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Performance Analysis of Improved Subcarrier Index Modulation OFDM Using a Novel Decision Rule over AWGN Link

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Abstract—Subcarrier Index Modulation Orthogonal Frequency Division Multiplexing (SIM-OFDM) is a modulation technique that extends information transmission beyond conventional subcarriers, incorporating their presence or absence. However, inaccurate determination of subcarrier status at the receiver can result in a high Bit Error Rate (BER). In response, this paper introduces an enhanced version named Improved SIM-OFDM (iSIM-OFDM). iSIM-OFDM employs a novel decision rule based on the summation of absolute values of the real and imaginary parts of each received symbol. Through simulations conducted over an Additive White Gaussian Noise (AWGN) link using Python, we performed a comparative study with conventional SIM-OFDM, specifically focusing on the electrical energy-per-bit per noise ratio E_b/N_0 for various constellation sizes. The results reveal that iSIM-OFDM outperforms conventional SIM-OFDM in terms of BER performance, achieving a maximum gain in E_b/N_0 of up to 2dB. This improvement is followed by the added advantage of reduced computational complexity while maintaining equivalent spectral efficiency. Furthermore, in the context of Power Reallocation Policy (PRP) versus Power Saving Policy (PSP), iSIM-OFDM achieves a gain of approximately 3 dB in E_b/N_0 with PRP. Additionally, iSIM-OFDM demonstrates similar BER performance in PRP policy with only half the transmitted power compared to PSP policy. Considering these aspects, iSIM-OFDM emerges as a robust candidate in wireless communication fields where energy constraints are stringent, and rapid computational processing is imperative.

Keywords— SIM-OFDM; AWGN; Power Saving Policy; Power Reallocation Policy; Spectral efficiency; BER; Computational complexity.

I. INTRODUCTION

In telecommunication area, the ever-increasing demand for high data rates and robust communications systems stands as an imperative. Addressing these challenges, Orthogonal Frequency Division Multiplexing (OFDM) emerges as a highly promising solution [1-4]. In OFDM technique, data are emitted over bandwidth-limited communication channels [2]. Demonstrating its efficiency as a modulation technique, OFDM has achieved widespread integration across diverse communication standards, including but not limited to Wi-Fi, 4G LTE, and 5G networks [5]. Within the OFDM domain, pivotal challenges revolve around the energy efficiency and computational complexity, particularly in the context of applications requiring low power [4]. In response to these challenges, a modulation technique known as Subcarrier Index Modulation Orthogonal Frequency Division Multiplexing (SIM-OFDM), has been proposed [6]. This approach aims to enhance resilience against channel-induced delay spread while optimizing throughput and ensuring efficient energy consumption [7]. Unlike Traditional OFDM systems, in addition to carrying data, subcarriers in SIM-OFDM are also used to convey information data about the indices of active subcarriers (called BOOK). This innovative structure facilitates the mitigation of the Peak to Average Power Ratio (PAPR) and achieves an improved balance between spectral and energy efficiency. Therefore, SIM-OFDM can be implemented with minor modifications to existing OFDM designs, potentially reducing development and implementation costs. In the SIM-OFDM receiver, the accurate detection of subcarrier indices is vital for proper data demodulation. Any error in the identification of these indices can propagate and adversely affect the demodulation of subsequent subcarriers, a phenomenon referred to as error propagation. To overcome this issue, an improved version of SIM-OFDM, known as ESIM-OFDM [8], was proposed. This enhanced technique assigns two (02) subcarriers per virtual bit transmission, resulting in a decrease in the system's peak power while halving the throughput. Another approach [9] for determining the subcarrier state was proposed and evaluated, demonstrating a significant improvement in the bit error rate (BER) compared to the traditional decision rule based on subcarrier power for ESIM-OFDM. A comparative study [10] is proposed in terms of complexity, spectral efficiency and BER performance between OFDM with SIM-OFDM and ESIM-OFDM methods for an AWGN channel. Simulation results show that SIM-OFDM and ESIM-OFDM achieve good performance in signal-to-noise ratio compared to 4-QAM OFDM under a power re-allocation policy (PRP), but traditional OFDM exhibits better spectral efficiency for higher M-ary orders. Also, performance studies were conducted to identify the beneficial operating zone [11] for the SIM-OFDM scheme compared to conventional OFDM, providing guidelines for choosing to deploy SIM-OFDM. The performance of error detection probability with bit error rate (BER) of the index for generalized SIM-OFDM were simulated and analyzed by authors in [12]. A novel SIM-OFDM using overlaid data suppression pilots [13] was introduced to enhance pilot detection and effectively exploit the subcarrier index corresponding to overlaid pilots for transmitting additional information. Furthermore, a scheme was proposed for using SIM-OFDM in multi-user uplink transmission in MIMO systems [14]. SIM-OFDM technique has also been demonstrated to be robust against laser phase noise [7] and tolerant to fiber nonlinearity attenuation in a long-distance Coherent Optical OFDM (CO-OFDM) system. A modulation scheme combining SIM with Asymmetrically Clipped Optical-OFDM (ACO-OFDM) multiplexing was proposed for Optical Wireless Communication (OWC) systems [15]. In the same context, a Radio over Fiber (RoF) system using SIM-OFDM signal, was experimentally demonstrated [16]. The results showed that spectral efficiency of SIM-OFDM can be improved compared to conventional OFDM systems. An experimental prototype demonstrating a Visible Light Communication Intensity Modulation/Direct Detection (VLC IM/DD) system was reported using SIM-OFDM [17]. A subcarrier index-based power allocation (SIPM-OFDM) [18] was also experimented in optical fiber transmission. To improve the energy efficiency of the SIM-OFDM system, a signaling strategy assisted by Compressed Sensing (CS) detection and a detector based on Iterative Residual Check (IRC) was introduced [19]. To effectively reduce the PAPR without degrading the BER performance, a selectively mapped phase sequences was used in SIM-OFDM [20]. In order to distinguish the data conveyed by the BOOK from the symbols of the IFFT (Inverse Fast Fourier Transform) in SIM-OFDM, a threshold was employed in an innovative technique referred to as Threshold SIM–OFDM (TSIM–OFDM) [21].

Numerous studies have focused on evaluating the spectral efficiency of SIM-OFDM while exploring aspects related to energy consumption. For example, a SIM-OFDM technique based on double-sided pulse interval modulation [22] is shown to exhibit higher spectral efficiency than conventional SIM-OFDM. This is the same concept behind using FSK modulation with QAM in SIM-OFDM [23]. A Subcarrier Power Modulation (OFDM-SPM) is also a novel SIM-OFDM approach [24], that aims to provide high spectral efficiency data transmission with low latency and reduced complexity for 6G wireless communication systems. To offer a substantial reduction in PAPR value and better bandwidth utilization [25], a Reduced-Size SIM-OFDM (RIM-OFDM) algorithm was proposed. A spectral efficiency frequency division multiplexing SIM-OFDM (SEFDM-SIM) system [26] was studied in Multiple Input Multiple Output (MIMO) wireless networks, proving to outperform MIMO-OFDM and MIMO-OFDM-SIM in terms of BER. In [27], a precoded NOFDM-SIM system is proposed to enhance the spectral efficiency of multicarrier systems while maintaining similar PAPR to that of conventional SIM-OFDM systems. In [28], the probability in Huffman coding is showed to be adaptively adjusted to optimize spectral efficiency, bit error rate, or the energy efficiency of SIM-OFDM. For channel estimation in SIM-OFDM communication, a new Zadoff-Chu pilot data sequence was proposed [29] and proved to be more effective than using pilot symbols. Furthermore, after the introduction of SIM-OFDM, OFDM with Index Modulation (OFDM-IM) [30] emerged as a concept that now garners comparable interest to SIM. Designed to operate on channels with selective frequency fading and rapid temporal variation, OFDM-IM transmits information through M-ary constellations like classical OFDM, as well as through the indices of activated subcarriers based on the incoming binary stream, similar to SIM-OFDM. Although this system exhibits a lower error rate than classical OFDM in ideal and realistic conditions, its complexity is significantly higher than that of SIM-OFDM. Another improved technique called as Enhanced OFDM-Symbol Nulling Modulation (OFDM-SNM), was suggested [31]. It uses the flexible arrangement of subcarriers to achieve coding gain in high Signal-to-Noise Ratio (SNR) regions. Enhanced OFDM-SNM is highly reliable and represents a promising candidate for the Internet of Things (IoT) with Machine Type Devices (MTD) subject to slow fading.

In this paper, inspired by the decision rule outlined in [9] for determining the subcarrier status in ESIM-OFDM system, we proposed an improved demodulation approach for conventional SIM-OFDM [6]. Our method imparts lower complexity and explores various power allocation policies taking into account different QAM constellations. The remainder of this document is organized as follows: Section II introduces the principle of SIM-OFDM and its various power allocation policies. The approach proposed in this study is described in Section III. Section IV presents the performance results obtained and discusses the outcomes, while Section V concludes the paper.

II. Overview of SIM-OFDM

SIM-OFDM is a modulation technique that combines the advantages of Subcarrier Index Modulation (SIM) and Orthogonal Frequency Division Multiplexing (OFDM). It reduces the number of subcarriers used for data transmission while maintaining relatively high performance in terms of spectral efficiency and robustness against interference. In conventional OFDM, data is divided into multiple blocks and transmitted simultaneously on different orthogonal subcarriers. Each subcarrier carries a portion of the data, allowing for high-speed data transmission while avoiding inter-symbol interference. In SIM-OFDM, data is also transmitted on orthogonal subcarriers, but not all subcarriers are used for data transmission.

2.1 Principle of SIM-OFDM

SIM-OFDM is inspired by Spatial Modulation (SM), a technique that employs antenna indices in a Multiple-Input Multiple-Output (MIMO) system as an additional dimension for data transmission. This additional dimension can be extended from the spatial domain to the frequency domain in an OFDM system, and it is used to convey information in the form of On-Off Keying (OOK). This novel concept is driven by an attempt to optimize energy, a crucial aspect in today's era of "green communication". The energy of each active subcarrier is received from both transmitted M-QAM symbol and encoded additional OOK bit [8]. The principle of SIM-OFDM involves dividing the incoming binary frame into different blocks of $N_{IFFT}\left(\frac{log_2(M)}{2}+1\right)$, where N_{IFFT} represents the total numbers of subcarriers in an OFDM packet, and M the QAM constellation size. Each block of $N_{IFFT}\left(\frac{log_2(M)}{2}+1\right)$ bits is then split into two parts:

- The first N_{IFFT} bits, represent a sub-block, referred to as BOOK;

- The remaining $N_{IFFT}\frac{log_2(M)}{2}$ bits form the sub-block called BQAM, as illustrated by Fig.1.

Each BOOK sub-block is analyzed to determine the majority bit which is the bit (either 1 or 0) that appears most frequently in the BOOK frame. All subcarriers within an OFDM packet, whose positions align with a value equal to the majority bit in the OOK frame, are categorized as "active," while the remaining subcarriers are designated as "inactive" (Cf. Fig. 1). The inactive subcarriers receive an amplitude value of (0 + 0j), where $j=\sqrt{-1}$. To encode the BQAM sub-block, the first $\frac{N_{IFFT}}{2}$ active subcarriers are allocated amplitudes corresponding to those of the QAM symbols. The remaining active subcarriers are employed to signal the majority bit to the receiver side. To achieve this, their amplitudes are configured to the average energy of the QAM constellation. Another possible alternative involves signaling the majority bit either through secure communication channels or by reserving a specific subcarrier to transmit the desired value with a sufficiently high SNR [6], [7].

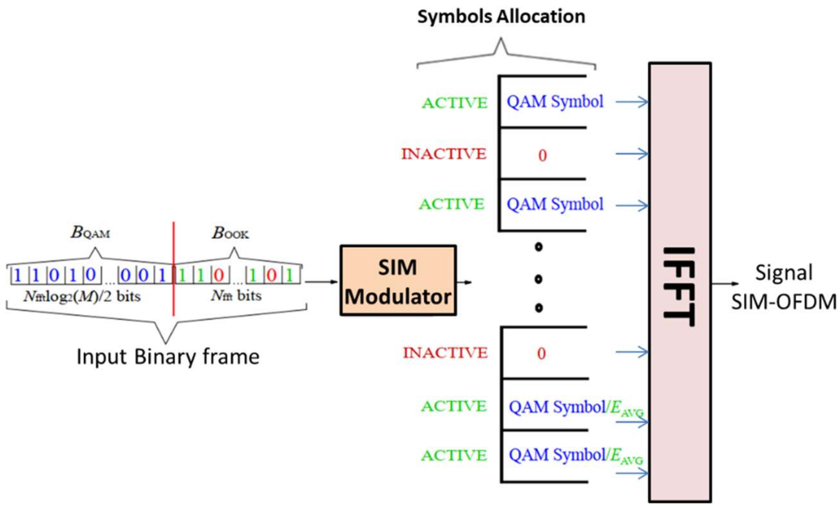

Fig. 1. Principle of SIM-OFDM modulation [8].

Fig. 2 illustrates the demodulation phase of SIM-OFDM. The received signal undergoes a Fast Fourier transform (FFT), wherein the output of each subcarrier is meticulously analyzed:

- a subcarrier is considered as "*active*" if its power exceeds a carefully chosen threshold, which is set to be less than the minimum power of the QAM constellation employed; otherwise, it is classified as "*inactive*";
- each BOOK sub-block is reconstructed based on the identified subcarrier states and the acknowledged majority bit;
- first $\frac{N_{IFFT}}{2}$ "*active*" subcarriers are demodulated according to the employed M-QAM constellation. Then, they are used to reconstruct the corresponding BQAM sub-block [6], [8].

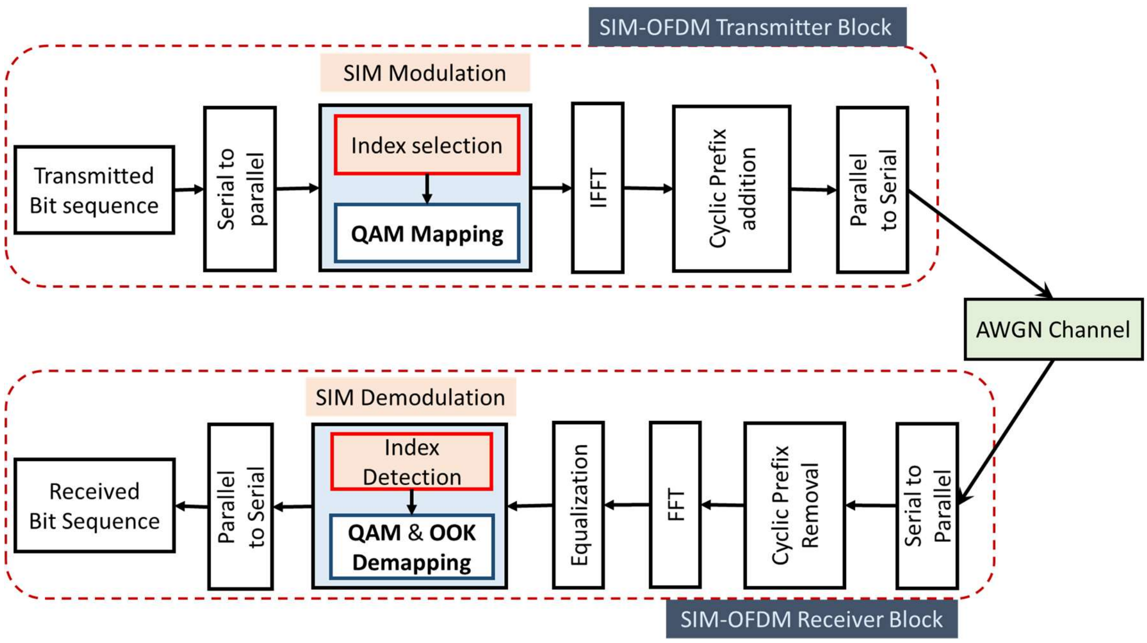

Fig. 2. Block diagram of a SIM-OFDM link under AWGN.

2.2 SIM-OFDM Power Allocation Policies

To improve the energy efficiency or enhance the bit error rate performance in SIM-OFDM systems, two power allocation policies can be implemented, taking into account the possibility of inactive subcarriers. These policies are the Power Saving Policy (PSP) and the Power Reallocation Policy (PRP). In PSP, the focus is on minimizing energy consumption by decreasing transmitted power on unused subcarriers. Specifically, in the case of PSP SIM-OFDM, the power assigned to inactive subcarriers is entirely eliminated, leading to enhanced energy efficiency. This strategy optimizes power allocation by conserving energy on subcarriers that are not actively transmitting information. Hence, the average SNR per active subcarrier under PSP mode can be expressed (1) as follows [6]:

$$\boldsymbol{SNR_{PSP} = 10\, log_{10}\left(\frac{P_T}{N_{FFT}}\right) - 10\, log_{10}(n)} \qquad \textbf{(1)}$$

Where P_T is the total power allocated to an emitted OFDM symbol, N_{IFFT} is the total number of subcarriers, $\boldsymbol{n}$ the additive white Gaussian noise power.

The PRP aims to improve transmission quality by redistributing the power initially assigned to "inactive" subcarriers equitably among the designated "*active*" subcarriers. Thus, the power allocated to each active subcarrier is increased compared to conventional OFDM. This leads to an enhanced BER performance [6] owing to an improved SNR under the PRP mode, as indicated by (2):

$$\boldsymbol{SNR_{PRP} = 10\, log_{10}\left(\frac{P_T}{E\left[N_{ma_j}\right]}\right) - 10\, log_{10}(n)} \qquad \textbf{(2)}$$

Where N_{maj} represents the number of active subcarriers and E[*] the average number of majority bit-value. Power allocation is crucial to ensure quality transmission and efficient resource utilization in SIM-OFDM systems

III. Materials and Methods

In this section, we present the methodology and materials employed. Firstly, we outline the principles of our proposed SIM-OFDM technique. Then, a simulation is carried out to investigate the performance achieved over an Additive White Gaussian Noise (AWGN) channel.

3.1 Proposed SIM-OFDM Demodulation Approach

Indeed, to determine which subcarriers are "active" or not, the authors in [9], proposed for ESIM-OFDM, a different decision rule for subcarrier demodulation instead of the conventional decision rule based on the electrical power or amplitude calculation. Inspired by this decision rule, we propose in this work, its implementation within the conventional SIM-OFDM demodulation with slight modification. Hence, in our approach, the SIM-OFDM transmitter remains identical to that of conventional SIM-OFDM. At the receiver side, for any demodulated symbol $\boldsymbol{S(i)}$ at the $\boldsymbol{i^{th}}$ subcarrier, we compute parameter $\boldsymbol{A(i)}$ by summing the absolute values of the corresponding real and imaginary parts of $\boldsymbol{S(i)}$ as shown by (3):

$$\boldsymbol{A(i) = |\mathfrak{Re}[S(i)]| + |\mathfrak{Im}[S(i)]|, \qquad i = 1, 2, \ldots, N.} \qquad \textbf{(3)}$$

where $\boldsymbol{N}$ is the number of subcarriers. This parameter $\boldsymbol{A(i)}$ is then compared to a selected threshold A_{th}, ensuring it is below A_{min}, to determine whether the state of the $\boldsymbol{i^{th}}$ subcarrier is active $(\boldsymbol{A(i)} \geq A_{th})$ or not. Here, A_{min} represents the minimum value of parameter $\boldsymbol{A}$, taking into account all M symbols from the employed M-QAM constellation. The relationship between A_{th} and A_{min} is expressed as follows:

$$\boldsymbol{A_{th} = \alpha \cdot A_{min}, \qquad 0 < \alpha < 1.} \qquad \textbf{(4)}$$

An extensive series of simulation tests has demonstrated that α=0.5 stands out as the optimal value for subcarrier status decision. Furthermore, the operation |x| + |y|, representing the parameter used in this approach, involves determining the respective absolute values of the variables x and y, and then adding them together. This necessitates two absolute value operations and one addition operation, all of which are executed in constant time. Across multiple iterations, the computational time remains constant for each iteration. On the other hand, the operation $\boldsymbol{b = \sqrt{x^2 + y^2}}$ used in the conventional SIM-OFDM amplitude, involves calculating the square root of the sum of the squares of variables x and y. This requires two square operations, one addition operation, and one square root operation. Square and addition operations are performed in constant time, but the square root can be computationally expensive. The computational complexity of square root calculation is not linear and closer to $\boldsymbol{O(log_2(u))}$ than $\boldsymbol{O(u)}$, where $\boldsymbol{u}$ is the value for which the square root is being calculated. Over multiple iterations, the computational time of operation $\boldsymbol{b}$ can therefore increase proportionally to the number of iterations. In terms of computation time over multiple iterations, the proposed approach demonstrates greater efficiency, resulting in advantages in terms of cost and energy consumption when compared to the traditional decision rule. This advantage arises from its constant complexity, which remains unchanged regardless of the size of the elements at its input.

3.2 Simulation setup

In the rest of the paper, the proposed SIM-OFDM approach is referred to as “improved SIM-OFDM” and abbreviated as “iSIM” while the conventional SIM-OFDM is abbreviated simply as “SIM”. To analyze its performance in comparison with SIM over an AWGN channel link, we employed the Python programming language [32] within the Anaconda distribution [33], a free and open-source platform. Python is a high-level, interpreted, and object-oriented programming language. The AWGN channel is a commonly used model to characterize noise in communication systems. It is a theoretical model that simplifies the modeling of random disturbances affecting transmitted signals. This model assumes that the noise in the transmission channel is white and Gaussian, meaning it is random, memoryless, and follows a normal distribution. The BER for both SIM and iSIM techniques was evaluated using Monte Carlo simulations in an AWGN channel. This involved statistically modeling multiple transmission scenarios to assess the system's performance under varying conditions. The results were then analyzed in terms E_b/N_0, for different QAM constellation sizes, providing a comprehensive understanding of the techniques' robustness in the presence of noise. The simulation parameters are detailed at Table I.

TABLE I. SIMULATION PARAMETERS

Parameters	Values
FFT size	64
Number of OFDM symbols	1024
Cyclic Prefix	1/4
QAM size	4, 16, 64, 256
Eb/N_0	0 ~ 30 dB

Additional simulations were performed to explore the Power Saving Policy (PSP) and Power Reallocation Policy (PRP) for the iSIM technique over the AWGN channel. The BER performance was evaluated and then analyzed with respect to the E_b/N_0 considering half the emitted power in the PRP policy compared to the PSP policy.

IV. RESULTS AND DISCUSSION

The following section presents the obtained results and analysis.

4.1 Performance Comparison of iSIM-OFDM with SIM-OFDM over AWGN channel

In this section, we undertake a comparative analysis of the Bit Error Rate (BER) performance between the improved SIM-OFDM and conventional SIM-OFDM for different QAM constellations. Fig. 3 shows the BER variation as a function of the E_b/N_0, within the Power Saving Policy scenario, taking into account different constellation sizes.

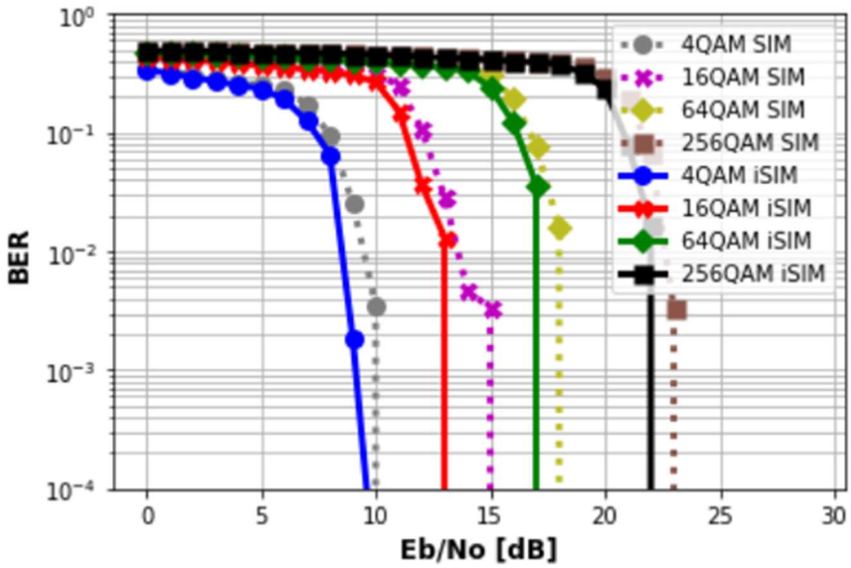

Fig. 3. BER against E_b/N_0, for improved SIM-OFDM and conventional SIM-OFDM under Power Saving Policy and different constellation sizes.

Depending on the constellation size, it is noted that the two techniques demonstrate nearly identical BER performances until reaching a specific E_b/N_0 value (e.g., up to approximately 6 dB for 4-QAM or up to 10 dB for 16QAM). Additionally, a slight enhancement is evident with iSIM-OFDM, exhibiting a maximum gain in E_b/N_0 of up to about 2 dB compared to conventional SIM-OFDM. This can be explained by the decrease in incorrectly identified active or inactive subcarriers achieved by the iSIM-OFDM technique at a specific E_b/N_0 level, for example at 10 dB with 16QAM.

Moreover, at E_b/N_0 target of 13 dB, the achieved BER is 10^{-4} with the iSIM-OFDM compared to $8x10^{-2}$ with conventional SIM-OFDM, representing an improvement of nearly three decades in terms of BER. Hence, iSIM-OFDM demonstrates good BER performance compared to conventional SIM-OFDM, with the added advantage of being less computationally intensive while retaining equivalent spectral efficiency. In the next sub-section, we analyze the performance of the improved SIM-OFDM in PSP and PRP scenarios.

4.2 Performance of iSIM-OFDM under PSP and PRP scenarios

In Fig. 4, the BER variation of the iSIM-OFDM is shown as a function of E_b/N_0 for different constellation sizes under PSP and PRP power allocation policies. It is seen for any QAM constellation, that the iSIM-OFDM consistently exhibits good BER performance in PRP power allocation policy compared with PSP. A gain of approximately 3 dB in E_b/N_0 is shown when compared to PSP policy. This improvement can be attributed to the fact that, in the PRP policy, the power saved from inactive subcarriers in the PSP policy is redistributed among all active subcarriers, elevating their E_b/N_0. The observed 3dB gain in E_b/N_0 indicates the possibility of achieving a comparable BER performance in PRP iSIM-OFDM with only half the transmitted power when compared to PSP iSIM-OFDM. The results presented in Fig. 5 confirm these suggestions, showcasing quasi-similar performance. Considering all these aspects, the iSIM-OFDM technique is seemed to emerge as a strong candidate for modulation in wireless communication fields where there are stringent energy constraints and a requirement for rapid computational processing.

BER against E_b/N_0, for improved SIM-OFDM under PRP and PSP power allocation policies for different constellation sizes.

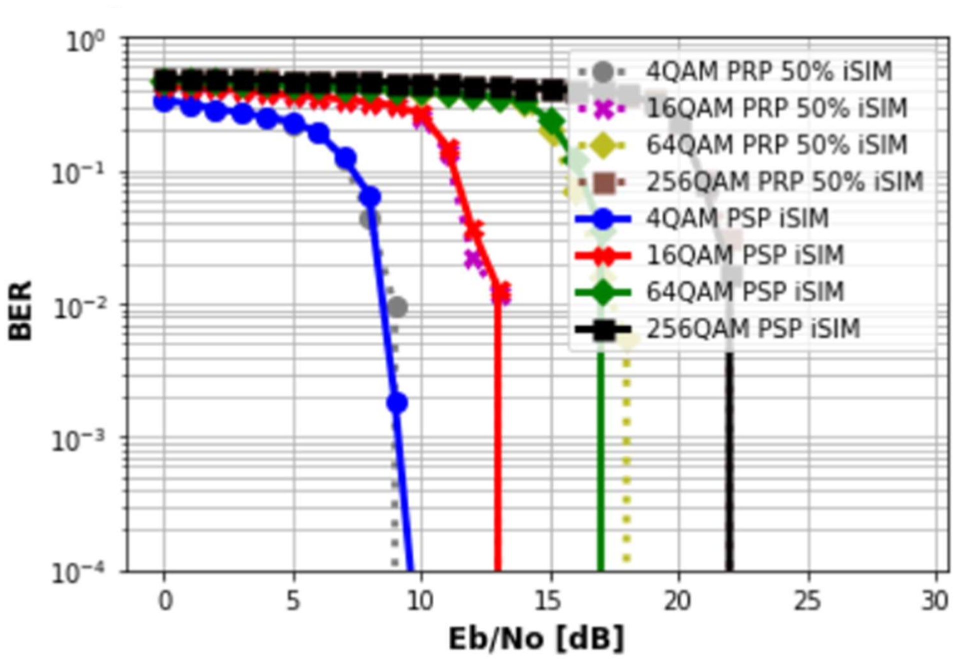

Fig. 4. BER against E_b/N_0, for improved SIM-OFDM under PSP and PRP when PRP uses 50% of the PSP emitted power for different constellation sizes.

V. Conclusion

We introduced an improved Subcarrier Index Modulation OFDM (iSIM-OFDM) technique which presents a similar transmitter as the conventional SIM-OFDM. At the reception, a novel decision rule is applied in terms of the amplitude calculation of the active subcarriers. Through implementation over an AWGN channel link using Python, we conducted a comparative study with conventional SIM-OFDM, focusing on E_b/N_0 for different constellation sizes. After simulation, we showed that iSIM-OFDM exhibits good BER performance compared to conventional SIM-OFDM achieving a maximum gain in E_b/N_0 of up to about 2dB. This improved performance is followed by the added advantage of being less computationally intensive while retaining equivalent spectral efficiency. In conclusion, for wireless applications prioritizing energy efficiency, a Power Saving Policy iSIM-OFDM solution is preferable. For those emphasizing low BER and where energy constraints are not a significant factor, a Power Reallocation Policy iSIM-OFDM technique is highly recommended. In future studies, it would be interesting to conduct a performance evaluation of iSIM-OFDM in realistic channel conditions, such as those encountered in optical communications.

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