An Efficient Maximum Subcarrier Power Detection Scheme for OFDM-IM Systems

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Abstract— **As a promising technology, Orthogonal Frequency Division Multiplexing-Index Modulation (OFDM-IM) has received significant attention in wireless communication systems. However, as the number of subcarriers increases, the complexity of the Maximum Likelihood (ML) detector grows exponentially. In this paper, we propose a novel detection method, referred to as the Maximum Subcarrier Power (MSP) detection algorithm. The MSP algorithm leverages the power information of each subcarrier to detect its activation status and employs a power threshold to determine the appropriate modulation method. Specifically, the MSP algorithm switches from SIPM-OOFDM to OFDM-IM in low signal-to-noise ratio (SNR) scenarios. In comparison to ML detection and Log-Likelihood Ratio (LLR) detection techniques based on optimum transceiver design in OFDM-IM, the proposed MSP detection algorithm has lower complexity and is more robust in terms of Bit Error Rate (BER) performance at varying noise levels. Additionally, the MSP algorithm effectively reduces the cost of Digital Signal Processing (DSP) and the detection time. This consequently leads to enhanced communication efficiency, demonstrating great potential for future low-latency B5G/6G wireless networks.**

Index Terms—**OFDM-IM, ML detection, MSP detection, Signal processing, Robustness**

I. INTRODUCTION

The optimization of energy efficiency is crucial in enhancing spectrum efficiency and the utilization of limited communication resources in wireless communication systems. Multi-carrier modulation techniques, such as modulating data onto parallel, low-speed sub-carriers, can improve spectral efficiency in restricted spectrum resources. Orthogonal frequency division multiplexing (OFDM) is a typical representative of this approach and can further enhance spectrum efficiency. When there are sufficient sub-carriers, the spectrum efficiency of OFDM approaches that of an ideal low-pass transmission function [1].

The concept of OFDM can be traced back to 1966 when Chang proposed the use of nine overlapping sub-carriers for multi-carrier transmission [2]. In 1971, Weinstein and Ebert suggested the utilization of the discrete Fourier transform (DFT) in the modulation and demodulation process of OFDM, greatly reducing its implementation complexity [3]. OFDM technology has undergone ongoing refinement and improvement, including techniques to combat the effects of multipath propagation and co-channel interference [4], the use of cyclic prefixes to further reduce inter-symbol interference [5], and progress in channel estimation [6]. By the 21st century, OFDM technology had been widely adopted in wireless communication standards such as Wireless LAN and 4G LTE, thanks to its high spectrum utilization rate and strong resistance to fading [7]. OFDM is also used in optical communication through the application of Optical Orthogonal Frequency Division Multiplexing (OOFDM) [8].

The next generation of communication technology requires higher spectral and energy efficiency. In 2009, Abu Alhiga and Hass proposed the integration of spatial modulation into the OFDM system, resulting in the OFDM-based index modulation (SIM-OFDM) technique [9], and in 2013, Basar proposed the index of classical orthogonal multicarrier modulation OFDM with Index Modulation (OFDM-IM) [10]. OFDM-IM technology has shown lower bit error rates (BER), faster transmission rates, and higher spectrum efficiency. However, the unique index modulation mechanism of OFDM-IM systems makes the complexity of the Maximum Likelihood (ML) detection algorithm at the receiver exponentially increase with the number of activated sub-carriers, making it difficult to implement in practice [11]. In optical communication, J.M. Tang proposed the subcarrier index-power modulated optical orthogonal frequency division multiplexing (SIPM-OOFDM) transmission technique [12], which introduces a new power dimension for carrying information and a power threshold $P_{threshold}$ for symbol detection. This paper proposes a novel detection method, known as maximum subcarrier power (MSP) detection, for the first time, by introducing the concept of power threshold detection in SIPM-OOFDM into OFDM-IM. Through comparison, the MSP hard detection algorithm is found to significantly reduce the algorithm complexity and improve the BER at high signal-to-noise ratio when compared to the conventional ML hard decision algorithm and LLR soft decision algorithm.

This paper addresses the issue of reducing detection complexity in OFDM-IM systems by proposing a novel detection method, known as maximum subcarrier power detection (MSP detection), to enhance the efficiency of communication. The main contributions of this paper are summarized as follows:

- We first proposed the MSP detection method for high SNR scenarios, where the subcarrier's activation status is directly detected by selecting the k subcarriers with the highest power.
- We incorporated the power threshold detection concept from SIPM-OOFDM into OFDM-IM for low signal-to-noise ratio scenarios. The use of a power threshold improves the system's performance in low

SNR conditions and increases the robustness of the detection algorithm.

- The performance of the MSP detection method was also evaluated by comparing the bit error rate (BER) of different detection algorithms. The complexity of MSP detection was also evaluated by comparing the time required for different detection algorithms and for different numbers of subcarriers.

This paper is organized as follows: In Section II, we present a comprehensive description of the OFDM-IM system model, where particular emphasis is given to the subcarrier power threshold calculation and its corresponding MSP decision algorithm. Then, in Section III, we perform simulations to determine the optimum transceiver parameters that achieve the optimal BER for the OFDM-IM system. In Section IV, we conduct an analytical investigation, by simulating and comparing the MSP, ML, and LLR detection algorithms in an AWGN channel based on the optimum transceiver parameters obtained in Section III. Finally, Section V concludes the paper, summarizing the results obtained from the simulations and the main contributions of the article.

II. OFDM-IM Operating Principle

As a novel multicarrier modulation technique, OFDM-IM is essentially an extension of conventional OFDM. However, in contrast to conventional OFDM, it does not activate all subcarriers and send modulation symbols on all subcarriers. Instead, it selects a subset of subcarriers to activate and send modulation symbols on those activated subcarriers. This approach allows for the division of the transmitted information bits into two parts: the first is carried by the combination of activated subcarrier indices, referred to as index bits, and the second is carried by the modulation symbols sent on the active subcarriers, referred to as symbol bits.

As shown in Fig. 1(a) for the transmitter of OFDM-IM, in each transmission block, an m-bit binary bit sequence is evenly divided into g groups, with each group consisting of p = m/g bits. These p bits are then mapped to OFDM-IM subblocks of length n = N/g. Finally, the g OFDM-IM subblocks are combined to form an OFDM-IM transmission block of length N [10].

As the OFDM subblocks operate independently of each other, the index mapper selects k active subcarriers from the n available subcarriers. As a result, the combination of active subcarriers for each OFDM-IM subblock β is expressed as:

$$I_{\beta} = \{i_{\beta}(1),\ \ldots,\ i_{\beta}(k)\} \tag{1}$$

The p bit sequence is divided into an index bit sequence p_1 and an information bit sequence p_2. The number of index bits carrying active subcarrier information in an OFDM-IM transmission block can be expressed as:

$$m_1 = p_1 g = \lfloor \log_2 C\,(n,\ k) \rfloor\, g \tag{2}$$

Similarly, the number of bits of modulation symbols carried by an OFDM-IM transmission block is:

$$m_2 = p_2 g = k\,(\log_2 M)\, g \tag{3}$$

As depicted in Fig. 1(b), with $n = 4$ and $k = 2$, the OFDM-IM system under 64QAM has an index bit of $p = 2$ and an information bit of $p = 6$, consistent with the aforementioned theory.

For each OFDM-IM subblock β, the index bit p_1 is utilized to select k out of the n subcarriers as the active subcarriers via the index mapper. At the same time, the symbol bit p_2 is mapped by the M-ary modulator, producing a vector with k modulation symbols. Therefore, the combination of active subcarrier indices can be expressed as:

$$S_{\beta} = \{s_{\beta}(1),\ \ldots,\ s_{\beta}(k)\} \tag{4}$$

As for the index mapping method, there are two main approaches: (1) the look-up table method and (2) the combinatorial method [10].

(1) Look-up table method: Taking the number of carriers, $n = 4$, and the number of activated subcarriers, $k = 3$, as an example, Table I below displays the relevant data.

TABLE I
Index Mapping Table

Bits	Subcarrier index combination	Sub block
0 0	2, 1, 0	$[0\ \ s(1)\ s(2)\ s(3)]$
0 1	3, 1, 0	$[s(1)\ 0\ \ s(2)\ s(3)]$
1 0	3, 2, 0	$[s(1)\ s(2)\ 0\ \ s(3)]$
1 1	3, 2, 1	$[s(1)\ s(2)\ \ s(3)\ 0]$

(2) Combinatorial method: Computation of index mappings is typically accomplished through combinatorial methods. If the number of active subcarriers is k, the index positions of the k active subcarriers arranged in descending order can be denoted as $J = \{c_k, ..., c_1\}$. In the combinatorial number method, for any positive integer $Z \in [0, C(n,k) - 1]$, a unique set of J can always be found, resulting in a one-to-one mapping between Z and J. For instance, when the number of active subcarriers is 4, the mapping relationship can be expressed as:

$$Z = C\,(c_4, 4) + C\,(c_3, 3) + C\,(c_2, 2) + C\,(c_1, 1) \tag{5}$$

At the transmitter, the $p1$ bit of information is converted directly to a positive decimal integer Z. For the determined Z, look for the largest c_k such that $C\,(c_k, k) \leq Z$, then select the largest c_{k-1} such that $C\,(c_{k-1}, k-1) \leq\ \ z - c\ \,(c_k, k)$, and so on to determine all the index positions. For example, $n = 8, k = 3, C(8,3) = 56$, it would look like this:

$$\begin{gathered} 55 = C(7,3) + C(6,2) + C(5,1) \rightarrow J = \{7,6,5\} \\ 54 = C(7,3) + C(6,2) + C(4,1) \rightarrow J = \{7,6,4\} \\ \cdots \\ 1 = C(3,3) + C(1,2) + C(0,1) \rightarrow J = \{3,1,0\} \\ 0 = C(2,3) + C(1,2) + C(0,1) \rightarrow J = \{2,1,0\} \end{gathered}$$

Based on the above theoretical analysis, the OFDM-IM symbols can be expressed as:

$$X_{\beta} = \{x_{\beta}(1),\ \ldots,\ x_{\beta}(n)\} \tag{6}$$

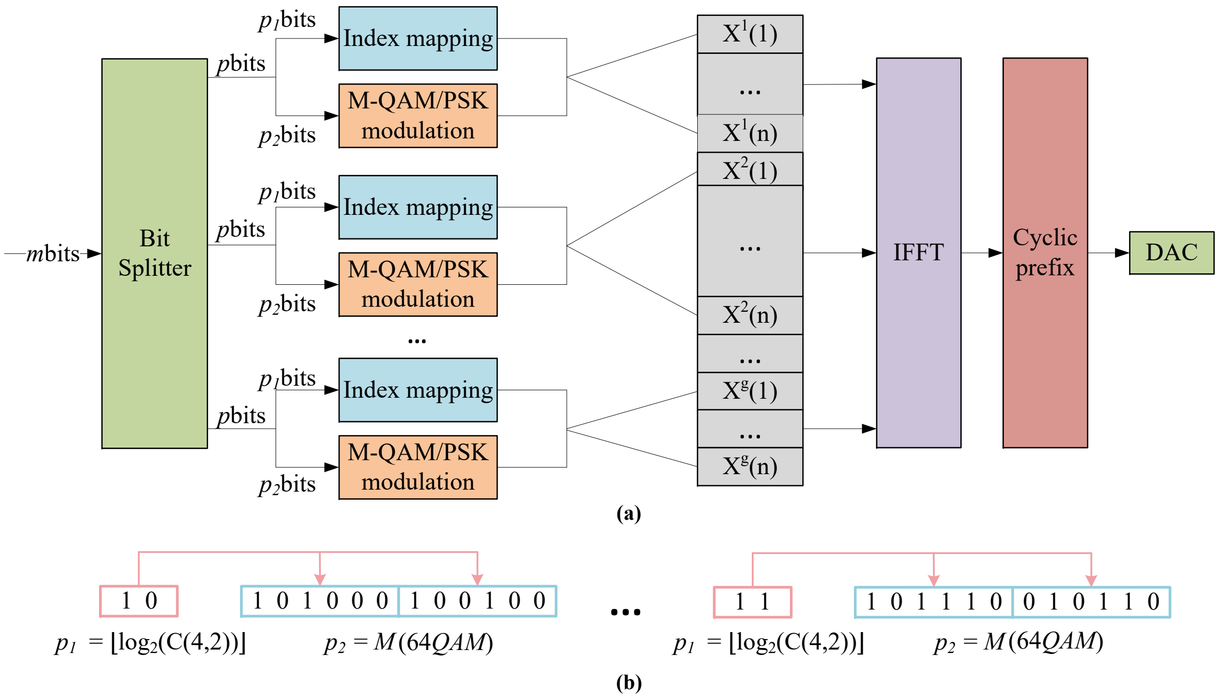

Fig. 1. Schematic illustration of the principle of OFDM-IM: (a) is the transmitter of OFDM-IM, and (b) is the example of the division between the index bit and information bit in OFDM-IM (The number of subcarriers is 4 and the actived one is 2 under 64QAM).

Finally, orthogonal operation in OFDM-IM is completed by IFFT algorithm.

$$Y = \text{IFFT}\left\{X_\beta\right\} \tag{7}$$

The objective of the receiver is to identify the combination of active subcarrier indices and transmission symbols on the activated subcarriers. In contrast to conventional orthogonal frequency division multiplexing, the data conveyed by OFDM-IM via index modulation is transmitted on the OFDM-IM subblock instead of a single subcarrier. Therefore, it is crucial to use the optimal receiver for the OFDM-IM subblock to independently recognize the index symbols and information symbols on the OFDM-IM subblock. In conventional OFDM-IM systems, the maximum likelihood (ML) hard decision algorithm and the log-likelihood ratio (LLR) soft decision detection algorithm are generally employed. The ML detection algorithm is considered the best detection algorithm for OFDM-IM systems. It requires searching all carrier selection schemes and selecting the scheme with the smallest mean square error between the received signal and the received signal as the detection output. However, as the number of carrier paths increases, the complexity of the ML detection algorithm increases exponentially, making it challenging to implement in practice. To address this issue, Ertugrul and other researchers [10] proposed a low complexity detection method based on LLR. This method can effectively reduce the complexity of the index modulated signal detection algorithm, making it a more feasible option for practical implementation.

A. ML detection

The detector of the ML algorithm considers all possible subblock implementations by searching the combinations of index $\hat{I}^i$ and modulation symbol vectors s^i of all possible active subcarriers. The ML algorithm minimizes the value of the following formula:

$$\left(\hat{I}^i, \hat{s}^i\right) = \arg\min_{I^i, s^i} \sum_{a=1}^{n} \left|y^i(a) - x^i(a)\right|^2 \tag{8}$$

The active index combination of each subblock is $\hat{I}^i$, and the modulation symbol vector is $\hat{s}^i$. $y^i(a)$ is the received signal, $x^i(a)$ is the send signal.

B. LLR detection

As the subcarrier may or may not be activated, the LLR detection algorithm determines the activation status of the subcarrier by calculating the logarithm of the ratio of the a posteriori probability of each subcarrier in the case of activation or deactivation. The LLR of each subcarrier of the subblock is calculated as follows:

$$LLR^i(a) = \ln \frac{\sum_{x=1}^{M} P\left(x^i(a) = s_x \middle| y^i(a)\right)}{P\left(x^i(a) = 0 \middle| y^i(a)\right)} \tag{9}$$

According to the Bayes formula, the prior probability is:

$$\begin{aligned} \sum_{x=1}^{M} P\left(x^i(a) = s_x\right) &= \frac{k}{n} \\ P\left(x^i(a) = 0\right) &= \frac{n-k}{n} \end{aligned} \tag{10}$$

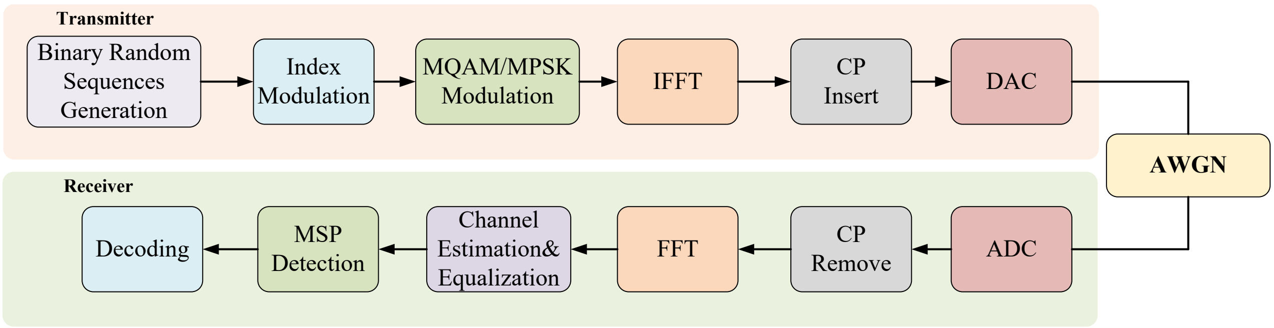

Fig. 2. Schematic of the OFDM-IM transceiver architecture under MSP detection.

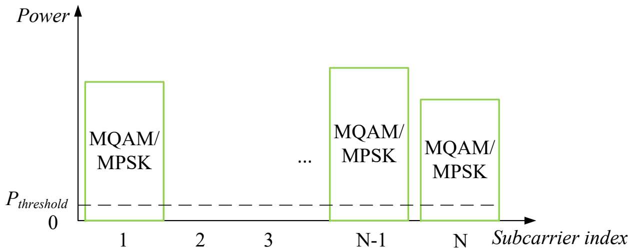

Fig. 3. MSP detection algorithm schematic diagram.

Finally, further expansion leads to:

$$LLR^i(a) = \ln\left(\frac{k}{n-k}\right) + \frac{|y(a)|^2}{N_0} + \ln\left(\sum_{x=1}^{M} e^{-\frac{1}{N_0}|y(a)-h(a)s_x|^2}\right) \quad (11)$$

Upon calculation of the Log-Likelihood Ratio (LLR) values of the N subcarriers in a subblock, the receiver selects k subcarriers with the most elevated LLR values as the estimated number of active subcarriers. Correspondingly, the likelihood of subcarrier activation increases with a rise in its LLR value ($LLR^i(a)$).

Nevertheless, the receiver faces the challenge of exponential growth in the complexity of the Maximum Likelihood (ML) detection algorithm with the increase in the number of activated subcarriers, making its practical implementation formidable. While the LLR algorithm mitigates the algorithmic complexity, it can still lead to a higher Bit Error Rate (BER) and Symbol Error Rate (SER) than the ML algorithm.

C. MSP detcetion

Thus, this paper introduces the concept of a power threshold, $P_{threshold}$, for decision-making in SIPM-OOFDM that is incorporated into OFDM-IM. As depicted in Figure 3, in the transmission block at the transmitter, the non-activated subcarriers have a power of zero, while the activated subcarriers have non-zero power. This characteristic is employed to augment the SER by incorporating a power threshold, $P_{threshold}$, at the receiver under low SNR. Under high SNR, the k subcarriers with the highest power are directly selected for detection, and this detection algorithm is known as MSP detection. When it is at low SNR, the power threshold $P_{threshold}$ can be calculated using the following formula:

$$P_{threshold} = \alpha N_0 \quad (12)$$

where α denotes the coefficient of the power threshold, while N_0 stands for the noise power at the corresponding SNR. Subcarriers whose power exceeds the power threshold $P_{threshold}$ are chosen. In cases where the number of qualified subcarriers, m, falls short of the number of active subcarriers, k, one subcarrier with the highest power is eliminated from the subcarriers whose power is less than the power threshold $P_{threshold}$, and the remaining subcarriers are picked to increase interference under low SNR, resulting in the improvement of the BER.

III. Transceiver Parameter Optimization of OFDM-IM Under MSP Detection

This section aims to determine optimal parameters to enhance transmission performance in the OFDM-IM system under MSP detection, as illustrated in Fig. 2. The transceiver structure is similar to that of the conventional OFDM transceiver [13]. The transmitter performs functions such as index modulation, MQAM/MPSK coding, IFFT algorithm implementation, adding a cyclic prefix to the output end of IFFT, completing digital-to-analog (DAC) conversion, and finally outputting to the AWGN channel.

In the receiver, as shown in Fig. 2, the received signal is converted to analog-to-digital (ADC), the cyclic prefix is removed, and the output is obtained by FFT algorithm. At this point, channel estimation and equalization operations are carried out to eliminate the influence of the channel on the MSP detection algorithm. This paper adopts the ideal zero-forcing (ZF) equalization:

$$Y_E = \frac{H_h}{H_h \cdot H} Y \quad (13)$$

where Y is received signal by FFT, H is the estimated channel impulse response, H_h is the complex conjugate transpose of H.

The entire receiver process is completed by employing the MSP detection algorithm and the corresponding modulation format decoding, as shown in Fig. 4. In an AWGN channel, Fig. 4 highlights the optimal quantization bit and power threshold coefficient α for the ADC/DAC detected by MSP. Fig. 4(a) demonstrates that the optimal quantization bit is 9 bits. As the quantization bit increases, the quantization error introduced by the ADC/DAC also increases, resulting in an increase in BER. Conversely, increasing the quantization bit beyond 9 does not improve the system's performance. Fig. 4(b) and Fig. 4(c) show the optimized curves of the power threshold coefficient α at 0dB and 4dB under high SNR, respectively. When the SNR is 0dB, a power threshold coefficient of 0.04 can improve the system's performance, and when the SNR is 4dB, a power threshold coefficient of 0.01 can improve the system's performance. This is because as the SNR decreases, the power threshold α disturbance increases, making it easier to improve the transmission performance. Additionally, Fig. 4(d) confirms this conclusion by demonstrating that at low SNR, the optimal power threshold coefficient α decreases as the SNR increases. Thus, when designing MSP, the flexibility of software-defined networking (SDN) [14] can be used to adaptively set the appropriate power threshold coefficient to enhance detection performance, improving the algorithm's robustness under low SNR conditions. Conversely, the MSP detection algorithm demonstrates a significant improvement in performance, with a 1.5dB SNR penalty when BER is 1.0×10^{-2}. Moreover, Fig. 5(b) and Fig. 5(c) indicate that the MSP detection algorithm outperforms ML and LLR detection algorithms under low SNR conditions, with a 3dB SNR penalty when SER is 1.0×10^{-2} at 0dB SNR.

In conclusion, the simulation results demonstrate that the MSP detection algorithm performs better than traditional ML and LLR detection algorithms in the OFDM-IM system under low SNR conditions. This performance improvement can be attributed to the power threshold α introduced in the detection process, which enhances the detection algorithm's robustness. Therefore, the MSP detection algorithm is suitable for the OFDM-IM system under low SNR conditions, and the flexibility of SDN can be utilized to adaptively set the corresponding power threshold coefficient to enhance detection performance.

IV. Simulation Results

Table II exhibits the optimal simulation parameters that were obtained by integrating the optimal parameters from Section III. Unless specified otherwise in this section, all simulation parameters refer to Table II.

Fig. 5 presents the BER and SER performance versus electrical SNR of the three detection algorithms in an AWGN channel. Fig. 5(a) compares the MSP, ML, and LLR detection algorithms and reveals that the ML maximum likelihood estimation detection algorithm still provides the optimal transmission performance, while the LLR and ML detection algorithms have consistent performance in this case. Compared with the ML detection algorithm, there is a 0.1 dB SNR penalty when the BER is 1.0×10^{-2}.

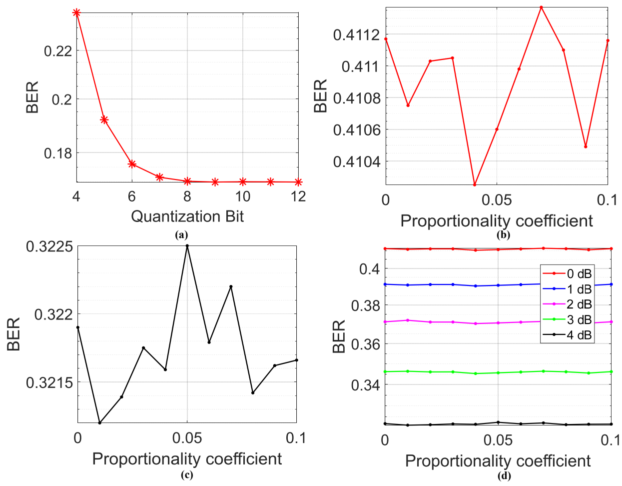

Fig. 4. Schematic illustration of optimal parameters: (a) is the optimal quantization bit in the OFDM-IM, (b) is the optimal threshold power coefficients α of 0dB in the OFDM-IM, (c) is the optimal threshold power coefficients α of 4dB in the OFDM-IM, and (d) is the optimal threshold power coefficients α from 0dB to 4dB in the OFDM-IM.

TABLE II
The Simulation Parameters Setting

Parameters	Value
Subcarrier numbers	6
Activated subcarriers	3
Length of sequence	140000
Modulation formats	64QAM
CP	0.125
DAC & ADC quantization bit	9
Threshold power coefficient	0.01∼0.04
SNR under the AWGN	0∼20dB
Low SNR	0∼5dB

In Fig. 5(b), the effect of the power threshold is explored by applying it to SNR levels ranging from 0 to 5 dB to evaluate performance. Results indicate that the power threshold disturbance can improve BER and SER performance under low SNR conditions, thereby confirming the robustness of the MSP detection algorithm highlighted in previous studies. While the improvement brought by the power threshold disturbance is relatively minor under ideal conditions, it is expected to be more significant in actual wireless and optical communication scenarios where noise levels are higher.

Additionally, as previously noted, the complexity of the ML detector increases exponentially with the number of subcarriers. In Fig. 5(c), where half of the subcarriers are activated, the MSP algorithm demonstrates low complexity as the number of subcarriers increases. This is due to the MSP algorithm's low operational complexity (which does not involve exponential operations) in comparison to the LLR algorithm, as well as its smaller number of operations compared to the ML algorithm.

From the actual simulation time in Table III and Fig.

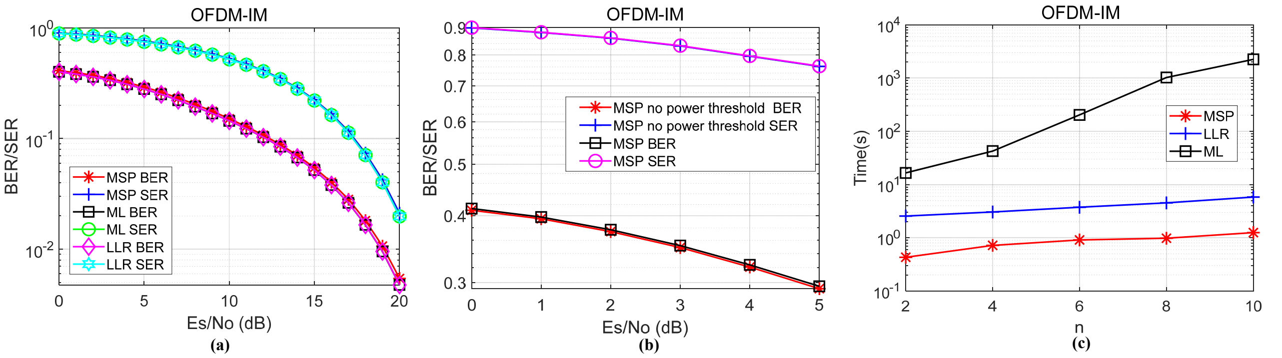

Fig. 5. Simulation of the detecion algorithm: (a) is the BER and SER simulation comparing MSP detecion with the ML, LLR detection, (b) is the BER simulation under low SNR between MSP detection and MSP detcection without power threshold, and (c) is the time consumption of detection algorithms under different subcarrier numbers.

TABLE III
TIME CONSUMPTION OF DETECTION ALGORITHMS

Detection Algorithms	Time of Simulation
ML	203.49s
LLR	3.74s
MSP	**0.91s**

5(c), we can conclude that the MSP detection algorithm maintains an acceptable level of BER while having a lower complexity than the LLR and ML detection algorithms. Furthermore, as the number of subcarriers exceeds 10, the complexity of the MSP detection algorithm is significantly lower than that of the ML detection algorithm. In essence, the MSP detection algorithm can significantly improve the system's operational efficiency while maintaining transmission performance. It is worth noting that further research and experimentation are necessary to validate the proposed MSP detection algorithm in practical applications. Additionally, exploring the algorithm's performance in different types of channels and under various modulation schemes can provide insights into its robustness and applicability in different communication systems.

V. CONCLUSION

In conclusion, this paper introduces the MSP Detection algorithm for OFDM-IM systems, which incorporates a power threshold and optimal parameters to enhance transmission performance. The simulation results confirm that the MSP detection algorithm exhibits low complexity and high efficiency, rendering it suitable for large-scale subcarrier systems. Specifically, the MSP detection algorithm is approximately 223.6 times faster in terms of system transmission and approximately 4.1 times more efficient than the LLR detection in systems with 6 subcarriers and 3 active subcarriers, as compared to the traditional ML detection. Nevertheless, it is imperative to acknowledge that further research and experimentation are necessary to validate the proposed MSP detection algorithm in practical applications. The potential of the algorithm to significantly reduce complexity, improve system transmission efficiency, and decrease the cost of DSP components make it a highly attractive candidate for low-delay 5G wireless communication systems and enhanced stability in B5G/6G communication systems in future extreme environments.

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