BER PERFOMANCE OF OFDM-IM SYSTEM IN FADING CHANNELS

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Abstract — Orthogonal frequency division multiplexing (OFDM) with index modulation (IM) is a recently proposed modulation technique for performance improvement of OFDM based systems. The basic concept of this modulation scheme assumes that the information is conveyed to the receiver by standard *M*-ary signal constellations and, at the same time, by the indices of the active OFDM subcarriers which are chosen for carrying those constellation symbols. Due to the additional information bits transmitted in that way, spectral efficiency of the system is increased, as well as energy efficiency, because not all OFDM subcarriers are active in transmission. However, these performance improvements are achieved at the price of bit error rate (BER) degradation at lower signal-to-noise ratio (SNR) values. In this paper we examine BER performance of OFDM-IM system in case of frequency selective fading channels, assuming both Rayleigh and Rician fading statistics.

1. INTRODUCTION

Multicarrier transmission techniques are now widely accepted in high speed wireless communications systems. Among them, OFDM (Orthogonal Frequency Division Multiplexing) represents a dominant and well-established multicarrier technique, due to its ability to deal with deteriorate effects of multipath propagation, as well as due to its high spectral efficiency. Namely, OFDM is very robust to frequency selectivity of multipath fading channel, as it turns this type of channel in a set of parallel frequency-flat channels, and it can efficiently cope with inter-symbol interference (ISI) by introducing guard interval (GI), thus providing high speed communications in highly unfavorable channel conditions. As such, OFDM is integrated in many contemporary wireless communication standards, such as LTE, LTE-Advanced, IEEE 802.11a/g/n/ac WLAN (Wireless Local Area Network) standards, WiMAX, DAB (Digital Audio Broadcasting), DVB-T (Digital Video Broadcasting – Terrestrial) standards, etc., [1]. There is still strong research interest for performance improvement of OFDM modulation, in order to enable its implementation

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in different upcoming communication systems, and to provide smooth transition towards new generation of wireless communication systems.

One of the newly proposed concept is OFDM with Index Modulation (OFDM-IM), which is introduced as an extension of spatial modulation (SM) principle, originally referring to multiple-input-multiple-output (MIMO) systems. SM represents an alternative to existing MIMO transmission techniques. Essence of SM is that information is conveyed by means of standard amplitude/phase modulations, as well as by selection of indices of active antennas, [2]. The same principle has been proposed for OFDM subcarriers. Namely, information is transmitted by M-ary signal constellations, in the same way it is transmitted in classical OFDM system, as well as by combination of active subcarriers. Each subcarrier has its own index and transmission subcarriers are selected by their indices, depending on incoming information bits. In this way, the system spectral efficiency is increased, as additional information are assumed to be transmitted to destination, just through selection of certain subcarriers. Thus, for example, in OFDM-IM system having 2^N subcarriers, let us assume that only one subcarrier is used for information transmission. Each subcarrier index can be represented by combination of N bits. Information bits are splitted into two flows, where one flow is used for creating M-ary symbol constellation to be transmitted, and the other flow, having N bits, denotes which subcarrier should be selected for transmission of the created symbol.

OFDM-IM has been first time considered in [3], and after that, many researchers have analyzed its performance, as well as different modifications have been proposed, [4]-[10]. According to [4], OFDM-IM uses frequency selectivity as a benefit, boosting in this way performances of the system in time/doubly dispersive fading channels. If compared to classical OFDM system (in the following text denoted as ”OFDM” system), spectral efficiency can be increased due to additional bits transmitted, as well as energy efficiency, because only a part of subcarriers is being used. Increase in spectral efficiency of OFDM-IM system has been obtained at the expense of slightly worse BER performance, compared to OFDM. However, for high signal-to-noise ratios (SNR) values, OFDM-IM can reach, or even outperform OFDM system, in terms of BER performance [5].

In [4], two different ways for mapping information bits into groups of active subcarriers were proposed. The first method is a simple look-up table, which contains connections between specific combinations of incoming bits and corresponding indices that are activated for transmission. Look-up table is implemented together with Maximum-Likelihood (ML) detector at the receiver. In case of a larger group of OFDM subcarriers, look-up table should contain a huge number of registrations, which makes this method impractical. Therefore, another technique based on combinatorial number theory has been proposed, which determines combination of active indices of subcarriers on the basis of input bits, whereas Log-Likelihood Ratio (LLR) detector is employed at the receiver side. In [6], generalization schemes for OFDM-IM have been presented, OFDM with generalized index modulation 1 (OFDM-GIM1) and OFDM with generalized index modulation 2 (OFDM-GIM2). The idea of OFDM-GIM1 is that number of active subcarriers in OFDM subblocks can be different and not constant, as it was the case in OFDM-IM. Another generalization of OFDM IM, called OFDM-GIM2 takes into consideration separation of „in-phase“ and „quadrature“ components of subcarriers, so that index modulation is applied independently to these two components. Further on, in [7], an interleaved subcarrier index modulation technique has also been proposed to mitigate poor BER characteristics for lower SNR values with OFDM IM.

As it can be seen from the given overview, OFDM-IM has attracted lately a lot of attention of researchers and some possible applications of this concept have already been suggested. OFDM-IM can be interesting candidate for low-power, wide range communications, as only few subcarriers can be used for information transmission in different IoT (Internet of Things) based applications, [10]. It is also interesting candidate for 5G mobile communication systems, [10]. Some authors have also explored and suggested the possibility of application of OFDM-IM to V2X (vehicular to everything) communications, [11]. In [12], OFDM-IM has been proposed for Underwater Acoustic (UWA) communications. OFDM has already been recognized as a strong candidate for UWA communications, because of its robustness to intersymbol interference. However, OFDM-IM system can be regarded as even stronger candidate, because certain number of subcarriers remains inactive, which also mean a lower level of intercarrier interference (ICI).

In our research work, we have created simulation model of OFDM-IM system, and we examine BER performances in cases of Rayleigh and Rician fading channels, for different realizations of OFDM index modulation, assuming LLR detection. The obtained BER performances are compared to BER performance of the OFDM system in the same channel conditions, and we also provide insight in spectral efficiency enhancement achieved with OFDM-IM. The paper is organized as follows. Section 2 provides description of the OFDM IM system model. Section 3 gives BER simulation results of the analyzed systems and their discussion, while Section 4 concludes the paper.

2. SYSTEM MODEL

Fig. 1 presents block-scheme of OFDM-IM transmitter.

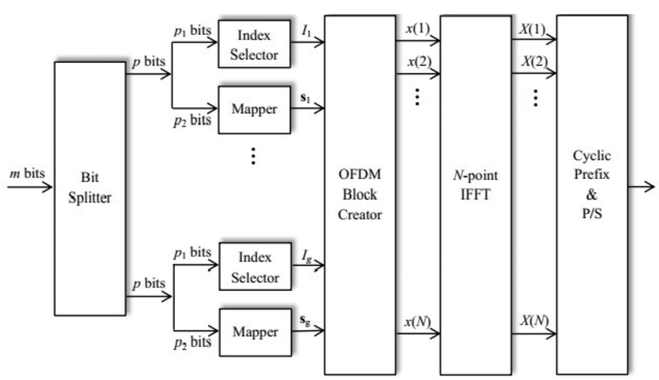

Fig. 1. Block-scheme of OFDM-IM transmitter

In OFDM-IM transmitter, a total number of N OFDM subcarriers are divided into g groups, each having $n=N/g$ subcarriers. Information entering the system are splitted into g groups of p bits in the bit splitter, thus having $m=p\bullet g$. After bit splitter block, in each of the g branches, p bits are again subdivided into two groups having p_1 and p_2 bits, where $p_1+p_2=p$. As it is earlier explained, in OFDM-IM system, information are transferred to receiver not only by data symbols, but also through selection of appropriate subcarriers to be used for symbol transmission, as each subcarrier has its own index. In that manner, p_2 information bits in each sub-branch are mapped to M-ary symbol constellations, while p_1 bits are going into index selector block, and are used for selecting k active subcarriers, which will be used to transmit M-ary symbols, from total number of n subcarriers contained in each of g groups.

Number of bits used for selection of indices can be presented as:

$$p_1 = \log_2\left(C\left(n,k\right)\right), \tag{1}$$

where $C(n,k)$ is a binomial coefficient. Remaining p_2 bits are being mapped into M-ary symbols that are going to be transmitted by k active subcarriers. From this, it follows that:

$$p_2 = k \cdot \log_2 M \, . \tag{2}$$

At the level of the entire OFDM block,

$$g \cdot p_1 = g \cdot \log_2\left(C\left(n,k\right)\right) \tag{3}$$

bits are transmitted by selecting the active indices, and

$$g \cdot p_2 = g \cdot k \cdot \log_2 M \tag{4}$$

are transmitted by M-ary symbols.

The created M-ary symbols are going to be transmitted by selected subcarriers, while the rest of subcarriers are remaining inactive, i.e. they are set to zero. This process is carried out by OFDM block creator. After this block, standard OFDM modulation is performed, which means that signal goes through N-point IFFT, then parallel-to-serial conversion and cyclic prefix addition.

Index selector can be implemented in two ways, [4]. One way is realization by employing a simple look-up table, which is used on both transmitter and receiver sides. At the transmitter side, the active indices are read from the table depending on incoming p_1 bits, while at the reception the opposite action is taking place. This method is simple but efficient only for small values of n and k, because it is not practical to work with large look-up tables. At the reception side maximum likelihood (ML) detector is used, because it needs to have an information about all possible indices combinations. Log-likelihood Ratio (LLR) detector cannot be used with a look-up table, because it cannot make a decision, if detected combination of indices does not exist in the table. Table 1 presents an example of look-up table.

Table 1. Example of look-up table

Bits	***Indices***
[0 0]	{1,2}
[0 1]	{1,3}
[1 0]	{2,3}
[1 1]	{1,4}

In the given example, n=4, k=2, p_1=2. There are six possible combinations of the k=2 active subcarriers, in the group of n=4 subcarriers. However, since two bits (p_1) can map four combinations of active indices, then two combinations (2,4), (3,4) will not be used. Assuming that binary phase shift keying (BPSK) is used, then 2 bits are transmitted as BPSK symbols on 2 active subcarriers (k=2, p_2=2). Therefore, in this example, number of bits transmitted by each of the g branches is p_1+p_2=4. More specifically, if sequence of bits entering the first branch of the OFDM-IM transmitter is, for example [0 1 1 0], this means that the first p_1=2 bits (0 1), point on the first and the third subcarriers to be active in this transmission (from the look-up table). The following p_2=2 bits (1 0) are mapped into BPSK symbols to be transmitted on the selected subcarriers, i.e. the bit 1 will be transmitted on the first subcarrier, while the bit 0 will be transmitted on the third subcarrier.

ML detector takes into consideration all possible realizations and makes a joint decision about active indices and constellation symbols for each subblock.

The other way of index selection is the method of combinatorial numbers, which represents mapping of natural numbers into strictly descending sequence of active indices. Bits entering the index selector are first converted into decimal number Z, by means of binary-to-decimal convertor. The sequence of active indices $J(c_k, c_{k-1} ..., c_1)$, $c_k \geq c_{k-1} \geq \ldots \geq c_1$, $c \in [0,\ldots,n\text{-}1]$, can be calculated using the equation:

$$Z = C\left(c_k, k\right) + C\left(c_{k-1}, k-1\right) + \ldots + C\left(c_1, 1\right) \tag{5}$$

In (5), c_k values are calculated by finding the maximal c_k satisfying the condition: $C(c_k,k) \leq Z$, and after that finding maximal c_{k-1}, for which it is satisfied $C(c_{k-1},k\text{-}1) \leq Z\text{-}\ C(c_k,k)$ and so on. Actual indices of subacarriers to be used for transmission are then obtained by adding 1 to obtained c_k values, because the subcarriers set of indices are $[1,\ldots n]$. The same algorithm is used at the receiver side for obtaining number Z from active indices and afterwards for converting it into the sequence of bits, by means of decimal-to-binary converter.

For example, let us assume an OFDM-IM system with n=8 subcarriers in each of the g groups, and k=4 active subcarriers per group. Based on the relation (1), p_1=6 bits are needed for mapping the active subcarriers. If BPSK modulation is used then p_2=4, thus having that

$g\cdot(p_1+p_2)=g\cdot10$ bits are delivered to the receiver per one OFDM symbol. If the sequence of bits entering the branch is [0 1 0 1 1 1 0 1 1 0], then the first p_1=6 bits (0 1 0 1 1 1) are going through the index selector block and are used for selection of active subcarriers, while the following p_2=4 bits (0 1 1 0) are mapped to BPSK symbols. Bits (0 1 0 1 1 1) entering the index selector are converted into the decimal number 23. Since we have k=4 active subcarriers in this example, the next step is finding maximal $C(C_4,4)$, then maximal $C(C_3,3)$, $C(C_2,2)$ and maximal $C(C_1,1)$, that satisfy the relation (5), for Z=23. Maximal C_4 satisfying this condition is 6, since $C(6,4)=15 < 23$. In the next step C_3 is calculated (C_3=4, since $C(4,3)=4 < 23-15=8$), then C_2 (C_2= 3, since $C(3,2)=3 < 23-15-4=4$), and C_1 (C_1=1, since $C(1,1)=1=23-15-4-3$). Finally, active subcarriers are calculated by adding 1 to the obtained values of C_k set (6,4,3,1), thus having their indices to be (7,5,4,2). Remaining p_2=4 bits (0 1 1 0) are then transmitted as BPSK symbols, on subcarriers with indices 7, 5, 4 and 2.

The described method is implemented with LLR detector. LLR detector determines the logarithmic ratio between a-posteriori probabilities that on the given subcarrier is transmitted a symbol or zero. If y_f represents the received signal, and x represents the sent signal in frequency domain and s_i, $i\epsilon[1,\ldots,M]$ is modulation alphabet, then for each subcarrier α, the value of $\lambda(\alpha)$ is:

$$\lambda(\alpha) = \ln \frac{\sum_{i=1}^{M} P(x(\alpha) = s_i \mid y_f(\alpha))}{P(x(\alpha) = 0 \mid y_f(\alpha))} \tag{6}$$

The higher value of $\lambda(\alpha)$ denotes the higher probability that subcarrier α was active in the transmission. In each OFDM subblock, out of n subcarriers, the highest k values of $\lambda(\alpha)$ marks k subcarriers that were selected to be active at the transmitter side. After that, evaluation of the first p_1 transmitting bits is provided from the estimated active indices, by means of algorithm opposite to the one applied at the transmitter side. The remaining p_2 transmitted bits are discovered by demodulation of the constellation symbols on active subcarriers.

3. SIMULATION RESULTS

In this section, performances of OFDM-IM system, in terms of bit error rate (BER), are evaluated. Active subcarriers are modulated using BPSK, with different system parameters, while LLR detector is implemented at the receiver side.

A. Simulation model

The subsequent presented simulation results assume perfectly synchronized OFDM-IM system. Simulation results are obtained through Monte Carlo simulations. Only the frequency domain part of the OFDM-IM system is taken into consideration, which is possible approach, as perfectly time and frequency synchronization is assumed. Subcarriers' channel transfer functions are generated as zero mean (or non-zero mean for Ricean fading channel), independent, circularly symmetric complex Gaussian random variables, with variances 1/2, so their magnitudes are Rayleigh (Ricean) distributed.

B. BER performance assessment

We have chosen to present BER performance comparison between the OFDM and OFDM-IM system having the same, or approximately the same spectral efficiency as OFDM. Rayleigh fading channel is assumed. OFDM-IM with *n*=16 and *k*=5 needs 12 bits for selecting indices of active subcarriers and 5 bits are transmitted by constellation symbols in each group, which is $g{\cdot}17$ bits in total per OFDM-IM symbol, while OFDM transmits $g{\cdot}16$ bits per symbol to be carried on $g{\cdot}16$ subcarriers. However, as OFDM-IM uses only $g{\cdot}5$ active subcarriers per symbol, it provides more than 68% energy efficiency improvement, at the price of worse BER performance for lower E_b/N_0 values.

OFDM-IM scheme with *n*=8 and *k*=3 uses 5 bits for selecting the indices of active subcarriers and 3 bits for creating symbol constellations to be transmitted per group, which is $g{\cdot}8$ bits per OFDM-IM symbol in total, i.e. the same as in the OFDM system with $g{\cdot}8$ subcarriers. In this case, OFDM-IM uses only $g{\cdot}3$ subcarriers for a symbol transmission, which means that it has 62% better energy efficiency than the OFDM system.

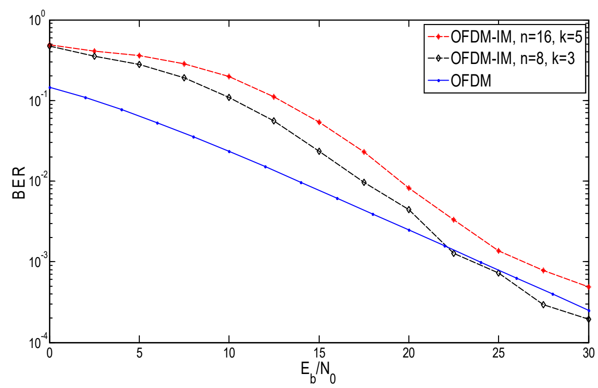

Fig. 2 BER performances of OFDM and OFDM-IM in Rayleigh fading channel

The results presented at Fig. 2 confirm that OFDM system has better BER performances than OFDM-IM systems for the low and medium values of E_b/N_0. However, for the higher E_b/N_0 values, OFDM-IM system may prevail in BER performances. Thus, we have that OFDM-IM with configuration *n*=8, *k*=3 achieves lower BER values than the OFDM for E_b/N_0 higher than 24dB. From the Fig. 2 we can also conclude that BER of OFDM-IM system strongly depends on the system configuration, i.e. on the total number of the subcarriers per group (*n*), and the number of the active subcarriers (*k*). Namely, as it can be seen in Fig. 2, OFDM-IM system having *n*=8, *k*=3 does not reach BER performances of the OFDM system for all the presented E_b/N_0 values up to 30dB.

In the following, we examine influence of the number of active subcarriers on BER performances of the OFDM-IM systems. Thus, we give simulation obtained BER results for different configurations of OFDM-IM system, i.e. for different number of active subcarriers (k=2, k=8 and k=13) in a system having n=16 subcarriers in each of the g groups. Rayleigh fading channel statistics is modeled.

Among the considered systems, the highest spectral efficiency is achieved for n=16 and k=13. Namely, this system uses 9 bits for selection of the active subcarriers in each group, and $g \cdot 13$ bits are transmitted through the BPSK symbol mapping. System configuration with n=16 and k=2 is the most energy efficient among the presented ones, as it uses only $g \cdot 2$ active subcarriers per OFDM-IM symbol, while $g \cdot 6$ bits are delivered to the receiver through indices of the active subcarriers. The third configuration, having n=16 and k=8 represents a trade-off between the previous two systems. It transmits $g \cdot 8$ bits which are used for symbol mapping and $g \cdot 13$ bits per OFDM-IM symbol are contained in indices of the selected active subcarriers.

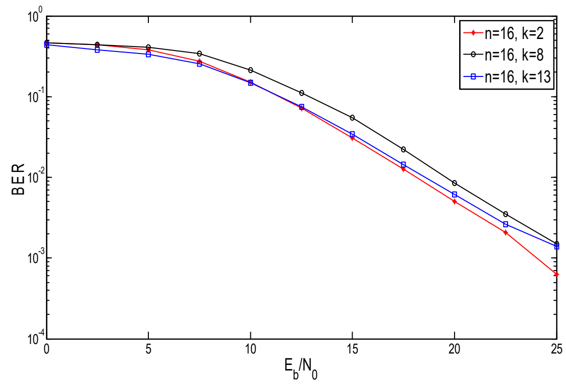

Fig. 3 BER performance of OFDM-IM system with different configurations

From the Fig. 3 it is clear that the worst BER performances has the system with exactly 50% of the active subcarriers (k=8, n=16). Increasing or decreasing the number of active subcarriers brings improvement in BER performances. Thus, for example, for the BER value of 10^{-2}, the system with k=8 needs about 1dB higher E_b/N_0 than the two other system configurations considered. It is also interesting to notice that the best BER performance for E_b/N_0 values above 10dB has the most energy efficient system (with k=2), while for the lower E_b/N_0, the most spectral efficient system among the analyzed ones, with k=13, attains the lowest BER values.

Fig. 4 presents BER performances of OFDM and OFDM-IM systems in both Rayleigh and Rician fading channels. In the case of Rician fading, the Rician K factor is assumed to be 8dB. For the OFDM-IM system a configuration with n=16 and k=8 is modeled.

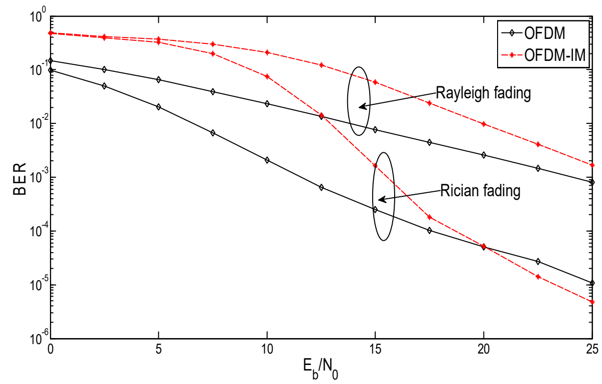

Fig. 4 BER performances of OFDM and OFDM-IM in Rayleigh and Rician fading channels

If we analyze the obtained BER results, it can be seen that for the scenario with Rician fading, OFDM-IM system prevails in BER performances over OFDM system at lower E_b/N_0 values, when compared to scenario with Rayleigh fading. Thus, for example, the OFDM system is outperformed in terms of BER by OFDM-IM for E_b/N_0 values of above 20dB. On the other side, in the scenario with Rayleigh fading, OFDM attains better BER performances for all the presented E_b/N_0 values up to 25dB.

At the Fig. 5, BER performances of OFDM and OFDM-IM systems are compared. Rician fading channel is assumed. Two cases are analyzed, with Rician K factor of 8dB and 10dB. The analyzed OFDM-IM system has n=16 subcarriers, and k=8 active subcarriers in each group.

As it is expected, BER performances of both OFDM and OFDM-IM systems are significantly better in case where Rician K factor is 10dB. For example, for BER value of 10^{-5}, OFDM-IM system in Rician fading channel characterized with the K factor of 8dB, has about 5dB worse performance than the same system in the channel having K=10dB. It can also be seen that for the scenario where K=8dB, OFDM-IM outperforms OFDM system in terms of BER performance, for E_b/N_0 values above 20 dB, while for K=10dB, OFDM-IM achieves the same BER performance like OFDM system for E_b/N_0 value about 19dB.

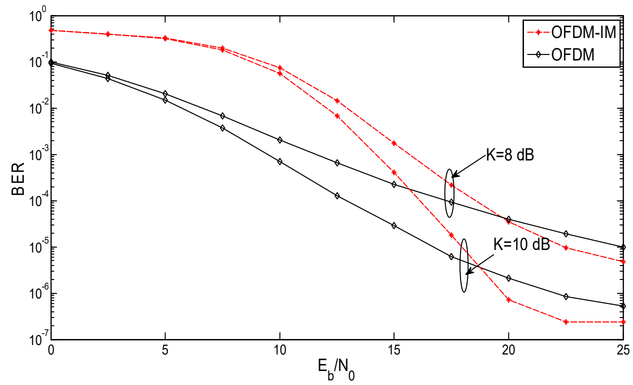

Fig. 5 BER performances of OFDM and OFDM-IM in Rician fading channel

4. CONCLUSIONS

The main idea of index modulation in OFDM system (OFDM-IM) is that additional information can be conveyed to receiver by selecting the appropriate subset of subcarriers for transmission. Index modulation applied in OFDM system brings energy efficiency improvement, and, depending on the number of the selected active subcarriers, can also significantly increase spectral efficiency. Due to these advantages over OFDM system, OFDM with IM can be considered as a very interesting multicarrier transmission technique for the future wireless communications. Various systems are already considering possible deployment of OFDM-IM concept, such as low-power communication, 5G mobile communication systems, V2X systems and underwater acoustic communications (UWA).

In this paper, BER performance of OFDM-IM system is examined for different system configurations, in terms of the total number of subcarriers per group, and in the number of the active subcarriers in system. Presented results are obtained in different fading channel conditions, i.e. in Rayleigh and Rician fading channels. These results of OFDM-IM BER performance are compared to BER performance of OFDM system. It has been shown that for lower E_b/N_0 values, OFDM system achieves better BER performances than OFDM-IM, but with increase of E_b/N_0 values, OFDM-IM is performing better, and can even outperform OFDM in terms of BER. It has also been shown that in good channel conditions, like it is in the case where exists direct line of sight communications (Rician fading), OFDM-IM prevails in BER performance over OFDM system at E_b/N_0 values about 19dB (Rician K factor of 10dB). In the case of Rayleigh fading statistics, OFDM-IM system outperforms OFDM for E_b/N_0 values above 25dB.

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