

## Comparative study of selected subcarrier index modulation OFDM schemes

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### Abstract

Orthogonal frequency division multiplexing with subcarrier index modulation (SIM-OFDM) is recently proposed to enhance the performance of traditional OFDM. By incorporating the index modulation in OFDM, the data can be sent on the indices of subcarriers as well as the subcarriers themselves reducing the system complexity. In addition, the Peak to Average Power Ratio (PAPR) and Inter Carrier Interference (ICI) can be reduced by switching on /off some OFDM subcarriers in OOK fashion. In this paper, a comparative study of OFDM with SIM\_OFDM and Enhanced SIM\_OFDM methods in terms of complexity, spectral efficiency and bit error rate over AWGN channel using two power policies is presented. The simulation results showed that at bit error rate of  $10^{-3}$ , SIM\_OFDM and ESIM\_OFDM achieved gains in  $E_b/N_0$  of 1.1 dB and 2 dB over 4-QAM OFDM respectively under power reallocation policy. However, the results also showed that traditional OFDM has better spectral efficiency compared to both SIM\_OFDM and ESIM\_OFDM especially at high  $M$ -ary orders.

**Keywords:** ESIM\_OFDM, index\_modulation, SIM\_OFDM

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### 1. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is one of the most important enabling technology in broadband communications in last decades and crucial part in many wireless standards to meet the increasing requirements for high rate communication systems operating on multipath channels [1-6]. To serve many users and to get a high reliability. In multicarrier system the data is carried on low data rate subcarriers instead of single high data rate as in single carrier system. OFDM used in 4G wireless communication standards and a candidate for 5G due to its tremendous capacity in terms of number of subcarriers [5-7].

Many methods are proposed in the literature to improve the performance of OFDM system. Subcarrier Index Modulation OFDM (SIM\_OFDM) is proposed in [8] and [9] to enhance the performance of OFDM where the data are sent on the indices of subcarriers. BER performance of the SIM scheme in coded and uncoded scenarios are evaluated. The main problem of SIM\_OFDM is the high error rate due to the propagation of error in Additive White Gaussian Noise (AWGN) channel condition. This problem is solved by an enhanced scheme called ESIM\_OFDM, where the indexing is based on the use of subcarrier pairs. A further benefit of their enhanced structure, the Peak-to-average power ratio (PAPR) can be reduced [10]. In [1], a low complexity detector for OFDM with index modulation (OFDM\_IM) is proposed. In [7], a method that combines precoding and partial transmit sequence PTS to reduce the PAPR in SIM\_OFDM is presented. In [8] BER performance of the SIM scheme in coded and uncoded scenarios are evaluated. In [7] improved the SIM structured proposed in [8] and analyzed the PAPR of SIM systems. In [11], two systems are proposed to improve PAPAR and BER of SIM-OFDM. They are named: Half-Symbol BPSK modulated SIM\_OFDM (HS/BPSK/SIM-ODM) and double ASK-SIM. Finally, the authors in [12] studied the effect of Doppler spread in SIM-OFDM compared it with conventional OFDM.

In this paper, detailed descriptions of SIM\_OFDM and ESIM-OFDM methods will be presented. Deep analysis enhanced by numerical examples will be given to understand how these methods act to improve OFDM performance. MATLAB Simulation will be used to evaluate the performances of the two methods under different operating conditions as compared to traditional OFDM system.

**2. The Structure of OFDM and Subcarrier Indexed OFDM Systems**

In this section, the models of SIM\_OFDM and ESIM\_OFDM systems are presented, to better understand these systems and highlight the differences between them and the traditional OFDM system, a description to OFDM system is given first in Figure1.

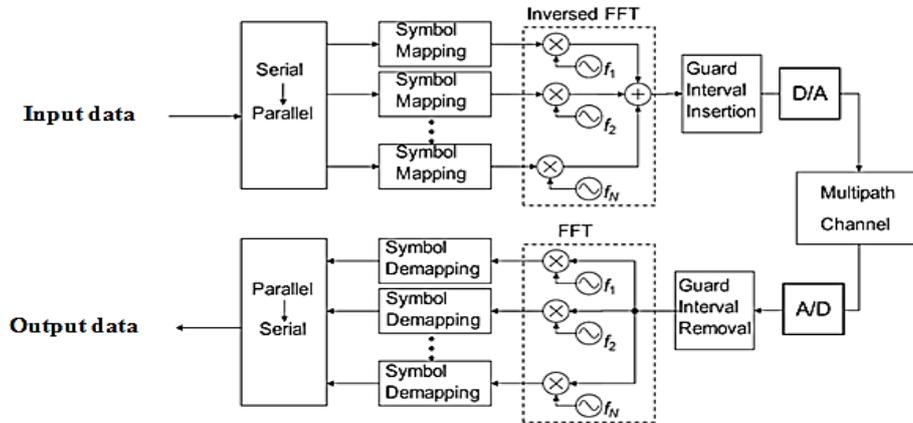


Figure 1. Structure of OFDM [11]

At the transmitter, the input bits are mapped by some modulation such as M-QAM to form QAM symbols which is fed to IFFT block. Then, the samples with guard interval insertion by D/A are converted from digital to analog signal and transmitted over the multipath channel. At the receiver side, the received signal is converted to samples by A/D and guard interval is removed. The samples get back to the original symbols After FFT block [4], [11].

**2.1. SIM\_OFDM**

In SIM\_OFDM method, the data bit-stream B are divided into two parts [8]: one part of the bit streams is transformed to M-QAM symbols as usual and another part used to select the indices of active subcarriers, Figure 2 shows the working principle of SIM\_OFDM system which consist of two functions. Firstly, depending on the value of each  $B_{OOK}$  bit, there are two subsets for  $B_{OOK}$  (ones and zeroes). By count zeros and ones based on  $N/2$  where N is the number of IDFT points, and select the one with the highest count as a majority bit. Secondly, the index of each subcarrier is related to the location of each  $B_{OOK}$  bit. The number of bits of the majority bit-value  $N_{maj}$  can be formulated as:

$$N_{maj} = \max \{ NB_{ook} \text{ ones}, (N_{FFT} - NB_{ook} \text{ ones}) \} \tag{1}$$

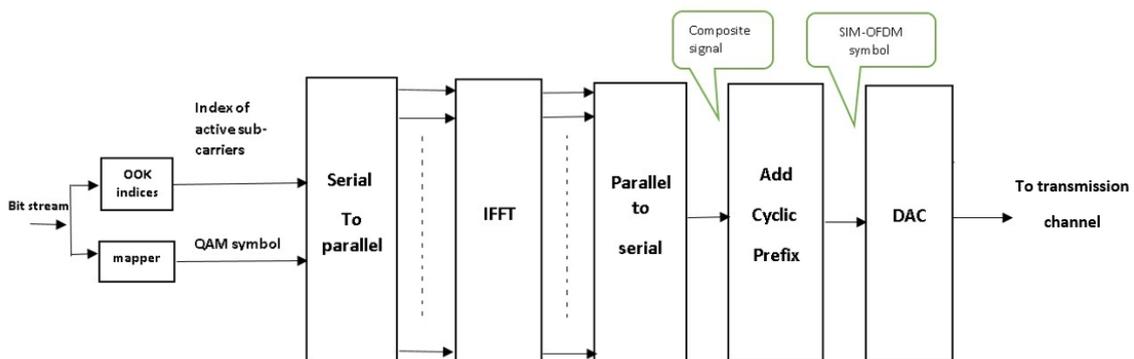


Figure 2. Structure of SIM-OFDM transmitter

the main concept of SIM OFDM is explained in Figure 3.

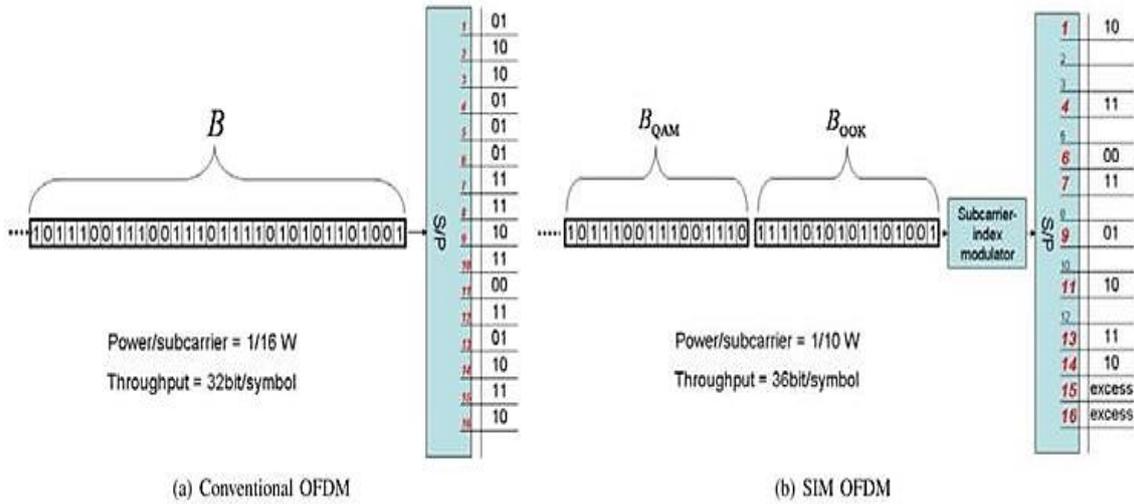


Figure 3. SIM\_OFDM modulation approach [8]

The symbols modulated by classical M-QAM constellation diagram can be represented by  $K_{M-QAM} = \frac{N}{2} \log_2 M$ . In addition, the indices bits can be represented by  $K_{OOK} = N$ . Where N is the total number of subcarriers. Therefore, the total bits per SIM-OFDM symbol  $K_b$  are [8]:

$$K_b = K_{M-QAM} + K_{OOK} = \frac{N}{2} \log_2 M + N \quad (2)$$

### 2.1.1. Power Saving Policy PSP and Power Relocation Policy PRP

For OFDM system, its maximum PAPR value can be written as

$$PAPR_{MAX} = 10 \log_{10}(N) \quad \text{dB} \quad (3)$$

where N is the number of subcarriers. For SIM-OFDM, its maximum PAPR value is:

$$PAPR_{MAX} = 10 \log_{10}(N_{SIM}) \quad \text{dB} \quad (4)$$

here,  $N_{SIM}$  is the number of active subcarriers. Since, in general,  $N_{SIM}$  is less than N, the maximum PAPR value of SIM\_OFDM is smaller than that of ordinary OFDM system. Therefore, SIM\_OFDM can reduce PAPR value to improve the PAPR performance [12]. In PRP, the excess power obtained by switching off some subcarriers can be reallocated to the active subcarriers. Hence SNR increases and BER is improved significantly. PRP  $\gamma_{SC}^{PRP}$  can be written as follows [8]:

$$\gamma_{SC}^{PRP} = 10 \log_{10} \left( \frac{P_{TX}}{E[N_{maj}]} \right) - 10 \log_{10}(n) \quad \text{dB} \quad (5)$$

where  $P_{TX}$  is the total transmit power allocated to the OFDM symbol,  $E[N_{maj}]$  is the average number of majority bit-value, and n is the per-subcarrier average Additive White Gaussian noise (AWGN) power. On the other hand, in PSP the excess power is not reallocated. Hence this leads to lower power consumption. The average SNR of an active subcarrier under PSP  $\gamma_{SC}^{PSP}$  can be written as follows [8]:

$$\gamma_{SC}^{PSP} = 10 \log_{10} \left( \frac{P_{TX}}{N_{FFT}} \right) - 10 \log_{10}(n) \quad \text{dB} \quad (6)$$

**2.2. Enhanced of SIM-OFDM**

In SIM\_OFDM each  $B_{ook}$  bit dictates the state of single subcarrier (active or inactive) this leads to error propagation as illustrate in [10]. In ESIM\_OFDM a single  $B_{ook}$  bit dictates the state of two adjacent subcarriers. The 1bit in the  $B_{ook}$  makes the first subcarrier active and the second subcarrier inactive while 0 bit makes the first subcarrier inactive and the second subcarrier active. In this scheme the require size  $B_{ook}$  bits is reduced to  $N/2$  compared to the original SIM-OFDM scheme which requires  $N$  bits. The advantage of this modification is that for each two consecutive subcarriers only one is active and the other one is inactive this leads to the elimination of the threshold detection and this means that the wrong detection of one subcarrier will not lead to the incorrect detection of the subsequent subcarriers, thus error will be localized. In addition, majority-bit calculation will no longer be required. Figures 4 and 5 illustrate the principle of the new encoding scheme These  $B$  bits are split into  $g$  groups each one having  $p$  bits, i.e.  $B=pg$ , each group of 3-bits is mapped to an OFDM subblock of length  $n$ , where  $n=N/g$  and  $N$  is the number of OFDM subcarriers, i.e., the size of the fast Fourier transform (FFT) [1].

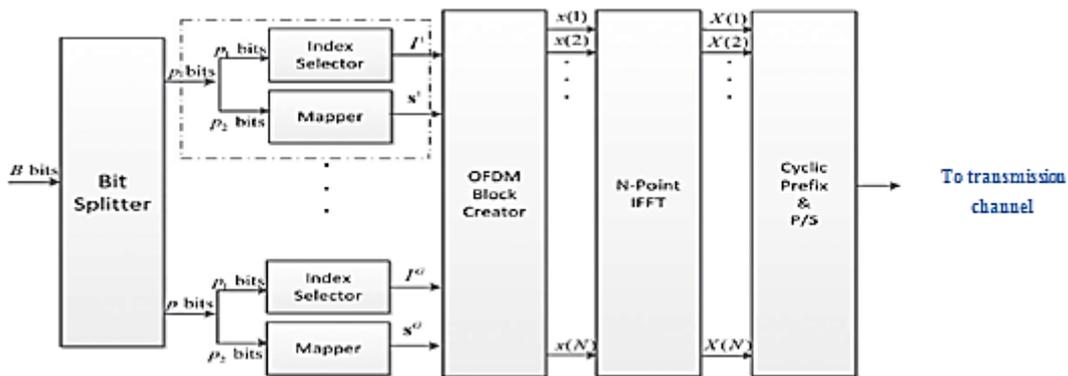


Figure 4. Block diagram of the OFDM\_IM transmitter in [1]

The only disadvantage of the modified scheme, compared to the former SIM\_OFDM, is the slightly reduced spectral efficiency. Spectral efficiency of SIM\_OFDM, measured in bits/carrier, is [10]:

$$\eta_{SIM-OFDM}^{OLD} = \frac{\log_2(M)}{2} + 1 \tag{7}$$

while the spectral efficiency of the enhanced SIM\_OFDM is

$$\eta_{SIM-OFDM}^{enhanced} = \frac{\log_2(M)}{2} + \frac{1}{2} \tag{8}$$

To mathematically prove that ESIM uses less bits as compared to SIM\_OFDM, consider the following numeric example: using (2) for SIM\_OFDM and assuming that  $N=8$ , and 4\_QAM modulation ( $M = 4$ ),  $\frac{8}{2} \log_2 4 + 8 = 16$  bits are transmitted per SIM\_OFDM symbol, while in ESIM\_OFDM,  $K_b$  bits are  $\frac{8}{2} \log_2 4 + \frac{8}{2} = 12$  bits are transmitted per ESIM\_OFDM symbol i.e. half number of  $K_{ook}$  bits are used and to improves the spectral efficiency of ESIM\_OFDM, all subcarriers are divided and involved into blocks each block has a fixed number of subcarriers. If  $L$  is the number of subcarriers in each block, and  $La$  is the number of active carriers of block, a general expression for the spectral efficiency becomes  $L!$  This can be written as [10]:

$$\eta_{SIM-OFDM}^{general} = \frac{La \log_2 M}{L} + \frac{\left\lceil \log_2 \left( \frac{L!}{La!(L-La)!} \right) \right\rceil}{L} \tag{9}$$

$$\eta_{OFDM} = \log_2 M \tag{10}$$



Figure 6 shows BER versus  $E_b/N_0$  for 4QAM\_OFDM and SIM\_OFDM with PSP. This figure shows that although SIM-OFDM with PSP, the power used is half the power required by OFDM but there is a degradation in BER performance. For instance, at  $BER=10^{-3}$ , the loss in  $E_b/N_0$  is 1.9 dB with PRP being used, the BER of SIM\_OFDM is improved and becomes comparable to OFDM when  $E_b/N_0$  exceeds 4 dB as illustrated in Figure 7. It can be noticed that at  $BER=10^{-3}$ , SIM\_OFDM outperforms OFDM by around 1.1 dB. This improvement is due to two reasons: Firstly, the power of activated subcarrier is increased, improves the detection quality of the signal constellation symbols. Secondly, the inherent high error rate performance of the coherent OOK detector, used to estimate the subcarrier activity, enhances the overall BER performance [8].

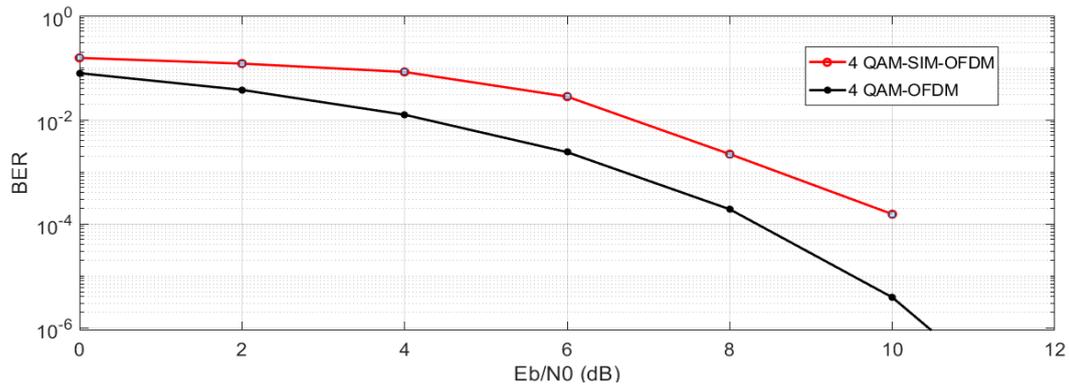


Figure 6. BER versus  $E_b/N_0$  for 4QAM\_OFDM and SIM\_OFDM with PSP

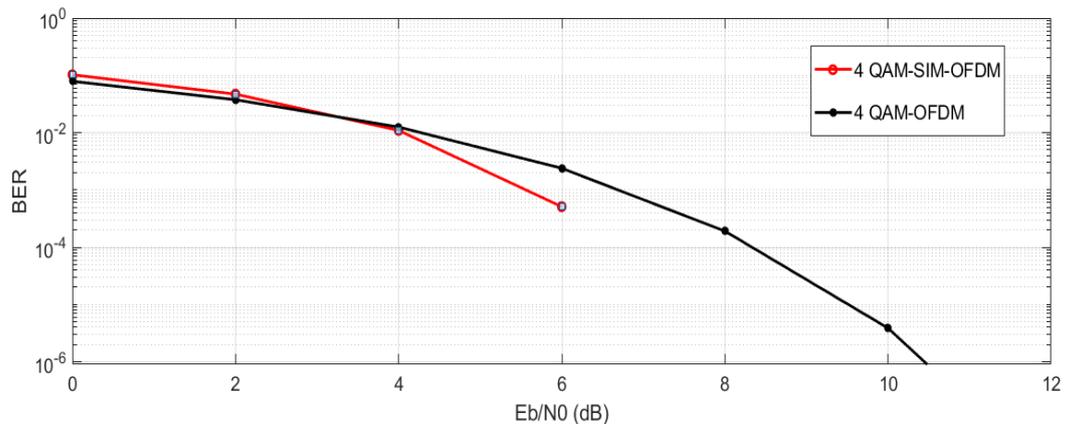


Figure 7. BER versus  $E_b/N_0$  for QAM\_OFDM and SIM\_OFDM with PRP

Figure 8 shows BER versus  $E_b/N_0$  for 4QAM\_OFDM and ESIM\_OFDM with PRP. The depicts clearly that ESIM\_OFDM effectively improves the Bit Error Rate performance. For instance, when BER is  $10^{-3}$ , ESIM\_OFDM achieves 2 dB gain in  $E_b/N_0$  over QAM\_OFDM. This is because the allocated transmit power per subcarrier increases when PRP is used, which yields in improved error rate performance compared to conventional OFDM. However, when PSP is used instead of PRP the performance of ESIM\_OFDM lags about 0.9 dB behind traditional OFDM as shown in Figure 9. Finally, the spectral efficiency of QAM\_OFDM is better than both SIM\_OFDM and ESIM\_OFDM especially at higher M values as illustrated in the performance curves shown in Figure 10 which are plotted using (7), (8) and (10). Figure 11 shows PAPR performance results of QAM\_OFDM, SIM\_OFDM and ESIM\_OFDM. It can be seen in this figure that SIM-OFDM has relatively worse PAPR performance compared to QAM\_OFDM. But from other hand ESIM\_OFDM has comparable performance to QAM\_OFDM.

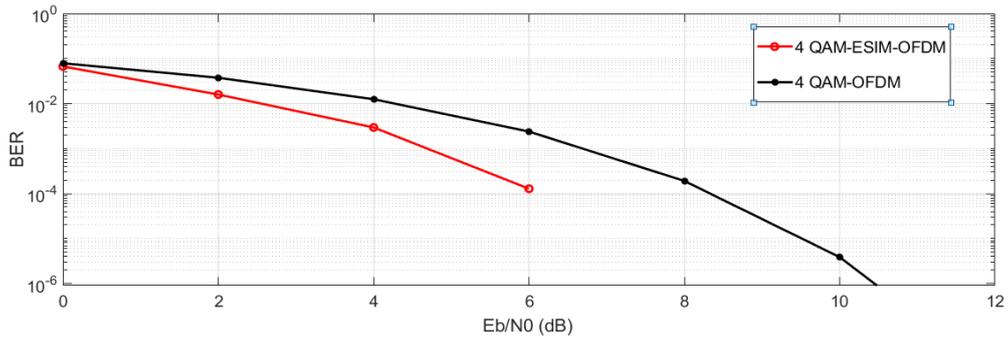


Figure 8. BER versus  $E_b/N_0$  for QAM\_OFDM and ESIM\_OFDM with PRP

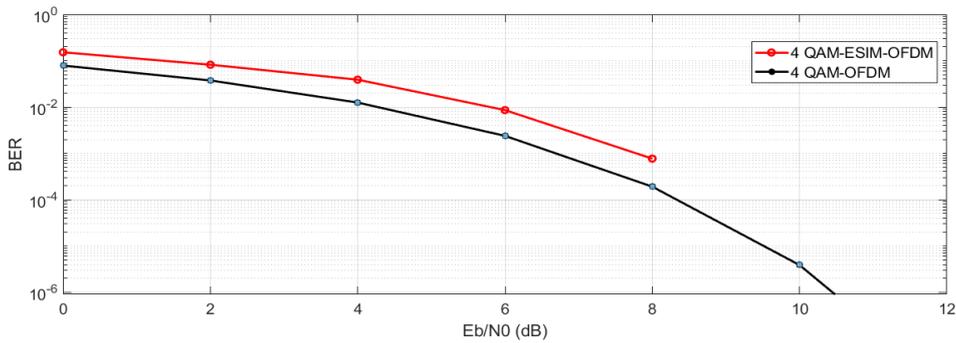


Figure 9. BER versus  $E_b/N_0$  for QAM\_OFDM and ESIM\_OFDM with PSP

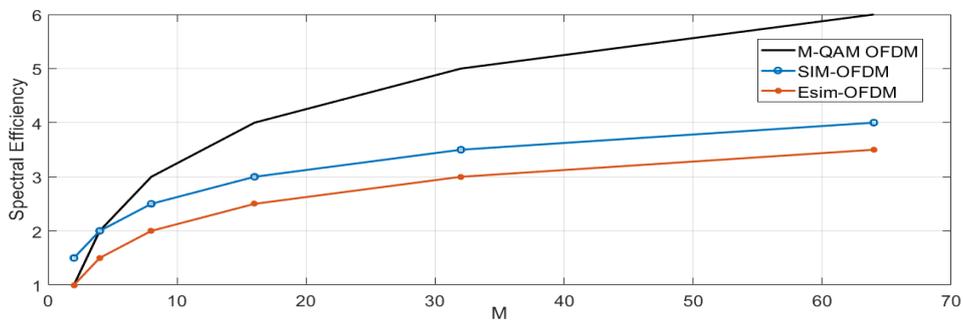


Figure 10. Spectral efficiency for OFDM, SIM\_OFDM and ESIM\_OFDM

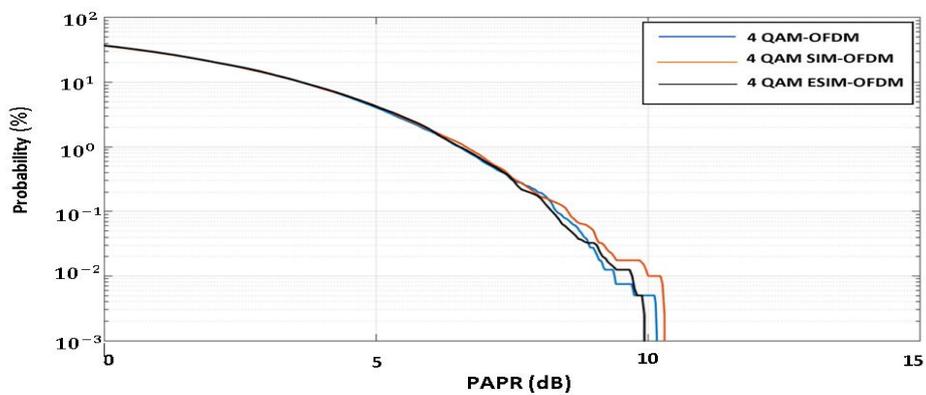


Figure 11. PAPR for 4QAM\_OFDM, SIM\_OFDM and ESIM\_OFDM

#### 4. Conclusions

SIM\_OFDM uses OOK bits for activating and/or deactivating some of the available subcarriers so each active OOK bit indicates the location of the active subcarrier and QAM symbol will be carried on this active subcarrier. If an incorrect detection is made to OOK bit this leads to incorrect demodulation not only to the QAM symbol it encodes but also to all consecutive QAM symbols. This is because they will have carried on incorrect sequence of the active subcarriers and in causes error propagation so for this reason ESIM was found to solve this problem by localizing errors, which supposed that each OOK bit control the state of two consecutive instead of one as in SIM\_OFDM. When 4-QAM is used, each active sub carrier will carry two bits and if there is any occurrence of error the total loss of transmitted bits will be three only in this case (1 for OOK and the rest for QAM symbol bits that transmitted on that active subcarrier), in other word, it leads to incorrect demodulation for the QAM symbol it encodes. When using PRP the allocated power per subcarrier is increased, this yields in improved BER performance compared to classical OFDM.

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