Multidiszciplináris tudományok, 12. kötet, 2. sz. (2022), pp. 112-122 **https://doi.org/10.35925/j.multi.2022.2.11**

AN OVERVIEW ON PAPR REDUCTION TECHNIQUES IN OFDM-IM

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Abstract

This paper is concerned with the novel multicarrier transmission technique, Orthogonal Frequency Division Multiplexing (OFDM) based on Index Modulation (IM), which acts as an alternative for conventional OFDM. The system generally shows improvements over conventional OFDM in achieving lower bit error rate, higher spectral efficiency, and better energy efficiency. Making it useful for various applications such as battery-powered communication devices, visible light communication, massive machine type communications, etc. Accordingly, becoming a suitable candidate for the next generation of wireless communication. In spite of its advantages over conventional OFDM, and due to their similarity, OFDM-IM suffers from the problem of high Peak to Average Power Ratio (PAPR). In this paper, a thorough review of the published works regarding PAPR reduction schemes in OFDM-IM is presented.

Keywords: *Orthogonal Frequency Division Multiplexing (OFDM) based on Index Modulation (IM), Peak to Average Power Ratio (PAPR), Active Constellation Extension (ACE), Selective Mapping (SLM), Partial Transmit Sequence (PTS)*

1. Introduction

Many attempts have been made to ensure that the coming generation of wireless communication (5G) can provide 1000 times increased network capacity as compared to the current generation (4G LTE). This rise can be gained throughout utilizing new emerging physical layer (PHY) technologies such as massive Multi Input Multi Output (mMIMO), massive Machine Type Communication (mMTC), Visible Light Communication (VLC), etc. (Idowu-Bismark et al., 2019; Basar, 2016).

A big challenge facing 5G is the Energy Efficiency (EE), whereas IM is a newly up-coming concept serving as a competitive EE system. IM is a type of modulation technique that uses the indexes of several medium elements to modulate information bits. Such medium elements are either actual, such as antennas and frequency carriers, or virtual, such as space-time matrix, antenna activation order, or virtual parallel channels. The information bits carried by the indexes usually use very limited or no power, thereby offering the required EE to the system (Dang et al., 2021; Basar et al., 2013; Siddiq, 2016; Basar, 2015).

IM can be applied to OFDM and become OFDM-IM in the attempt of exploiting both their significances. Unlike the conventional OFDM, OFDM-IM does not use all of the subcarriers to carry information instead it activates some of them to carry modulated symbols and leaves the others idle. The positions of active and idle subcarriers also convey information, resulting in saving power and hence higher EE (Wen, 2021; Idowu-Bismark, 2019).

Despite the added significances of OFDM-IM, however, it inherits the issue of high Peak to Average Power Ratio (PAPR). Generally, the same methods presented in the literature of reducing PAPR for classical OFDM can be extended directly without any change to OFDM-IM. On the other hand, there are some techniques specified for OFDM-IM in the reduction process in which they made use of the unique characteristics of OFDM-IM in applying the method (Gopi et al., 2020; Zheng et al., 2017). In this paper, a review of PAPR reduction methods for OFDM-IM systems is presented. The main approaches with different system parameters are compared in terms of PAPR reduction performance.

The rest of the paper is organized as follows. In section 2, the OFDM-IM system model is presented. In section 3, a brief background on PAPR is explained. In section 4, the different techniques of PAPR reduction in OFDM-IM systems are described. In section 5, these techniques are compared. Finally, concluding remarks are given in section 6.

2. OFDM-IM system model

The basic scheme of OFDM-IM system is illustrated in Figure 1. A total number of m information bits enters the system and splits into g groups of p bits (p=m/g). The number of subcarriers in the OFDM block, N, is then divided into g subblocks each containing n subcarriers (n=N/g). Only k subcarriers of the total n subcarriers per a subblock are activated to convey modulated symbols while the remaining (n-k) subcarriers are inactive and set to zero. The generation of each OFDM-IM subblock consists of two parts; index selector and symbol mapper. The former uses p_1 bits to determine the indices of the active subcarriers, as given in equation (1), and the latter uses p_2 bits to modulate the symbols using M-ary modulation schemes, as in equation (3) (Acar et al., 2019; Siddiq, 2017).

$$p_1 = \lfloor \log_2 C(n,k) \rfloor \tag{1}$$

where C(n,k) is the binominal coefficient that is the number of all possible (SAP) as in equation (2).

$$C(n,k) = \frac{n!}{(n-k)!\,k!} \tag{2}$$

It can be seen from equation (2) and that for n=4 and k=2 then, six possible SAPs are available for the given parameters as shown in Figure 2. However, only four combinations are selected neglecting the other two because $p_1 = 4$ bits, using equation (1) and the possible number of SAPs is equal to 2^{p_1}..

$$p_2 = k \log_2 M \tag{3}$$

M is the constellation size.

$$p = p_1 + p_2 = \lfloor \log_2 C(n,k) \rfloor + k \log_2 M \tag{4}$$

p is the total information bits transmitted by each subblock. The output of the index selector I for lth subblock is given by equation (5), where l=1, 2, …, g.

$$I^l = \{i_1^l, \dots, i_k^l\} \tag{5}$$

where $i_\gamma^l \in [1, \dots, n]$ for l=1, 2, …, g. and γ=1, 2, ..., k.

The output of the index mapper on the other hand for the same lth block is shown in equation (6).

$$s^l = \left[s_1^l, \dots, s_k^l\right] \tag{6}$$

where $s_\gamma^l \in S$ for l=1, 2, …, g, γ=1, 2, ..., k, and S is the set of M-ary constellation symbols.

After this process I^l and $s^l$are fed to the OFDM block creator to construct the frequency domain OFDM signal, XF, given in equation (7).

$$X_F = [X(1), X(2), \dots, X(N)]^T \tag{7}$$

where $X_\beta \in \{0, S\}$ for β=1, 2, …, N.

Moreover, as in Figure 1 the frequency domain signal is converted to its time domain counterpart x_T using Inverse Fast Fourier Transform (IFFT) as in equation (8).

$$x_T = \frac{N}{\sqrt{K}} IFFT\{X_F\} \tag{8}$$

where $\frac{N}{\sqrt{K}}$ is used for normalization.

Finally, a cyclic prefix is added to the time domain signal and the operation of parallel to serial is performed on the signal to be transmitted over the communication channel. At the receiver, the same operations are performed on the reverse order (Kalia, 2019).

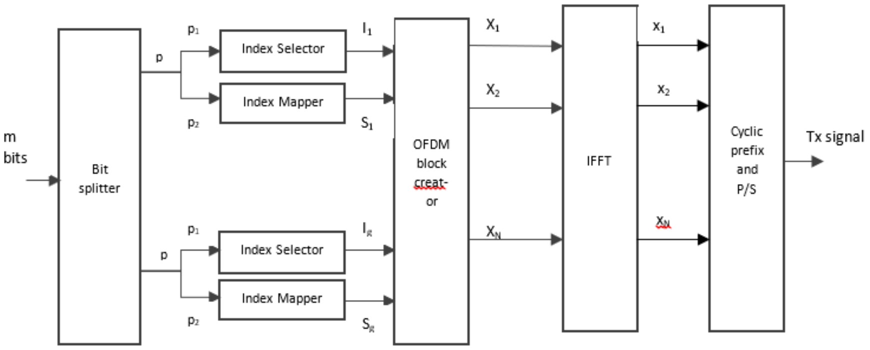


Figure 1. *Basic scheme of OFDM-IM transmitter system.*

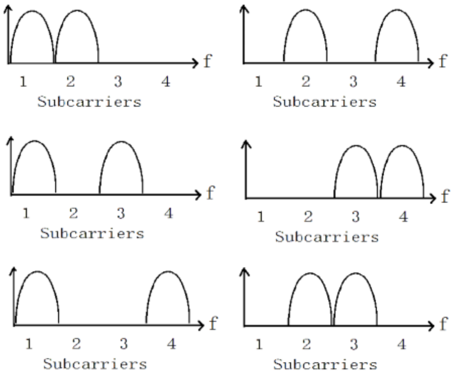


Figure 2. *Possible SAPs in OFDM-IM system (n=4 and k=2).*

3. General background on PAPR

As the name implies, PAPR is the ratio between maximum to average power values of the transmitted signal. Mathematically, it can be calculated according to equation (9) (Mishra, 2012).

$$PAPR = \frac{\max(|X_n|^2)}{E(|X_n|^2)} \tag{9}$$

where E(.) resembles the mean value.

High PAPR takes place because of the addition of many independent/orthogonal modulated subcarrier signals with each having different phases that can align with the frequency domain (Siddiq, 2015).

The transmitter of OFDM and OFDM-IM systems contain an amplifier with a dynamic range of amplification. When high PAPR occurs, the amplifier gets saturated to clip the high peaks causing signal in band and out of band distortion. Therefore, the range must be extended requiring more power consumption, resulting in a significant low power efficiency, and more system complexity. As a result, attempts toward decreasing PAPR are studied as shown in section IV (Mishra, 2012; Bandyopadhyay, 2020).

The PAPR performance is analyzed throughout Complementary Cumulative Distribution Function (CCDF), “the probability of exceeded PAPR in a certain PAPR threshold, γ” (Abdullah et al., 2017). CCDF can be mathematically expressed as in equation (10).

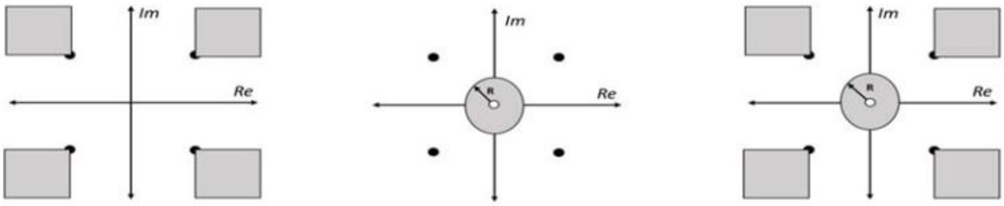
$$CCDF\gamma = Pr\{PAPR > \gamma\} = 1 - (1 - e^{-\gamma})^N \tag{10}$$

4. PAPR reduction techniques in OFDM-IM

In this section, PAPR reduction techniques for OFDM-IM systems are presented according to the adopted technique. The main techniques are the Active Constellation Extension (ACE), dither signals, Selective Mapping (SLM), multiple mapping, and Partial Transmit Sequence (PTS). The following are the main attempts for PAPR reduction in OFDM-IM systems.

4.1. ACE for PAPR reduction in OFDM-IM

The ACE technique can be directly borrowed from the conventional PAPR reduction in OFDM to OFDM-IM systems. The active and idle subcarriers can be referred to as super constellation, which need to be extended while keeping the minimum distance between the points the same, hence decreasing the PAPR (Wang et al., 2016). However, utilizing all of the subcarriers in OFDM and only the activated ones in OFDM-IM for the reduction purpose leads to a low PAP reduction performance in OFDM-IM as compared to the OFDM (Zheng et al., 2017; Memisoglu, 2018). Two other techniques had been suggested based on ACE and utilizing the IM concept. Method I is about extending the idle subcarriers with a particular range (radius) and method II suggests extending the outer points in addition to extending the idle subcarriers that resembles a mixture of ACE and the first method. The OFDM-IM signals in their time domain are clipped with a specified threshold value to reduce the high peaks, then the clipped signals that correspond to the inactive subcarriers are kept and the remaining samples are cancelled out. As for the second method, the active subcarriers are controlled, the clipped samples inside the feasible range are kept unchanged, and the other samples are set to zero. Figure **3**, demonstrates the constellation diagram of the three methods, where the unfilled and filled points (◦ and •) correspond to inactive and active subcarriers, respectively (Memisoglu, 2018).



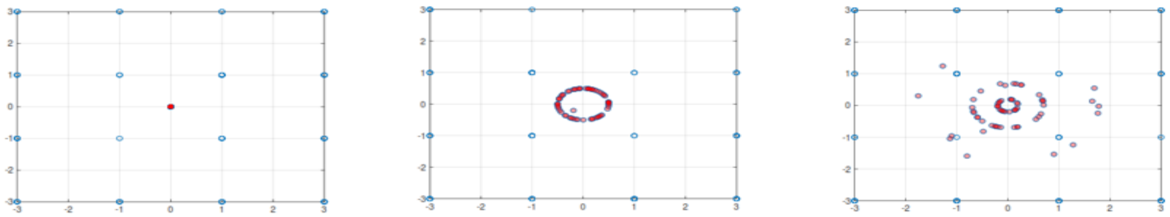
(a) (b) (c)

Figure 3. *Signal constellation for (a) ACE technique. (b) Method I. (c) Method II.*

4.2. Dither signal insertion

This technique can be considered as the first method for reducing PAPR applied only to OFDM-IM. It makes use of the IM unique characteristics to gain an efficient method for this purpose. It utilizes the inactive subcarriers to insert a dither signal while keeping the active subcarriers fixed. The amplitude of the dither signal must be in a particular range to avoid any error performance degradation caused by the signal and for this reason convex programming is used to control the range (Zheng et al., 2017).

Later on, an improved version of the work presented in (Zheng et al., 2017) is proposed in (Kim, 2019). It makes use of both active and idle subcarriers because the active subcarriers are not fixed in this case. Therefore, instead of single level dither signal, multilevel dither signals are used. The multilevel allows the amplitude of the dither signal to vary for each subblock. Each subblock dominated a constrained amplitude, thereby offering more freedom to the dither signals while the demodulation performance remains at a good level (Kim, 2019). Figure 4 shows the super constellation points when 16-QAM is employed in the active subcarriers.



(a) (b) (c)

Figure 4. *Super constellation points for (a) Original OFDM-IM. (b) Single level dither signal. (c) Multilevel dither signal.*

4.3. SLM for OFDM-IM

SLM is a distortion-less method for reducing the PAPR value of OFDM signals. However, in OFDM-IM the same method can be adopted for the same purpose with some different considerations. In addition, Side Information (SI) plays an important role in the conventional SLM scheme, it must be transmitted to carry information about the used phase sequence so that the receiver can recover the original signal SI which leads to a reduction of data transmission rate. On the other hand, incorrect detection of SI has serious impact on the Bit Error Rate (BER) performance that is why many researchers worked on the SI removal (Zhang et al., 2021; Gopi et al., 2020; Jo, 2018).The followings are the main SLM based schemes for PAPR reduction in OFDM-IM systems.

4.3.1. Polar coded OFDM-IM

This recent technique makes use of the polar coding property in which its frozen bits commonly referred to as “0” and they are rotated randomly, which is similar to the process of generating random symbols and rotating them in the conventional SLM. Furthermore, as in conventional SLM the phase rotation vector needs to be transmitted so that the receiver can perform the decoding algorithm properly. Polar decoding algorithms such as Successive Cancellation List (SCL), and Belief Propagation (BP) are used to distinguish the frozen bits thus, avoiding inefficient SI. Accordingly, decreasing the complexity and latency at the receiver (Vardy, 2015). Figure 4 illustrates the transmitter of this scheme. Firstly, the information bits u, must be transformed to polar codewords X_0. A number of frozen bits Fv need to be generated by the transmitter, then F_v is processed with the matrix product operation referred as, $G_{2.A^c}^{\oplus n}$ to produce random frozen bits P_v, which is called phase rotation vectors. After that, X_0 is multiplied using mod 2 with P_v to generate X_{v-1} candidates for IM. Finally, after the IM process s_{v-1} codewords are produced and the least PAPR candidates are selected for transmission (Zhang and Shahrrava, 2021).

4.3.2. Phase sequences and permutation functions

This method focuses on the fact that the conventional PAPR reduction schemes extended to OFDM-IM cannot provide desirable efficiency to the system because the unique characteristics of IM are not considered. The permutation procedure of SLM is investigated to analyze the optimal condition for the Phase Sequence (PSs) (Dae-Woon et al., 2006).

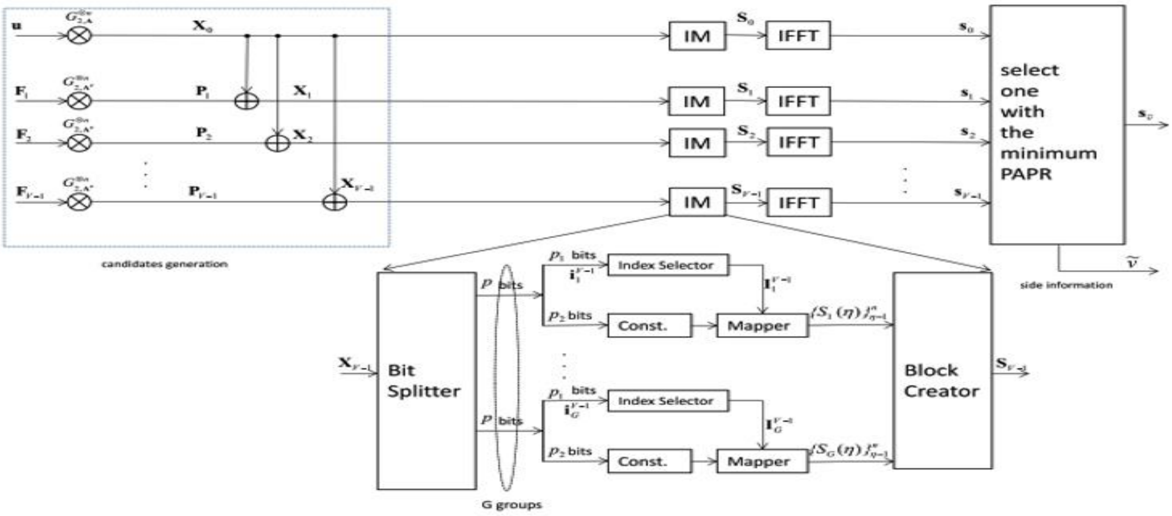


Figure 5.*Polar coded OFDM-IM scheme for PAPR reduction.*

PSs are the set of distinct phase factors that are known by both transmitters and receivers which are used to generate an original set of OFDM signals. They are used for rotating the modulated symbols in conventional SLM schemes. In order to transmit the PSs, additional SI is required. The same amount of SI is used in this novel scheme as in the conventional SLM scheme. The addition of permutation procedure is advantageous when the number of active subcarriers are much less than the total. However, if the ratio is high, it would be better to remove the permutation procedure. Furthermore, to guarantee the performance of PAPR reduction, optimal conditions for PSs and permutation procedure have to be taken into account (Kim, 2020). The block diagram shown in Figure 5 shows the permutation used in OFDM-IM system.

4.3.3. SLM for noncoherent OFDM-IM

An optimized version of conventional SLM (OSLM) exploits the characteristics of IM by utilizing the number of activated subcarriers to achieve PAPR reduction. Wherein the SLM for OFDM-IM normally offers a constant value β to be loaded onto the active subcarriers, OSLM offers a variable $\beta\{e^{j\theta_i}\}_i$value to be loaded instead. The motivation behind this change came when in (Gopi et al., 2020), it was concluded that if the constant value was equally divided into $+\beta$ and $-\beta$, the average power would be reduced to zero in the first samples of frequency domain. Because high peak powers occur in the first time domain samples which lead to low average power in their corresponding first samples of frequency domain. On the other hand, this can cause high peaks in the other samples. Therefore, OSLM adjusts this reduction by changing the phase factor in proper way to achieve the least possible PAPR reduction in noncoherent OFDM-IM (Gopi et al., 2020).

This novel scheme is based on noncoherent OFDM-IM in which the IM technique has been exploited as in (Vora et al., 2018) since not all of the subcarriers are activated. Thus, Channel State Information (CSI) which provides the properties of every channel of the subcarriers need not to be estimated by the receiver yielding in more energy efficiency and hence additional SI to carry the CSI will not be necessary to be sent (Gopi et al., 2020; Choi, 2018).

4.3.4. Multiple mapping rules

The multiple mapping rule is a new technique for PAPR reduction in only OFDM-IM because it makes use of the multiple mapping rules availability for IM. This technique is similar to the SLM scheme but while SLM uses phase sequences to generate the OFDM signals, IM multiple mapping rules use different multiple mapping for each group of subcarriers (cluster) to generate the OFDM-IM signals.

The scheme avoids the transmission of SI by using a combination of OFDM-IM blind search detector with the Maximum Likelihood (ML) detector. The transmitter can have multiple mapping rules from IM bits to IM symbols known as IM Mapping rules (IMM) in which the number of the mapping iteration equals the total possible combination number of subcarriers for each cluster. Therefore, different number of OFDM-IM signals can be generated and as in SLM, the signal with the lowest PAPR can be selected for transmission.

In addition, as the number of subcarriers increase, the possible combination of activated subcarriers increase as well as the generated OFDM-IM signals. Though it might seem as a desirable condition for the selection process, however it will increase the computational complexity of the overall system. Therefore, a limitation for the generated signals must be considered.

Moreover, to enable the receiver to apply blind search to estimate the IMM rules that had been used at the transmitter, phase rotation and symbol inversion for data symbol modulation have to be performed at the transmitter (Hanseong Jo, 2018).

4.3.5. PTS for OFDM-IM

The idea of this technique is to rearrange the frequency domain OFDM-IM signal X into disjoint Xv groups called, PTS groups. For simplicity, the subcarriers of each OFDM-IM subblock are put into the same PTS group. After applying IFFT the groups are transformed to their corresponding time domain signals and are multiplied with a Pv phase rotation vector. Finally, the groups are added up to generate $x^{(u)}$, where u =0, 1, …,V-1, candidates for the purpose of selecting the least PAPR group vector. As in the OSLM (Dan et al., 2018), the first vector $x^{(0)}$ is assumed to be without phase rotation and the following $x^{(V-1)}$ are with phase rotation. With careful phase rotations the least possible PAPR can be chosen. PTS can achieve approximately 3 dB higher PAPR reduction with respect to the original OFDM-IM signal and this value could be further improved to 6 dB by considering the optimal system parameters (Dan et al., 2018; Gopi et al., 2020).

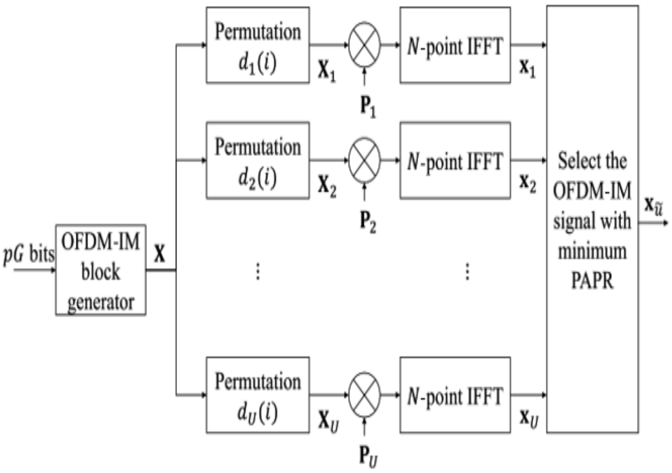


Figure 6. *The SLM scheme with permutation.*

5. Comparison of the approaches

The techniques can be summarized in terms of their efficiency in reducing the amount of PAPR. A comparison based on the simulation results of the researches mentioned in the literature is made in which each technique has distinct system parameters such as, the size of OFDM-IM block (N), the length of each subblock (n), the use of different modulation schemes, and the number of active subcarriers (k). The table cannot decide which technique is better than the others because of the different parameters used, their side effects on the system (such as, complexity, requiring additional SI, BER, etc.), and practical implementation is beyond the scope of this paper. Nevertheless, one aspect concluded from the comparison is that before applying the reduction techniques the same amount of PAPR is available for both conventional OFDM and OFDM-IM. Table 1 summarizes the amount of PAPR reduction for the approaches mentioned in the literature specified for OFDM-IM unless otherwise stated.

6. Conclusion

This paper emphasizes on the significance of adding IM to OFDM in the attempt of saving energy because the main criteria of OFDM-IM is that not all of the subcarriers are used for transmission thus preserving valuable resources to become an energy efficient system to fulfill the demands of the coming wireless communication generation.

OFDM-IM inherits the drawback of having high PAPR as in classical OFDM and inspite of the novelty of this system, many literature attempts have been made towards reducing the high PAPR. The researchers showed that the same approaches used in conventional OFDM could be adopted in OFDM-IM, however, they cannot gain the desired performance. Therefore, optimization and modification of the available techniques have been implemented specially for OFDM-IM.

A summary of the approaches was presented to conclude that generally the same amount of PAPR exists when no reduction technique is used in classical OFDM and OFDM-IM. Yet, no technique could be chosen as the fitting technique because of the different system parameters and their side effects on system performance.

Table 1. *Comparison of PAPR reduction performance*

<table>
<tr><th>System parameters</th><th colspan="2">Without reduction technique</th><th colspan="2">ACE</th><th colspan="2">Method I</th><th colspan="2">Method II</th></tr>
<tr><td rowspan="2">N=256
N=4
K=2
4-QPSK
(Memisoglu, 2018)</td><td>Classical OFDM</td><td>OFDM-IM</td><td>Classical OFDM</td><td>OFDM-IM</td><td>Classical OFDM</td><td>OFDM-IM</td><td>Classical OFDM</td><td>OFDM-IM</td></tr>
<tr><td>11.5 dB</td><td>11.5 dB</td><td>6.8 dB</td><td>8.2 dB</td><td>Non</td><td>5.1 dB</td><td>Non</td><td>5 dB</td></tr>
<tr><td rowspan="2">N=128
N=4
K=2
4-QPSK
16-vectors
(Zheng and Lv, 2017)</td><td colspan="2">Without reduction technique</td><td colspan="2">ACE</td><td colspan="2">Dither signal insertion (R=0.6)</td><td colspan="2">SLM</td></tr>
<tr><td colspan="2">10.6 dB</td><td colspan="2">9 dB</td><td colspan="2">2 dB</td><td colspan="2">6.9 dB</td></tr>
<tr><td rowspan="2">N=128
n=4
k=2
16-QAM
(Kim, 2019)</td><td colspan="4">Without reduction technique</td><td colspan="4">Multilevel dither signal insertion</td></tr>
<tr><td colspan="4">11.3 dB</td><td colspan="4">7.5 dB</td></tr>
<tr><td rowspan="2">N=128
BPSK
16-vectors
(Zhang et al., 2021)</td><td colspan="4">Conventional SLM</td><td colspan="4">SLM for polar coded OFDM-IM</td></tr>
<tr><td colspan="4">6.3 dB</td><td colspan="4">6.4 dB</td></tr>
<tr><td rowspan="2">N=128
n=8
k=3 (Gopi et al., 2020)</td><td colspan="3">Without reduction technique</td><td colspan="2">PTS (4-vectors)</td><td colspan="3">OSLM (16-vectors)</td></tr>
<tr><td colspan="3">13 dB</td><td colspan="2">9 dB</td><td colspan="3">7.3 dB</td></tr>
<tr><td rowspan="2">N=128
n=4
K=2
BPSK (Jo, 2018)</td><td colspan="4">Without reduction technique</td><td colspan="4">Multiple mapping rule for OFDM-IM (100 shared channels)</td></tr>
<tr><td colspan="4">10.9 dB</td><td colspan="4">7 dB</td></tr>
</table>

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