System optimization for index modulated OFDM

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Abstract. This paper introduces the system optimization scheme of OFDM-IM, an emerging modulation technology that combines OFDM technology and modulation index technology to improve spectral efficiency and system reliability while ensuring high-speed transmission. However, as a new technology, OFDM still has shortcomings. This paper investigates three system optimization schemes for OFDM-IM: he deep learning-based OFDM-IM optimization scheme, MIMO-OFDM-IM, and LDPC coding-assisted subcarrier index protection scheme. It is found that these three optimization schemes are indeed helpful for optimizing the performance of OFDM-IM through system simulation experiments. The IM-OFDM system optimization based on deep learning is very helpful for IM-OFDM in terms of channel estimation, signal detection, and modulation classification. MIMO-OFDM-IM can increase channel capacity and signal transmission reliability. By protecting the subcarrier index, LDPC codes can effectively reduce the subcarrier error rate and improve the reliability and performance of IM-OFDM systems. Due to their different technical characteristics, the three optimization schemes have different advantages. They also have their application scenarios in which they excel. However, considering these technologies are relatively new, there are still certain drawbacks to these three technologies. Researchers need to continue to study them in-depth and gradually overcome them.

Keywords: OFDM-IM, deep learning-based OFDM-IM optimization scheme, MIMO-OFDM-IM, LDPC coding-assisted subcarrier index protection scheme.

1. Introduction

In early OFDM systems, data was encoded as the amplitude and phase of subcarriers, so the transmission rate was limited by the number of subcarriers. [1] The concept of IM-OFDM was developed to improve the spectral efficiency and other functions of the system. The basic principle of IM-OFDM is combining indexed modulation techniques with OFDM techniques to transmit information in symbols. The transmitter maps the data onto a subcarrier with an index value and then performs an FFT transform to obtain the time domain signal. The receiver performs an IFFT transform to obtain the amplitude or phase information of the subcarriers, then decodes the index value and finally merges the information to obtain the original data. [2] Kaddoum et al. proposed an IM-OFDM system in a multi-user scenario to improve the system's performance by using an orthogonal subspace allocation scheme.[3] Ertugrul Basar proposed a scheme using multiple antenna techniques in an IM-OFDM system to further improve the reliability and spectral efficiency of the system by utilizing space-time coding techniques. [4] Over the years, after persistent research by scientists, index-modulated OFDM technology has gradually been applied in many fields, such as wireless communication systems, VLC systems, optical fiber communication systems, etc., and is considered one of the important technologies for next-generation wireless communication systems.[5][6]

In recent years, OFDM systems have been a hot research topic in wireless communications, mainly focusing on improving system capacity and performance while reducing power consumption and complexity. Many excellent OFDM system optimization schemes have emerged. For example, transmitting and receiving through multiple antennas can significantly improve the capacity and coverage of OFDM systems. As well as utilizing adaptive modulation and coding techniques, i.e., by adapting the modulation and coding methods according to the channel quality and data rate requirements, it can improve the performance and adaptability of OFDM systems. [7] And IM-OFDM, as a modulation scheme further optimized based on OFDM technology, has seen significant advances

in system optimization for IM-FODM at a time when OFDM technology has advanced. For example, some researchers have proposed a deep learning-based IM-OFDM system optimization, i.e., a convolutional neural network (CNN)-based IM-OFDM system optimization scheme, which allows adaptive selection of subcarriers and antenna numbers. The core idea of the scheme is to improve the performance of the IM-OFDM system by adaptively selecting the number of subcarriers and antennas using convolutional neural networks (CNNs). The scheme uses deep learning techniques to optimize the system and can select the optimum number of subcarriers and antennas for different transmission conditions. This improves the performance of the system.[8] Spatial modulation has also been applied to system optimization for IM-OFDM. This scheme allows for signal modulation using multiple antennas, thus increasing the spectral efficiency and capacity of the system. At the same time, the scheme uses spatial modulation to combine signals from different subcarriers, thus increasing the capacity and spectral efficiency of the transmitted data.[4] Rugui Yao uses Low-Density Parity Check Code (LDPC) to protect the subcarrier index.[9] LDPC is an efficient error correction code that improves decoding performance at the receiver side by adding redundant bits at the transmitter side. In IM-OFDM, LDPC can encode the subcarrier index to protect the reliability of the index information.[10] In this way, the BER performance of IM-OFDM can be improved by effectively reducing the false detection rate of the subcarrier index even under multipath fading and noise interference. Recent years' excellent system optimization schemes go far beyond the techniques described above. Due to space constraints, many excellent schemes are not available for presentation. The performance of IM-OFDM is also progressing in research. In recent years, IM-OFDM technology has been significantly improved in terms of spectral efficiency, interference immunity, and BER after system optimization These optimization solutions provide a more reliable and efficient solution for applying IM-OFDM technology.

OFDM-IM has many advantages. It can improve spectrum efficiency, strong anti-interference ability, low complexity, and other advantages. It is a very promising wireless communication technology. OFDM-IM has a wide range of application prospects in 5G communication, the Internet of Things, cable communication, and other fields. Through continuous technological innovation and optimization, OFDM-IM can meet more complex wireless communication needs and promote the development of the whole wireless communication field.

In Chapter 2 This article introduces three OFDM-IM improvement methods: deep learning-based OFDM-IM optimization scheme, MIMO-OFDM-IM, and LDPC coding-assisted subcarrier index protection scheme. In Chapter 3, simulation experiments are conducted on these three OFDM-IM improvement methods to verify that they are indeed very helpful in optimizing the performance of OFDM-IM, but because of the characteristics of their respective technologies, the improvement directions of the three optimization schemes differ. Chapter 4summarizes the article's content.

The object of this paper is the system optimization of OFDM-IM, which can be applied to new-generation wireless communication systems such as 5G and 6G, the Internet of Things, and high-speed mobile communications. [5]-[6],[11].

2. Principal Analysis of OFDM

2.1. Fundamentals of OFDM-IM

IM-OFDM is an improved OFDM modulation scheme, the basic principle of which is to transmit information using different phases and amplitudes on OFDM subcarriers to improve spectral efficiency. The system composition of IM-OFD is shown in Fig. 1 [12].IM-OFDM transmits information by assigning different index values on the subcarriers when transmitting information, matching the different index values with specific phases and amplitude corresponding to the phase and amplitude, and then transmitting the information by transmitting the phase and amplitude. This process can be achieved by matching the modulator and demodulator sides. Specifically, the modulator of IM-OFDM maps the input bit stream to different index values that correspond to specific phases and magnitudes. These phases and amplitudes are mapped to OFDM subcarriers for

transmission, thus transmitting different information on different subcarriers. The demodulator determines the transmitted index values from the received phase and amplitude and maps them back to the bit stream. However, IM-OFDM still has shortcomings, and the system optimization for IM-OFDM is currently focused on channel estimation, signal detection, and modulation classification.

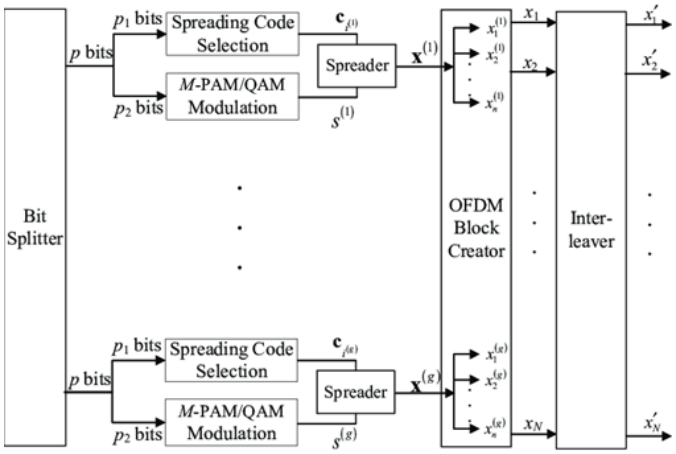


Fig 1. System composition of IM-OFDM

2.2. Main principles of three improved methods

Several studies have been conducted to prove that deep learning-based system optimization for IM-OFDM can significantly help IM-OFDM with channel estimation, signal detection, and modulation classification. The principle of deep learning-based system optimization for IM-OFDM is to use deep neural networks to improve the spectrum sensing and detection of OFDM signals, thereby improving communication performance and efficiency. Deep learning can automatically discover patterns in resource allocation by learning historical data, leading to more efficient and accurate resource allocation. By using deep learning techniques for resource allocation, the system's spectrum utilization and energy efficiency can be further improved. Deep neural networks can also adaptively learn channel state information and signal characteristics based on the incoming OFDM signal, thereby reducing redundancy and interference, and improving demodulation accuracy. One example is an IM-OFDM system optimization scheme based on Convolutional Neural Networks (CNN). A crucial component of CNN is the convolution layer. In CNN, the convolution formula deviates somewhat from the formal formulation. For instance, the following is the formula for two-dimensional convolution.

$$s(i,j) = \sum_m \sum_n x(i+m, j+n) w(m,n) \tag{1}$$

Convolutional neural networks have been proposed by some researchers as a method for training in-phase and orthogonal samples of OFDM signals. To avoid overfitting and improve recognition accuracy, the exit layer is then chosen. Furthermore, datasets with varying modulation patterns are used to validate the trained CNN. The results of the experiments demonstrate that the approach is more precise and reliable than the conventional method.

Spatial modulation is a technique that uses multiple antennas for information transmission, which can increase channel capacity and signal transmission reliability. This technique is useful for system optimization in IM-OFDM and can further improve system performance. In IM-OFDM systems, the use of space-time coding can improve the reliability of signal transmission and channel capacity. And space-time coding is a technique that enables spatially diverse transmission by encoding information in the phase and amplitude of multiple transmitting antennas. By encoding the IM-OFDM signal on the phase and amplitude of multiple transmit antennas, multiple receive antennas can be used at the receiver end to decode the signal, thus improving the system's performance. In IM-OFDM systems, using multiple transmit antennas to transmit signals to multiple receive antennas simultaneously allows multiple IM-OFDM signals to be transmitted to different receive antennas simultaneously,

thus improving the spectrum utilization of the system. Fig. 2[13] shows a MIMO-OFDM-IM transceiver architecture. By optimizing the antenna selection algorithm, suitable transmit and receive antennas should be selected to maximize the channel capacity and energy efficiency of the system and optimum system performance can be achieved.

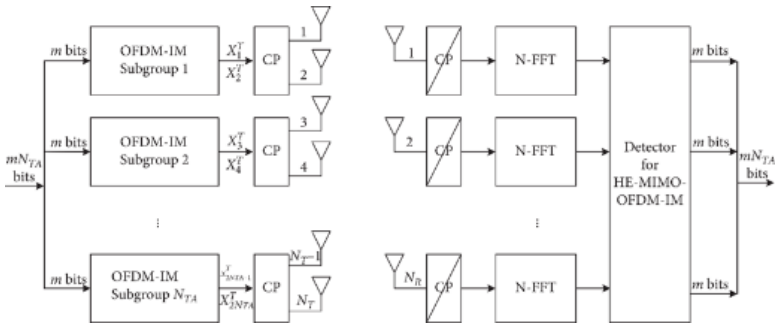


Fig 2. Transceiver architecture of a MIMO-OFDM-IM system

LDPC is an efficient error correction code that can improve decoding performance at the receiving end by adding redundant bits at the sending end. Specifically, LDPC can map the index information bits into a two-dimensional matrix, then generate redundant bits based on the matrix's parity rules and send them along with the index information bits. At the receiving end, the LDPC can use the redundant bits and the channel state information to recover the original index information bits. By protecting the subcarrier index, LDPC codes can effectively reduce the subcarrier error rate and improve the reliability and performance of IM-OFDM systems. At the same time, LDPC codes can be combined with other techniques, such as frequency interleaving and multi-antenna techniques, further to improve the performance and fault tolerance of the system. Calculate the subcarrier activation state LLR. Let the first i as frequency domain symbol transmitted on the lth subcarrier in the sub-block is$X^i(l)$, the corresponding received frequency domain symbol is$Y^i(l)$. Using Bayes' formula, the i sub-block l The probability that the first subcarrier is active can be expressed as

$$P_a^i(l) = \sum_{x=1}^{M} P\left(X^i(l) = S_x \,\middle|\, Y^i(l)\right) = \sum_{x=1}^{M} \frac{P\left(Y^i(l) \middle| X^i(l) = S_x\right) * P(X^i(l) = S_x)}{P\left(Y^i(l)\right)} \tag{2}$$

3. OFDM-IM system optimization-related experiments

3.1. Deep learning based OFDM-IM optimization scheme

In OFDM systems, Signal Modulation Identification (SMI) is crucial. Often, machine learning-based feature extraction is used to build SMI approaches. Nevertheless, standard techniques have difficulty extracting the features of OFDM signals, which results in a very low likelihood of accurate classification and makes it challenging to implement in real-world OFDM systems. To address these issues, deep learning techniques, with their advantages of adaptive tuning, a large amount of data training, and scalability, can be used to replace traditional methods, thereby improving performance, and reducing complexity. Using deep learning methods to improve SMI can result in higher accuracy and better consistency.

Specifically, a method for improving OFDM signals using convolutional neural networks (CNN) is shown in Fig. 3. This method combines three fully connected layers and two convolutional layers. 128 convolutional cores with a size of 1×16 are placed in the first convolutional layer. In the second convolution layer, 64 convolutional cores were established, each with a size of 2×8. The number of modulation modes is represented by the number of neurons in the three fully connected layers. Select the last fully linked layer as the activation function for all other possible layers. The parameter correction linear unit (PReLU) is selected as the modulation mode for all other layers. The probability

distribution matrix at the top level is created through Softmax. Dropping layers have been added to the first four layers to reduce over fitting.

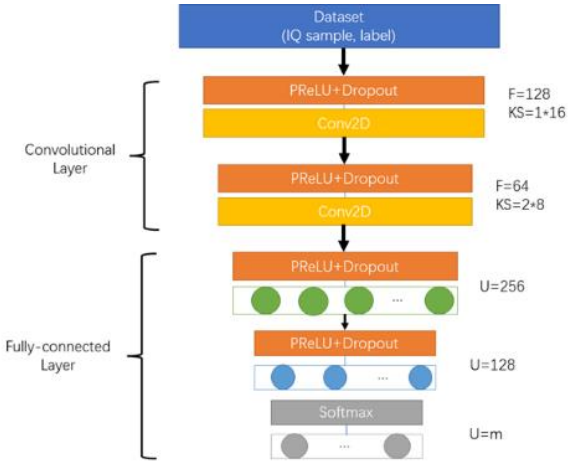


Fig 3. CNN structure of SMI

The researchers created a dataset that included BPSK, QPSK, 8PSK, and 16QAM modulation methods to conduct the experiments. In the experiments, the researchers evaluated and contrasted three popular machine learning-based and neural network-based classification techniques. As the signal-to-noise ratio increases, the probability of correct classification of the method proposed in this paper keeps increasing. In contrast, the classification accuracy of the other methods remains largely unchanged. The performance curves are shown in Fig. 4(a). Identifying IQ samples is simpler than AP samples. The approach presented in this work operates well, with an accuracy rate near to 100%, for signal-to-noise ratios larger than 20dB.

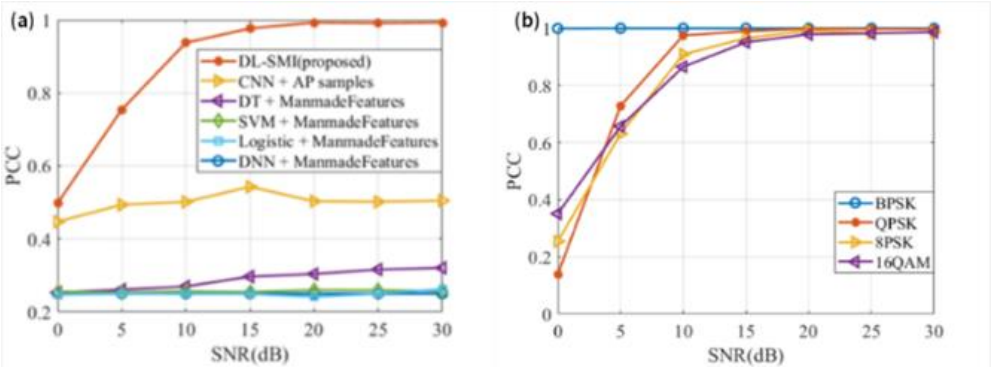


Fig 4. (a) Comparison of PCC using deep learning approach with conventional approach (b) Comparison of PCC with different modulation methods

In Fig. 4(b), a CNN trained on IQ samples depicts the probability of accurate classification for various modulations. The findings show that both low and high signal-to-noise ratios allow for accurate bPSK identification. The accuracy rate steadily stabilizes as the S/N ratio rises. Overall, these experimental findings suggest that the approach has a high signal modulation recognition accuracy.

This approach was chosen due to the prominence of deep learning in current research, as it possesses powerful data-driven and feature-learning capabilities that can automatically extract high-level features from extensive datasets. This enables the effective representation and classification of data, thereby resolving many complex and high-dimensional problems. IM-OFDM is also recognized as a critical technology for next-generation wireless communication systems, as it has diverse application scenarios and significant potential. The combination of the two has great potential in the future, extending beyond the abovementioned applications. Thus, the CNN-based IM-OFDM system optimization scheme represents an innovative and effective method for exploiting the full potential of IM-OFDM technology in the wireless communication field.

3.2. MIMO-OFDM-IM

Due to its advantages over single-antenna systems, multiple-input multiple-output (MIMO) transmission techniques have been the subject of intense research during the past 10 years. It is one of the MIMO options for the future generation of energy- efficient and spectrum-efficient communications systems.[2] MIMO-OFDM-IM is a high-performance multi-carrier transmission technology that may be thought of as a traditional MIMO-OFDM alternative. It was created by merging MIMO and OFDM-IM transmission techniques. Given the benefits of OFDM and MIMO transmission methods, its integration is unquestionably a potent substitute for 5G and wireless networks.

Fig. 4 displays the MIMO-OFDM-IM transceiver's block diagram [14]. A MIMO system with T transmit and R receive antennas is employed by the researcher. As shown in Fig. 5, the MIMO-OFDM-IM transmitter receives a total of mT information bits for each frame sent. The OFDM indexing modulator processes the associated m bits at each transmitter branch after first dividing these mT bits into T groups. At each transmitter branch, the m incoming information bits are utilized to create OFDM-IM blocks. These m bits are separated into groups G in accordance with the OFDM-IM concept to create OFDM-IM sub-blocks. Just K of the N sub-carriers are chosen by the index selector of each sub-block g as active sub-carriers; the other N-K sub-carriers are inactive and set to zero. In contrast, the remaining p2 = Klog2(M) bits are mapped into the M-ary signal constellation under consideration.

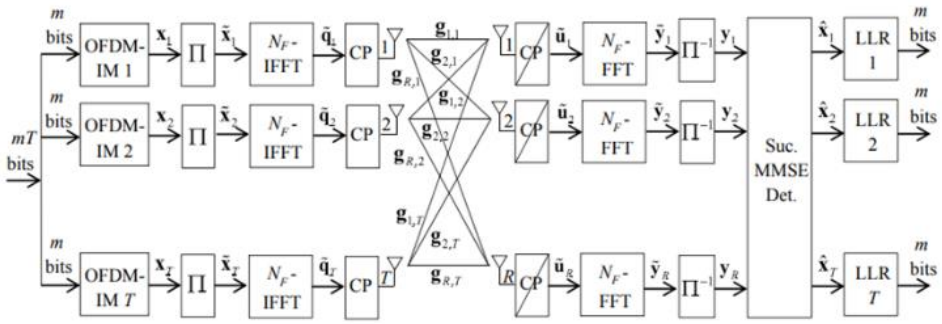


Fig 5. MIMO - OFDM - IM transceiver

The BER performance of the MIMO-OFDM-IM method with N = 4 and K = 2 is compared to the traditional V-BLAST-OFDM employing ML detector and BPSK modulation in Fig. 6[14]. Two MIMO configurations, 2×2 and 4×4, are taken into consideration. For these configurations, both techniques attain the same spectral efficiency values of 1.87 and 3.74 bits/s/Hz, respectively. As shown in Fig. 5, both schemes obtain a diversity order of R using ML detection. The MIMO-OFDM-OFDM-IM scheme significantly improves BER performance compared to the classical V-BLAST-OFDM.

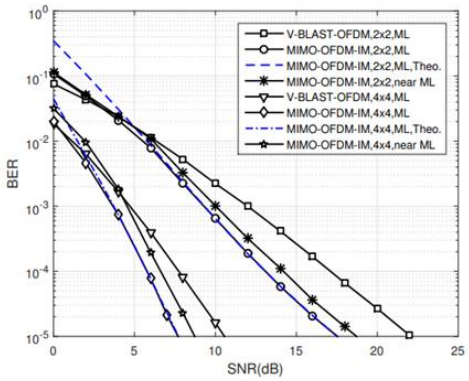


Fig 6. Performance comparison of V-BLAST-OFDM and MIMO-OFDM-IM

One of the MIMO options for spectrum-oriented and power-efficient next-generation communication systems is spatial modulation (SM). In recent years, SM has received a lot of research

attention and become a hot issue in the field of wireless communication. Many computer simulations have shown that MIMO-OFDM-IM schemes have made significant progress in complexity, spectral efficiency, and error performance.

3.3. LDPC coding-assisted subcarrier index protection scheme

As a forward error correction (FEC) technique, LDPC (low-density parity-check) codes are utilized in 5G NR, ATSC, and other most recent communication systems 3.0. To create fresh index information for subcarrier index modulation, the index information bits are LDPC coded at the transmitter side. If the spectral efficiency is equal to or higher than that of the traditional OFDM-IM transmission method, this technique can achieve improved BER performance.

The block diagram of the transmitter for an LDPC-encoded IM-OFDM-QOS system is shown in Fig. 7(a)[10]. The information bits are first put into the FEC encoder block and encoded using the LDPC and BCH codes. The LDPC code's parity-check matrix is applied in this case. The bit splitter divides the encoded bits into groups and assigns the constellation and index bits according on how many bits are needed for each group. Each group consists of three blocks: the QOS selector, the mapper, and the expander, which each individually conduct the constellation and IM mapping. Based on the input index bits, the QOS is chosen for expansion in the QOS selector. The constellation symbols are produced using the same mapper used in traditional OFDM systems. The constellation symbols are being sent to all of the group's sub-carriers using the spreader and the chosen QOS.

A block schematic of the receiver for an IM-OFDM-QOS system with LDPC coding is shown in Fig. 7(b)[10]. By the use of an N-point FFT, a CP remover, and a serial-to-parallel (S/P) converter, the received signal is transformed into the frequency domain.

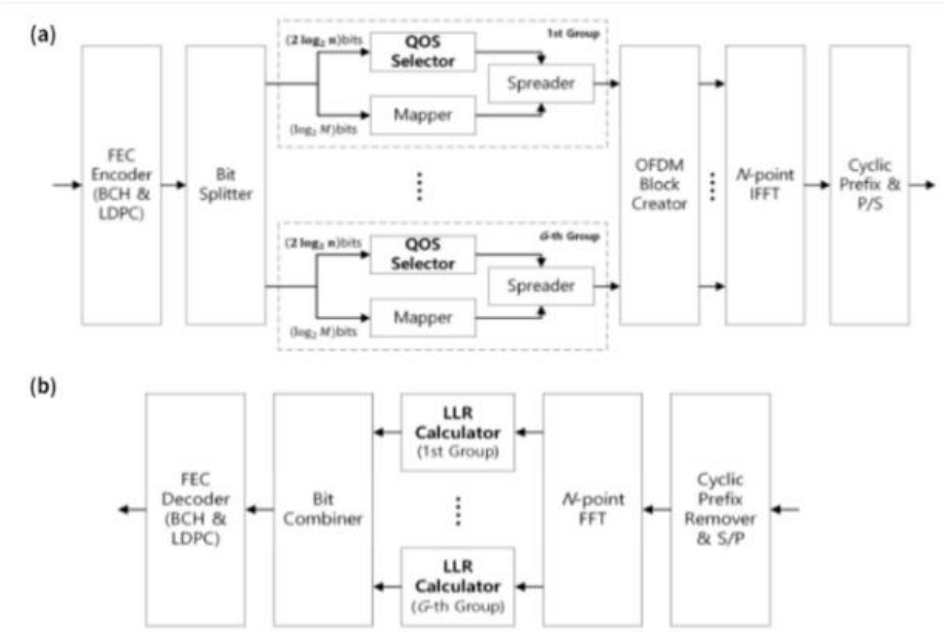


Fig 7. (a) Transmitter frame of an LDPC-encoded IM-OFDM-QOS system (b) Receiver frame of an LDPC-encoded IM-OFDM-QOS system

MATLAB software simulation verifies the BER performance of the proposed LDPC coding-assisted subcarrier index protection scheme. Fig. 8[9] gives the BER performance simulation results of the LA-OFDM-IM transmission scheme and the conventional OFDM-IM transmission scheme with BPSK modulation. LA-1 and LA-2 denote the indexed and modulated bits of the former, and LLR-1 and LLR-2 denote the indexed and modulated bits of the latter, respectively. As can be seen from Fig. 4, at a BER of 10-4, LA-OFDM-IM achieves a gain of about 19 dB compared to the indexed bit portion of OFDM-IM. The LA-OFDM-IM modulation bit part still achieves a gain of 5 dB due to the significant improvement in the correct SAP judgment rate. In terms of overall BER performance, the LA-OFDM-IM transmission scheme has a gain of around dB.

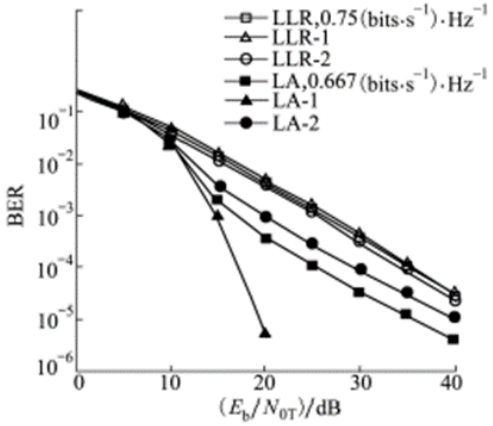


Fig 8. BER of different detection schemes

In OFDM-IM, the SAP judgment error of the LLR detection algorithm can seriously impact the overall BER performance. Based on the strong error correction capability of LDPC codes, the LDPC coding-assisted subcarrier index protection scheme proposed above can effectively reduce the error rate of SAP judgement by coding the index bits while designing the LA detection algorithm at the receiver side.

3.4. Contrast

Table 1. Comparison Of Three Technologies

	Deep learning based OFDM-IM optimization scheme	MIMO-OFDM-IM	LDPC coding-assisted subcarrier index protection scheme
Application objects	1.Various wireless communication systems and equipment	1.High-speed data transmission 2.Multi-user communication systems	1.High-speed, highly reliable wireless communication systems are required.
Research scenarios	1.Theoretical studies and simulation experiments for wireless communication systems 2.Next generation wireless communication systems	1.High-speed mobile communications 2.Large-scale antenna systems 3.Indoor local network 4.Internet of Things 5.Asymmetric Communication	1.Communication channels 2.Coding schemes 3.Modulation method 4.System Architecture
Methodological features	1.Adaptive 2.Reliable 3.Efficient and 4.General	1.Efficient 2.Robustness 3.Flexibility 4.Low cost 5.Wide range of applications	1.Low Density Parity Check Encoding 2.Modulation optimization 3.High-speed data transmission
Disadvantages	1.High training data requirements 2.Complex training process 3.Poor model interpretation 4.High system complexity	1.Higher complexity 2.High sensitivity 3.Technical standards are not yet mature 4.Limited reliability 5.Needs to be properly regulated	1.High system complexity 2.High requirements for latency and bandwidth 3.Sensitive to channel conditions 4.Frequency synchronization required

From the Tab. 1, all three methods are very helpful in optimizing the performance of OFDM-IM. However, because of the characteristics of their respective technologies, the three optimization schemes have their specialized application targets and different research scenarios. Because of the different optimization schemes, the characteristics of their methods vary, but the similarity is that they all contribute significantly to the improvement of the system performance of OFDM-IM, and have clear advantages in their respective application objects. However, considering that these technologies are relatively new, researchers need to continue to study them in-depth and improve them continuously. At present, all three techniques have certain drawbacks. The researchers' next goal is to overcome these disadvantages and maximize the advantages and minimize the disadvantages of the technologies.

4. Conclusion

In this paper, three OFDM-IM optimization schemes are discussed in detail: the deep learning-based OFDM-IM optimization scheme, MIMO-OFDM-IM, and the LDPC coding-assisted subcarrier index protection scheme. It is demonstrated that all three schemes are very helpful for the performance optimization of OFDM-IM. The deep learning-based IM-OFDM system optimization is significantly helpful for IM-OFDM for channel estimation, signal detection, and modulation classification. MIMO-OFDM-IM can improve the reliability of signal transmission and channel capacity. LDPC codes can effectively reduce the subcarrier error rate and improve the reliability and performance of IM-OFDM systems.

OFDM-IM is a new wireless communication technology based on the improvement of OFDM, its unique modulation and multiplexing technology makes it many advantages over OFDM. It can improve spectrum efficiency, strong anti-interference ability, low complexity, and other advantages. OFDM-IM is a promising wireless communication technology and a hot research topic today. OFDM-IM has a wide range of application prospects in several application fields, including 5G communication, Internet of Things, cable communication, wireless LAN, wireless TV, etc. The development prospect of OFDM-IM is very broad. It can be developed with higher spectral efficiency, better anti-jamming performance, higher data transmission rate, and lower power consumption. Through continuous technological innovation and optimization, it can meet more complex wireless communication needs and promote the development of the entire wireless communication field.

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