paper. The generalization is proposed in two forms. First, a more flexible selection of active subcarriers is proposed to further improve the spectral efficiency. However, the generalization in this aspect cannot fundamentally overcome OFDM-IM's difficulty in adopting QPSK symbols. In the second aspect of generalization, the in-phase component and quadrature component of QPSK symbols are split into two independent components so that index modulation is applied independently on these two components. Furthermore, to reduce the BER (bit error rate) performance loss that may be incurred in our proposed generalization schemes in low SNR region, an interleaver is introduced to both schemes. Finally, noting that these two generalization schemes are incredibly compatible with each other in further improving the spectral efficiency, the combination of these two schemes is also investigated.

## 2. REVIEW OF OFDM IM

The block diagram of the OFDM-IM transmitter [1] is given in Fig. 1. This scheme transmits  $B$  bits per OFDM frame over a frequency selective Raleigh fading channel as follows. First  $B$  bits are divided into  $G$  groups and each group has  $p$  bits, i.e.,  $B = pG$ . Each group of  $p$  bits is assigned to one of  $G$  OFDM subblock having length of each subblock as  $n$ . Thus, the total number of OFDM subcarriers  $N$ , is  $nG$ . In classical OFDM, all  $n$  subcarriers in an OFDM subblock are active and carry in total  $n$   $M$ -ary signal constellation symbols, while in OFDM-IM, not all subcarriers are active. A subcarrier is defined as active if the subcarrier carries an  $M$ -ary signal constellation symbol and otherwise defined as inactive if the subcarrier carries zero. In OFDM-IM, not only active subcarriers but also the indices of active subcarriers carry information.

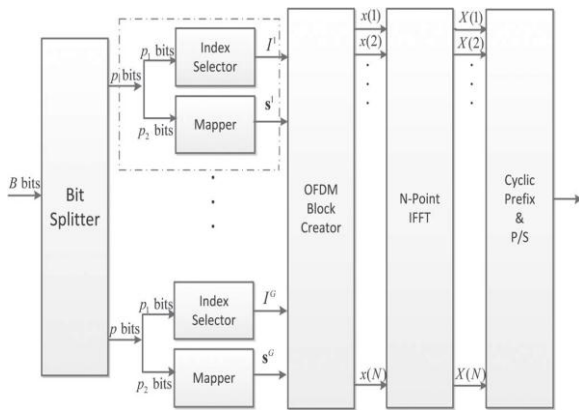


Fig -1: Block diagram of OFDM-IM transmitter

In the OFDM-IM scheme, the receiver detects both the information bits on the active subcarriers and the indices of those active subcarriers. Based on the kind of frequency domain symbols it is carrying the subcarrier status is determined as active or inactive.

In [1], two different types of detectors, i.e., Maximum Likelihood (ML) detector and Log likelihood Ratio (LLR) detector have been proposed. LLR Detector has a much lower decoding complexity and is more suitable for higher  $CKn$  when compared to ML detector. LLR detector evaluates the logarithm of the ratio of a posterior probabilities of non-zero to that of zero for every subcarrier. This ratio, providing the information about the active status of the corresponding subcarrier, is formulated as

$$\lambda(\alpha) = \ln(K) - \ln(n - K) + \frac{|Y(\alpha)|^2}{(N_{0,F})} + \ln\left(\sum_{m=1}^M \exp\left(-\frac{1}{(N_{0,F})} |Y(\alpha) - H(\alpha)S_m|^2\right)\right) \quad (1)$$

where  $\alpha = 1, \dots, N, S_m \in S$ . The larger the value of  $\lambda(\alpha)$ , the higher the probability that the subcarrier transmitting  $Y(\alpha)$  is active. After calculation of the  $N$  LLR values, the subcarriers with the highest  $K$  probabilities are assumed to be active. The set of active indices are then passed to the index demapper at the receiver to perform the inverse action of the index selector block given in Fig. 1. Demodulation of the constellation symbols on the active indices is then straightforward.

## 3. THE FIRST GENERALIZATION OF OFDM -IM

In the OFDM-IM scheme, the number of active subcarriers in each OFDM sub block is fixed to a value of  $K$  and the best performance in terms of BER and spectral efficiency is achieved when  $K = n/2$  if BPSK is used. The spectral efficiency is defined to be  $B/(N + L)$  in [1]. The OFDM-IM is generalized in such a way that the number of active subcarriers in an OFDM sub block may be different. This generalization is named as OFDM with generalized IM1, denoted as OFDMGIM1.

### 3.1 Main Concept

For an OFDM sub block, let  $n$  be the total number of subcarriers of the sub block. The number of subcarriers that are active to carry constellation symbols may vary dependent on the input signal to be transmitted. Let  $K$  be the set of all allowed numbers of active subcarriers with size of set as  $R$ . Thus, for an OFDM sub block,  $K$  is given by,

$$K = \{K_1, K_2, \dots, K_R\} \quad (2)$$

In the case of  $K_r$  active subcarriers for  $K_r \in K$  and  $r = 1, \dots, R$ , the indices of the selected  $K_r$  active subcarriers of the  $g$ -th sub block, denoted as  $I_r^g$ , is given by,

$$I_r^g = \{i_{r,1}^g, \dots, i_{r,K_r}^g\} \quad (3)$$

Where  $i_{r,k}^g \in \{1, \dots, n\}$  for  $g = 1, \dots, G, k = 1, \dots, K_r$  and  $i_{r,k_1}^g \neq i_{r,k_2}^g$  if  $k_1 \neq k_2$ . Similarly, the signal constellation symbols at the output of the mapper to be put onto the subcarriers with indices in  $I_r^g$ , denoted as  $S_r^g$ , is given by

$$S_r^g = \{s_{r,1}^g, \dots, \dots, s_{r,K_r}^g\} \quad (4)$$

For a certain  $K_r \in K$ , the total number of bits that can be transmitted by an OFDM sub block is given by

$$B_r^g = \lfloor \log_2(M^{K_r} C_n^{K_r}) \rfloor \quad (5)$$

and the total number of bits that can be transmitted by all  $K_r \in K$  of an OFDM subblock is given by

$$\sum_{K_r \in K} B_r^g = \lfloor \log_2(\sum_{K_r \in K} M^{K_r} C_n^{K_r}) \rfloor \quad (6)$$

Considering an extreme case where  $K = \{0; 1; \dots; n\}$  we have,

$$\sum_{r=1}^{n+1} B_r^g = \log_2(M + 1)^n \quad (7)$$

Hence, compared to the OFDM-IM scheme, more information bits per sub block can be transmitted in our OFDM-GIM1 scheme. However, compared to the implementation of OFDM-IM, several changes are

necessary to ensure the successful implementation of our proposed OFDM-GIM1 scheme.

1) The normalization factors in [1] needs to be adjusted such that  $E\{xx^H\} = N$ , set  $E\{s^g\{s^g\}^H\} = n$ , The normalization factor of IFFT is changed to  $\sqrt{N}$  and fft is changed to  $\frac{1}{\sqrt{N}}$

2) The index modulation block in Fig. 1 works for K containing only a single element. In OFDM-GIM1, p remains constant in each transmission subblock while p1 and p2 are varied based on different incoming input strings.

3) The LLR detector at the receiver to detect the active subcarriers and the M-ary constellation symbols carried by the active subcarriers are upgraded to adapt to a given set K with multiple elements.

### 3.2 Generalized Index Block

In this subsection, we consider  $n = 8$ ,  $K = \{1,3,5\}$  and  $M=2$  (i.e., BPSK) as an example to demonstrate how the generalized index modulation block works. The elements of the set K are assumed to be in strict ascending order. These parameters mean that for the g-th subblock consisting of 8 subcarriers, either a subcarrier, 3 subcarriers or 5 subcarriers out of 8 subcarriers may carry BPSK symbols. Hence, according to (16), 11 bits, i.e.,  $p = 11$ , can be transmitted by the g-th subblock. To map the 11 bits to the subcarrier indices and BPSK symbols, our method starts with  $K_1 = 1$ , i.e., a subcarrier out of 8 subcarriers is chosen and a BPSK symbol is put onto the selected subcarrier. From  $M^{K_1}C_n^{K_1} = 2^1C_8^1 = 16$ , it is known that in such a way 16 combinations out of  $2^p = 2^{11} = 2048$  combinations can be expressed. Since only one subcarrier is active when  $K_1 = 1$ , the number of the information bit which can be carried by the active subcarrier in BPSK symbol, denoted as  $p_2$ , is one, i.e.,  $p_2 = 1$  in this case. The combinatorial method introduced in [1] may be used for the mapping. The combinatorial method suggests that the range of input decimal numbers to be mapped should be a contiguous integer set starting from zero. However, for our proposed OFDM-GIM1, only when the input numbers are mapped based on the first element in K, i.e., mapped to  $K_1$  active subcarriers then the range of input numbers mapped based on the other elements, i.e.,  $K_r \in K$ ;  $r = \{2, \dots, R\}$ , is not necessarily starting from zero. As a result, an offset is introduced for each  $K_r$  to ensure that the range of the input decimal numbers satisfies the requirement of the combinatorial method.

Let  $Z_{p_1}$  represent the decimal number of the  $p_1$  bit binary string, and denote  $Z_{p_1}^r$  as the decimal number of the first combination of the  $p_1$  bits carried by  $K_r$  active subcarriers.

This  $Z_{p_1}$  is the offset to make the range of input numbers satisfy the requirement of the combinatorial method. Offsetting  $Z_{p_1}$  by a value  $Z_{p_1}^r$ , the resultant value, denoted as  $Z_{p_1}'$ , is  $Z_{p_1}' = Z_{p_1} - Z_{p_1}^r$ . For instance, for  $Z_p = 2$ , we have  $Z_{p_1} = 1$ ,  $Z_{p_1}^1 = 0$  and  $Z_{p_1}' = Z_{p_1} - Z_{p_1}^1 = 1$ . This  $Z_{p_1}'$ , together

with  $n = 8$ ,  $K_1 = 1$  are fed to the combinatorial method proposed in [1], [19], [20]. The output of the combinatorial method for this example is  $I_1^g = \{2\}$ , so that the second subcarrier in this subblock is the selected active subcarrier. Meanwhile, the  $p_2$  bit underlined, i.e., 0, is mapped to BPSK symbol  $s_1^g = [-1]$  and to be put onto the second subcarrier. Once the mapping for  $K_1 = 1$  is done, our method then proceeds to  $K_2 = 3$ , where 3 subcarriers out of 8 subcarriers are chosen and 3 BPSK symbols are put onto those selected subcarriers. The total number of combinations that  $K_2 = 3$  can represent is given by:

$$M^{K_2}C_n^{K_2} = 2^3C_8^3 = 448 \quad (8)$$

The output of the combinatorial method will be  $I_2^g = \{6,7,8\}$ , i.e., the sixth, seventh and eighth subcarriers are selected in this subblock as the active subcarriers. Meanwhile, the  $p_2$  bits in underlined type, i.e., 110, are mapped to BPSK symbols  $s_2^g = [1,1,-1]$  and to be put onto those selected subcarriers respectively. The procedure of the combination mappings for  $K_3 = 5$  continues. Theoretically, the total number of combinations that  $K_3 = 5$  can represent is given by:

$$M^{K_3}C_n^{K_3} = 2^5C_8^5 = 1792 \quad (9)$$

As 464 out of 2048 combinations have already been covered by  $K_1$  and  $K_2$  active subcarriers, only the remaining 1584 combinations are to be covered by using  $K_3 = 5$ . By noting this, the proposed index modulation block has one more level of operation than the original one. However, in the proposed technique, the p bit signal is split into different  $p_1$  and  $p_2$  bits for different input binary strings for a given set K. For a certain  $Z_p$ , the number of bits  $p_2$  entering the mapper is given by

$$p_2 = \begin{cases} K_1 \log_2 M, & Z_p \in [0, M^{K_1}C_n^{K_1} - 1] \\ K_2 \log_2 M, & Z_p \in [M^{K_1}C_n^{K_1}, M^{K_2}C_n^{K_2} - 1] \\ \vdots \\ K_R \log_2 M, & Z_p \in [M^{K_{R-1}}C_n^{K_{R-1}}, M^{K_R}C_n^{K_R} - 1] \end{cases} \quad (10)$$

In the example mentioned above, we have

$$p_2 = \begin{cases} 1, & Z_p \in [0,15] \\ 3, & Z_p \in [16,463] \\ 5, & Z_p \in [16,463] \end{cases} \quad (11)$$

Thus, the index modulation block in Fig. 1 is modified to the generalized structure in Fig.2, where the subblock splitter takes the p bit signal, the set K and M as input to determine the value of  $p_2$  for this particular p bit input (with decimal

value  $Z_p$ ) according to (11). Once  $p_2$  is determined, the number of bits entering the index selector is given by  $p_1 = p - p_2$ . Thereafter, the index selector takes the  $p_1$  most significant bits of the input binary string and generates the indices of  $p_2$  active subcarriers  $I_r^g$  using the combinatorial method with the offset  $Z_{p_1}^r$  considered, where r satisfies  $p_2 = K_r$  and  $r \in \{1, \dots, R\}$ . Meanwhile, the  $p_2$  least significant bits are sent to the mapper and are mapped to M-ary constellation symbols  $s_r^g$ . The constellation symbols  $s_r^g$

are then put onto the active subcarriers with indices in  $I_r^g$  respectively.

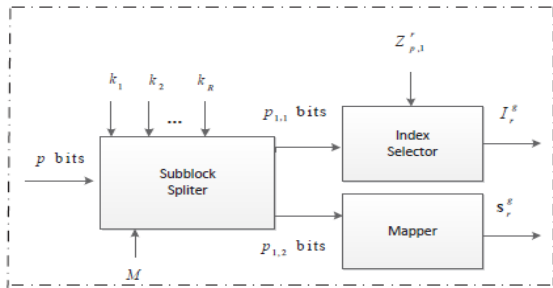


Fig -2: The generalized index modulation block of the g-th subblock for OFDM-GIM1

### 3.3 Upgraded LLR Detector

The ML detector is optimum in the detection of received symbols in OFDM-IM, as it considers all possible subblock realizations by examining for all possible subcarrier index combinations. However, in general, our proposed scheme has many more combinations than OFDM-IM, making ML detector generally impractical. According to [1], LLR detector is a practical choice to trade off between the detection precision and detection complexity. In this subsection, the upgraded LLR detector for OFDM-GIM1 is proposed. Our generalized scheme has a flexible  $K_r \in K$  for p bit input signal with various values in an OFDM subblock. The receiver knows the set K in advance for each received symbol. To detect the information, every possible  $K_r$  must be considered.

The detection procedure starts by calculating the LLR values of all the n subcarriers in the g-th subblock. According to (11), for every  $K_r \in K$ , we have

$$\lambda_r^g(\xi) = \ln \left( \sum_{m=1}^M \exp \left( -\frac{1}{N_{0,F}} |Y^g(\xi) - \sqrt{\frac{n}{K_r}} H^g(\xi) s_m|^2 \right) + |Y^g(\xi)|^2 + \ln(K_r) - \ln(n - K_r) \right) \quad (12)$$

$$Y^g(\xi) = Y(n(g - 1) + \xi) \quad (13)$$

$$H^g(\xi) = H(n(g - 1) + \xi) \quad (14)$$

$$\xi = 1, \dots, n \text{ and } s_m \in S \quad (15)$$

Here,  $Y^g(\xi)$  is the  $\xi$ -th received signal in the g-th subblock, and  $H^g(\xi)$  is the  $\xi$ -th channel fading coefficient in the g-th subblock. For BPSK modulation, by using the Jacobian logarithm to prevent numerical overflow, (22) can be further simplified to

$$\lambda_r^g(\xi) = \max(a, b) + \ln(1 + \exp(-|b - a|)) + \frac{|Y^g(\xi)|^2}{N_{0,F}} + \ln(K_r) - \ln(n - K_r) \quad (16)$$

Where

$$a = -|Y^g(\xi) - \sqrt{\frac{n}{K_r}} H^g(\xi)|^2 / N_{0,F} \quad (17)$$

$$b = -|Y^g(\xi) + \sqrt{\frac{n}{K_r}} H^g(\xi)|^2 / N_{0,F} \quad (18)$$

Based on the obtained  $I_r^g$  and  $s_r^g$  for all r,  $I_r^g$  and  $s_r^g$  are regarded as the set of active subcarrier indices and the M-ary constellation symbols carried by these subcarriers if the distance between the assumed transmitted signal (with channel conditions considered) and the received signal is minimum among all r, i.e.,

$$(I_r^g, s_r^g) = \arg \min_{r \in [1, \dots, R]} \left( \sum_{k=1}^{K_r} |Y^g(I_r^g(k)) - H^g(I_r^g(k)) s_r^g(k)|^2 + \sum_{\xi=1}^n |Y^g(\xi)|^2 \right) \quad (19)$$

Thereafter, the obtained  $I_r^g$  and  $s_r^g$  are passed to the index demodulation block at the receiver which performs the opposite action of the index modulation block in Fig.2, to provide an estimate of the p bit input binary string.

## 4. THE SECOND GENERALIZATION OF OFDM -IM

OFDM-IM successively increases the transmitting spectral efficiency and meanwhile improves the BER performance for signals with high SNR under BPSK symbols. However, OFDM-IM becomes ineffective when higher constellation symbols other than BPSK are implemented. However, the proposed OFDM-GIM1 cannot fundamentally solve the problem for QPSK symbols. The second generalization of OFDM-IM, aiming at QPSK constellation symbols is introduced and named as OFDM-GIM2.

### 4.1 Main Concept

The basic idea of our proposed generalization approach is to split the in-phase component and quadrature component into two independent components so that index modulation is applied independently on these two components, i.e., a subcarrier is not necessary to be active or inactive simultaneously for the in-phase and quadrature components. If two independent index modulations are applied to these two independent BPSK streams, the total number of combinations that can be represented is given by

$$2^k C_n^K 2^k C_n^K G = 4^k C_n^K C_n^K G \quad (20)$$

On the other hand, the total combination that OFDM-IM using QPSK represents is  $4^k C_n^K C_n^K G$ . As a result, we have

$$4^k C_n^K C_n^K G > 4^k C_n^K G \quad (21)$$

For example, when  $n = 16, K = 10$ , the total number of bits that our scheme can transmit is given by

$$((\log_2 2^{10} C_{16}^{10}) + (\log_2 2^{10} C_{16}^{10}))G = 44G \quad (22)$$

While the total numbers of bits that OFDM-IM and OFDM can transmit are both

$$(\log_2 4^{10} C_{16}^{10})G = (\log_2 4^n)G = 32G \quad (23)$$



In other words, when  $n = 16, K = 10$ , our proposed OFDM-GIM2 offers a 37.5% higher spectral efficiency compared to OFDM-IM.

### 4.2 Revised Index Modulation Block

Different from OFDM-IM, at the transmitter, the input bit strings allocated to each subblock are equally split into two parts, one for in-phase components' index modulation and the other for quadrature components' index modulation. The outputs of these two index modulation are then combined and constructed into a complex M-ary constellation symbol, as shown in Fig. 2. At the receiver, the revised index demodulation block will simply do the inverse procedures of the revised index modulation block.

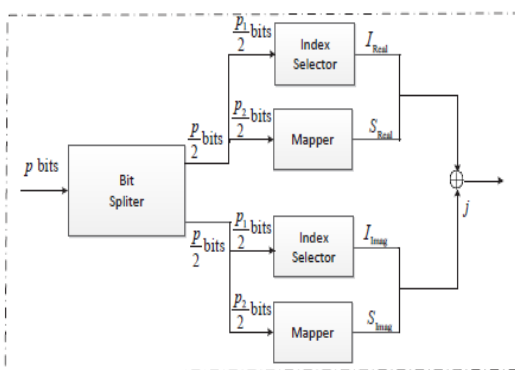


Fig -3: The generalized index modulation block of a subblock for OFDMGIM2.

### 4.3 Revised LLR Detector

The revised LLR detector for OFDM-GIM2 should have zero-forcing equalization first. For the  $\alpha$ -th frequency domain received signal  $Y(\alpha)$ , for  $\alpha = 1, \dots, N$ , let

$$Y''(\alpha) = \frac{Y(\alpha)}{H(\alpha)} \tag{24}$$

After equalization, what the detectors will detect are  $s_m \in S$  instead of  $Hs_m$ . Therefore, the revised LLR detector for the in-phase components is given by

$$\lambda_I(\alpha) = \ln(K) - \ln(n - K) + \frac{H^2(\alpha) |Re(Y''(\alpha))|^2}{N_{0,F}} + \ln\left(\sum_{m=1}^M \exp\left(-\frac{H^2(\alpha)}{N_{0,F}} |Re(Y''(\alpha)) - s_m|^2\right)\right) \tag{25}$$

where  $Re(Y(\alpha))$  returns the real part of  $Y(\alpha)$ . And the revised LLR detector for the quadrature components is given by

$$\lambda_Q(\alpha) = \ln(K) - \ln(n - K) + \frac{H^2(\alpha) |Imag(Y''(\alpha))|^2}{N_{0,F}} + \ln\left(\sum_{m=1}^M \exp\left(-\frac{H^2(\alpha)}{N_{0,F}} |Imag(Y''(\alpha)) - s_m|^2\right)\right) \tag{26}$$

where  $Imag(Y(\alpha))$  returns the imaginary part of  $Y(\alpha)$ . After that, the two sets of LLRs are independently fed to the inverse index modulation block to get an estimate of the input bit string.

## 5 OFDM WITH INTERLEAVED GIM1 AND GIM2

Both OFDM-IM and the proposed OFDM-GIM1 and OFDM-GIM2 suffer from BER performance loss at low SNR. An interleaved subcarrier-index modulation technique was proposed in [22] to mitigate the BER performance loss at low SNR for OFDM-IM. This interleaving technique may also be applied to the proposed. The output of OFDM block creator is first interleaved and then processed by  $N$ -point IFFT in the proposed OFDM with interleaved generalized index modulation, denoted as OFDM-IGIM1 and OFDM-IGIM2, respectively. At the receiver, the received sequence is first processed by  $N$ -point FFT and then deinterleaved. The resultant sequence is then fed to a revised LLR detector proposed for OFDM-IGIM1 and OFDM-IGIM2.

## 6 OFDM WITH INTERLEAVED GENERALIZED INDEX MODULATION 3(OFDM-IGIM3)

The two generalization schemes are adaptable with each other so their combination of OFDM-GIM1 and OFDM-GIM2, is named as OFDMGIM3. As a result, OFDM-IGIM3 represents OFDM with Interleaved GIM3. In the generalized index modulation block employing OFDM-IGIM3, the input bit strings allocated to different subblocks are equally split into two parts, one for in-phase components' generalized index modulation and the other for quadrature components' generalized index modulation. Both index modulations use the block in Fig. 2. The outputs of these two generalized index modulation block are then combined and constructed into one complex M-ary constellation symbol. At the receiver, the index demodulation block will simply do the inverse procedures of the generalized index modulation block.

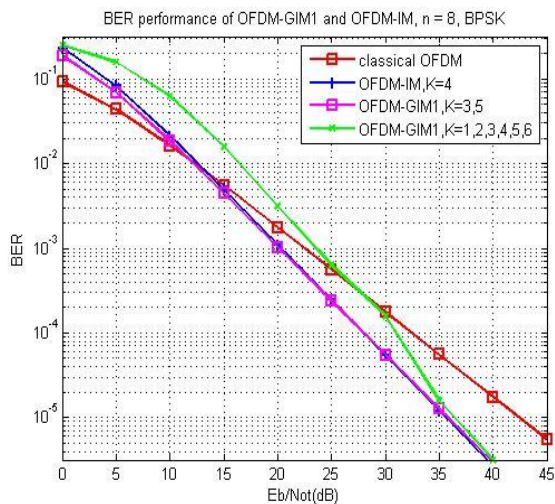
## 6 COMPLEXITY ANALYSIS

For OFDM-IM, the complex multiplications is  $\sim O(M)$  per subcarrier [1] when M-ary constellation symbols are carried. For OFDM-GIM1, the complex multiplications is  $\sim O(RMn)$  per subcarrier. For OFDM-GIM2, the complex multiplications is  $\sim O(2M)$  per subcarrier. The value 2 here indicates the complexity of the independent detections for in-phase and quadrature components. For OFDM-IGIM3, the complex multiplications is  $\sim O(2RMn)$  per subcarrier. The complexity incurred due to interleaving is negligible. Overall, for OFDM-GIM1, OFDM-GIM2, and OFDMIGIM3, the implementation complexity is linear with respect to  $R, M$  and  $n$ .

## 7 SIMULATION RESULTS

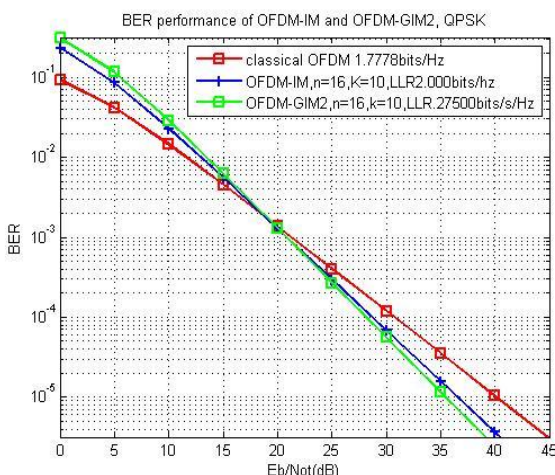
In this section, the simulation results of the proposed schemes are shown and compared with that of OFDM-IM under frequency selective channels. In all simulations, we

assumed the same system parameters as in [1], i.e.,  $N = 128$ ,  $V = 10$  and  $L = 16$ : The SNR is defined as  $E_b/N_{0,T}$  where  $E_b = (N + L)/B$  is the average transmitted energy per bit.



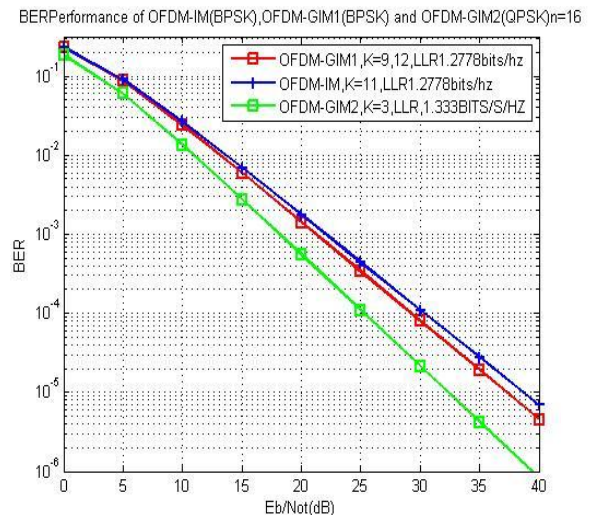
**Fig -4:** BER performance of OFDM-GIM1 and OFDM-IM,  $n = 8$ , BPSK

Fig.4 shows the BER performances of the OFDM-GIM1 schemes with two different  $K$  sets. The sub block size  $n$  is set to 8. When  $K = \{3, 5\}$ , according to (2), it is known that 11 bits can be transmitted per sub block. However, for OFDM-IM with  $n = 8$ , only 10 bits can be transmitted per sub block. Our proposed OFDM-GIM1 scheme achieves 10% higher spectral efficiency at the cost of a BER performance loss lower than 0.5 dB. When  $K = \{1, 2, 3, 4, 5, 6\}$ , according to (2), 12 bits can be transmitted per subblock, and thus a 20% higher spectral efficiency is achieved at the cost of a BER performance loss up to 2.5 dB. The 2.5 dB BER performance loss was observed at the BER probability of  $10^{-3}$ .



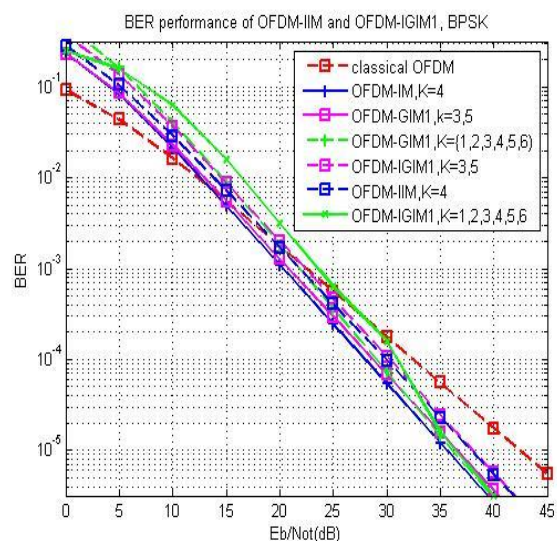
**Fig -5:** BER performance of OFDM-IM and OFDM-GIM2, QPSK

In Fig.5 the sub block size  $n$  is set to 16 and the number of active subcarriers in each sub block  $K$  is set to 10. Our proposed OFDM-GIM2 scheme achieves 37.5% higher spectral efficiency at the cost of up to 1 dB BER performance loss. The 1 dB BER performance loss was observed at the BER probability of  $10^{-3}$ . Then our proposed scheme outperforms OFDM-IM in [13] not only in spectral efficiency but also in BER performance, which clearly demonstrates the superiority of OFDM-GIM2.



**Fig -6:** BER performance of OFDM-IM (BPSK), OFDM-GIM1 (BPSK) and OFDM-GIM2 (QPSK),  $n = 16$ .

Fig.6 shows despite of OFDM-GIM2's a slightly higher spectral efficiency, OFDM-GIM1 and OFDM-GIM2 both achieve better BER performance than OFDM-IM. For our proposed schemes, trade off exists between the BER performance and spectral efficiency.



**Fig -7:** BER performance of OFDM-IM and OFDM-IGIM1, BPSK.



In Fig.7 the subblock size  $n$  is set to 8 and the number of active subcarriers in each subblock  $K$  is set to 4. For OFDM-GIM1 and OFDM-IGIM1, the subblock size  $n$  is also set to 8 and two different  $K$  sets, i.e.,  $K = \{3, 5\}$  and  $K = \{1, 2, 3, 4, 5, 6\}$  are used.

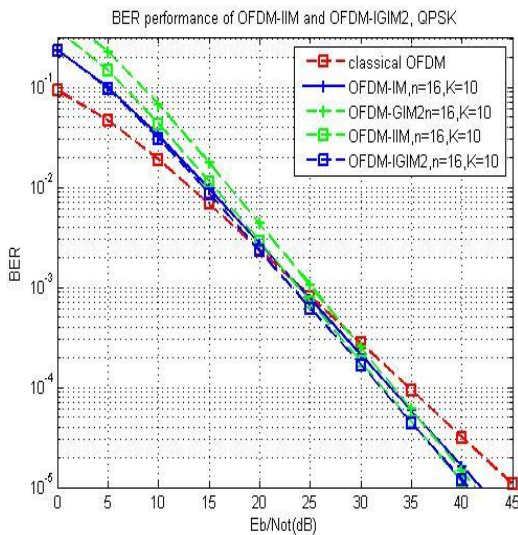


Fig -8: BER performance of OFDM-IIM and OFDM-IGIM2, QPSK.

In Fig.8 the subblock size  $n$  is set to 16 and the number of active subcarriers in each subblock  $K$  is set to 8. Figs. 7 and 8 indicate that compared to OFDM-IM in [1], our proposed OFDM-IGIM1 and OFDM-IGIM2 show significant BER performance improvement and at the same time, achieve higher spectral efficiency. Our proposed OFDM-IGIM1 and OFDM-IGIM2 also show significant BER performance improvement at a cost of negligible interleaving and deinterleaving overhead. Our proposed LLR detector greatly reduces the detection complexity. These comparisons clearly demonstrate the superiority of our proposed schemes.

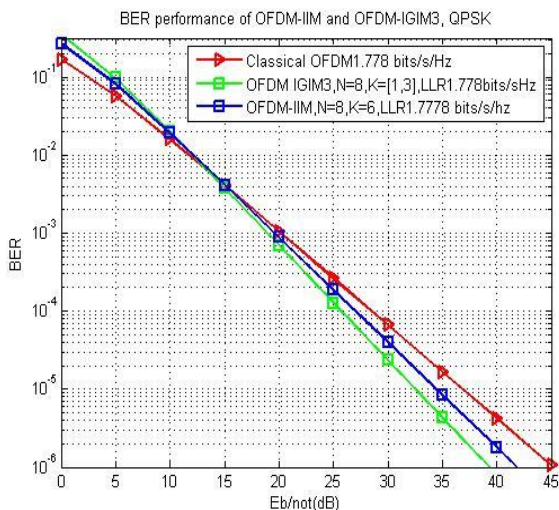


Fig -9: BER performance of OFDM-IIM and OFDM-IGIM3, QPSK

Fig. 6 shows the BER performances of classical OFDM, OFDM-IIM, and OFDM-IGIM3 for QPSK under the same spectral efficiency. Compared to the other 2 schemes, our proposed OFDM-IGIM3 shows significant BER performance improvement.

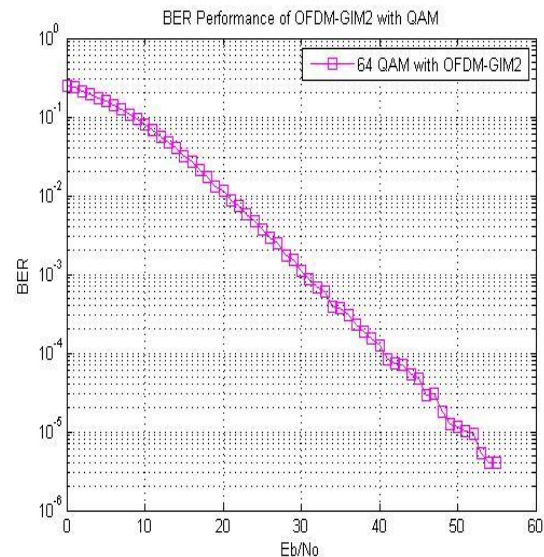


Fig -10: BER performance of OFDM-GIM2,QAM

Fig.10 shows BER performance of OFDM-GIM2,QAM modulation. The 64-QAM is implemented in OFDM-GIM2 which increases the transmission rate when compared to QPSK. The higher order modulation further increases the transmission rate with little higher complexity.

## 8 CONCLUSION

In this paper, two generalization schemes of OFDM-IM are presented. To implement these two schemes, generalized index modulation blocks and upgraded LLR detectors are proposed, respectively. Interleaving is introduced to improve the BER performance of our proposed schemes in low SNR region. Both generalization schemes achieve higher spectral efficiency than OFDM-IM. When the same spectral efficiencies are considered, our proposed generalization schemes show consistent BER performance gain in all SNR regions. We also demonstrate that the two generalization schemes are compatible with each other and their combined scheme is superior to existing works in spectral efficiency and BER performance, at the cost of a little higher complexity. OFDM GIM2 is implemented with QAM higher spectral efficiency is achieved. The scope for future work can be towards reducing BER performance loss in low SNR region.

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