Dual-Mode OFDM-IM by Encoding All Possible Subcarrier Activation Patterns

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Abstract. In traditional orthogonal frequency division multiplexing with index modulation (OFDM-IM), when the subcarrier activation patterns (SAPs) is not a power of 2, part of SAPs will not be used. This will result in low transmission efficiency and low bit error rate (BER) performance. We have proposed a new scheme namely bit-padding dual-mode orthogonal frequency division multiplexing (BPDM-OFDM). It exploits all of the possible SAPs to convey data to obtain a better BER performance. Meanwhile, the BPDM-OFDM uses the dual-mode orthogonal frequency division multiplexing (DM-OFDM) to improve the transmission efficiency. In addition, a subcarrier interleaving technique is adopted to further improve the BER performance and the idea of hard limit algorithm, which is applied to the log-likelihood ratio detector (LLR-HL) to reduce the detection complexity. Significant performance improvement of the proposed scheme, in terms of transmission rate, detection complexity and BER performance, over the traditional OFDM-IM scheme has been validated through theoretical analysis and extensive simulations.

Keywords: OFDM-IM · BPDM-OFDM · Transmission efficiency · Bit-padding · LLR-HL detector

1 Introduction

Index modulation (IM) is one of the promising transmission schemes for next-generation wireless communication systems due to its advantages [1]. It utilizes the indices of the building blocks of the corresponding communication systems to convey additional information bits in contrast to traditional modulation schemes that rely on the modulation of the amplitude/phase/frequency of a sinusoidal carrier signal for transmission [2]. In orthogonal frequency division multiplexing with index modulation (OFDM-IM) system, a subset of subcarriers in an OFDM block is activated to convey constellation symbols, the indices of the active subcarriers can be used to convey additional information [3].

In the OFDM-IM system, the active subcarriers are selected by the incoming data [4]. The correct determination of a subcarrier activation pattern (SAP) is essential for

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the correct detection of the associated information bits. Different mapping and detection techniques have been proposed, which indicate two major problems.

First of all, the detectors suffer from the possibility of detecting an invalid SAP since not all of the possible SAPs are used in OFDM-IM. By now, a look-up table mapping method and a combinatorial mapping method are mainly proposed [5]. But the two methods share a common disadvantage that they cannot make full use of all SAPs, unless the number of the SAPs is a power of 2. In this case, a method of using unequal-length of index bits to exploit all SAPs is proposed [6], but it is difficult for detection and the BER performance decreases. By changing the number of information bits corresponding to the traditional amplitude phase modulation, and the information bits carried by the OFDM block maintain constant, the literature [7] proposed an equiprobable subcarrier activation method which is easy for detection, whereas the transmission efficiency is not improved compared with the traditional OFDM-IM system. In this paper, to achieve a better BER performance and higher transmission efficiency, we propose a constructed index bits mapping method which use the concept of bit-padding (BP) [8] to build an equal-length bits transmission scheme for dual-mode OFDM (BPDM-OFDM).

The second problem is how to reduce the detection complexity while maintaining high transmission efficiency. In [9], a dual-mode method is proposed to improve transmission efficiency, but the log-likelihood ratio (LLR) detection algorithm which is adopted has high complexity, especially under high order modulation [10]. In our BPDM-OFDM system, a reduced-complexity approximate optimal LLR detector based on the hard limit algorithm (LLR-HL) is employed, in which the modulation symbol is detected by directly calculation instead of traversing all constellation points after the active subcarriers are obtained [11].

It is shown via computer simulation that, under additive white Gaussian noise (AWGN) channels and frequency-selective Rayleigh fading channels, our proposed BPDM-OFDM achieves an overall better BER performance. And there is an increase of 1 bit/s/Hz in transmission efficiency and a much lower detection complexity achieved compared to the traditional OFDM-IM.

The rest of the paper is summarized as follows. In Section II, the system model of BPDM-OFDM is presented. In Section III, the constructed index bits mapping method, which is the main concept of BPDM-OFDM system, are introduced. The performance of BPDM-OFDM compared with OFDM-IM is analyzed in Section IV. Finally, Section V concludes the paper.

2 Methods

The number of subcarriers of OFDM-IM system is set as N, which is equal to the fast Fourier transform (FFT). A total of m information bits enter the OFDM-IM transmitter for the transmission of each OFDM block. These m bits are then split into g groups each containing p bits, i.e., $m = pg$. Each group of p-bits is mapped to an OFDM subblock. The number of subcarriers of each subblock is n, where $n = N/g$. Suppose that the number of active subcarriers of each group is k, the number of SAPs is given by the binomial coefficient $C(n, k)$. The specific SAP of a subblock is determined by mapping a p_1-bit data code, where $p_1 = \lfloor \log_2 C(n,k) \rfloor$ and $\lfloor \cdot \rfloor$ is the floor function. A data segment of $p_2 = k \log_2 M$ bits is used such that k data codes of length $\log_2 M$ bits are mapped onto the M-QAM signal constellation to determine the data symbols that are transmitted over the active subcarriers. Therefore, a total of p bits ($p = p_1 + p_2$) are mapped to an OFDM subblock of n subcarriers. This traditional OFDM-IM scheme is shown in Fig. 1.

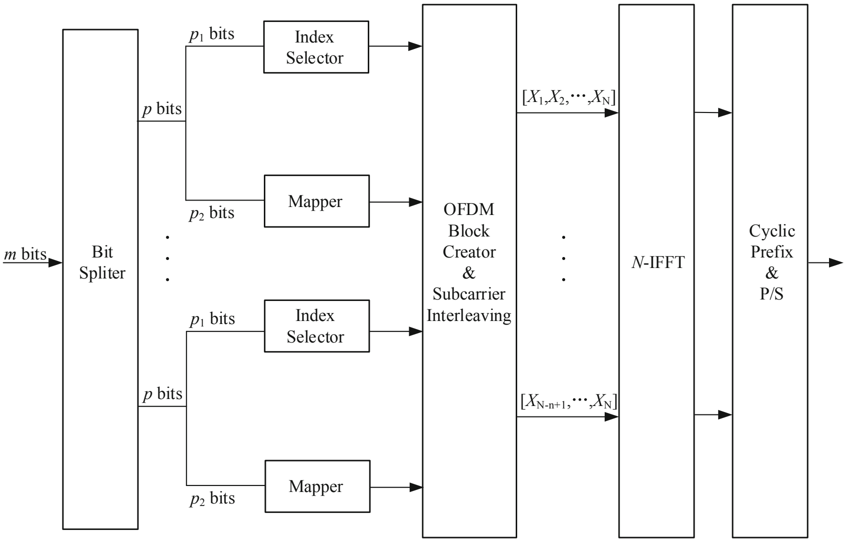

Fig. 1. The block diagram of the traditional OFDM-IM transmitter

As the OFDM-IM transmitter in Fig. 1, if the value of $C(n,k)$ is not a power of 2, there are always some SAPs that cannot be used. For example, for $n = 4$ and $k = 2$, the number of all possible SAPs is 6. Assume $p_1 = 2$ bits, the $2^{p_1} = 4$ SAPs are used. That means there are 2 invalid SAPs. In order to improve the transmission efficiency, we propose a constructed index bits mapping method to make use of all possible SAPs. Instead of the Index Selector and Mapper in Fig. 1, the p_1 bits will be processed by Backward Selection or Padding ‘1’ module according to the decimal value of p_1 bits. The detailed process will be discussed in Sect. 3. After the Backward Selection or Padding ‘1’ module, the constructed index bits are generated. Meanwhile, the p_2 bits are split into two parts and then modulated by the M_A and M_B order modulator, respectively. The value of M_A is equal to that of M_B, whereas the constellation points of M_A mapper and M_B mapper are different in amplitude and phase. This is called dual-mode index modulation (DM-IM) techniques. The block diagram of the above-mentioned scheme, which is called BPDM-OFDM transmitter is given in Fig. 2.

The transmitter combines g subblocks to form an OFDM symbol group. The N symbols are interleaved for the purpose of improving the error performance at low SNR region [12]. Then IFFT operation of point N is carried out to obtain the time domain transmitted signal $x = [x_1, x_2, \ldots, x_N]^T$, where $(\cdot)^T$ represents transpose operation. At

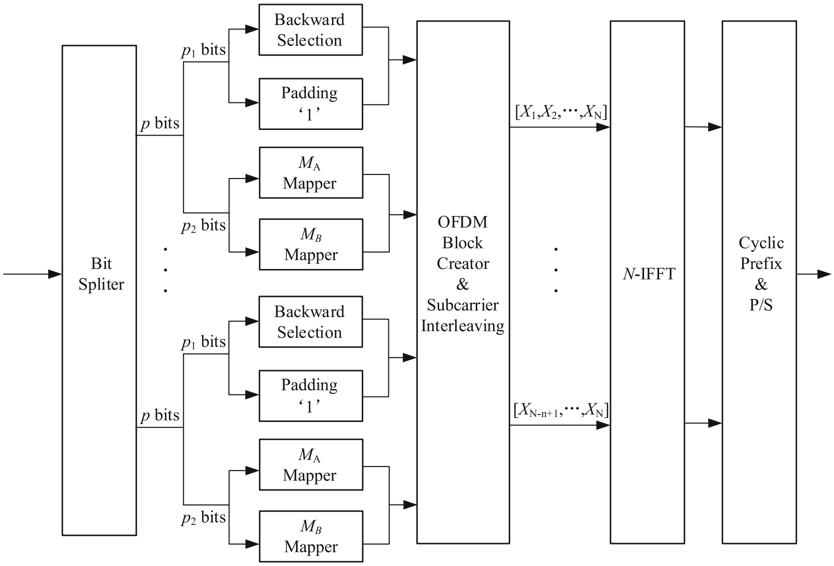

Fig. 2. The block diagram of the BPDM-OFDM transmitter

the output of IFFT, a cyclic prefix (CP) of length L samples $x = [x_{N-L+1}, \ldots, x_{N-1}, x_N]^T$ is appended to the beginning of the OFDM block. After parallel to serial (P/S) and digital-to-analog conversion, the signal is sent through a frequency-selective Rayleigh fading channel which can be represented by the channel impulse response (CIR) coefficients $h_T = [h_T(1)\ldots h_T(v)]^T$, in which $h_T(\sigma), \sigma = 1, \ldots, v$ are the cyclic symmetric complex Gauss random variable with $CN(0, \frac{1}{v})$ distribution, v represents the length of CIR. Supposing that the channel remains constant during the transmission of an OFDM block and the CP length L is larger than v, the coefficient of transfer function of frequency domain channel is the N-point FFT transform of h_T, which is represented as

$$\mathbf{H} = [H_1, H_2, \ldots, H_N]^T = \frac{1}{\sqrt{N}} FFT(\bar{h}_T) \tag{1}$$

where $\bar{h}_T = [h_T(1), \ldots, h_T(v), 0, \ldots, 0]^T$, $\frac{1}{\sqrt{N}} FFT(\cdot)$ represents FFT operation of point N.

At the receiver, after the CP removal operation and serial-to-parallel conversion, the FFT operation of point N and de-interleaving are performed to obtain the received signal $\mathbf{Y} = [Y_1, Y_2, \ldots, Y_N]^T$, where

$$Y_n = H_n X_n + W_n, 1 \le n \le N \tag{2}$$

In which W_n is the white Gaussian noise follows $CN(0, N_0)$ distribution.

In order to reduce the computational complexity, we use a low complexity log-likelihood ratio (LLR) algorithm to calculate the constellation diagram where the active symbols belonged. The basic idea is as follows: First, posterior probability is calculated according to formula (3), in which $1 \leq n \leq N$, $S_A(j) \in M_A$, $S_B(j) \in M_B$. If the sign of γ_n is positive, the subcarrier transmits the symbol modulated by M_A-QAM; if the sign of γ_n is negative, the subcarrier transmits the symbol modulated by M_B-QAM. Thus, the corresponding SAP is obtained.

$$\gamma_n = \ln\left(\frac{\sum_{j=1}^{M_A} \Pr(X_n = S_A(j)|Y_n)}{\sum_{j=1}^{M_B} \Pr(X_n = S_B(j)|Y_n)}\right) \tag{3}$$

Then, we determine the corresponding modulation symbol [11] of each subcarrier according to HL algorithm. Firstly, break the M-QAM symbols into N_1-PAM and N_2-PAM, where $M = N_1 \times N_2$. Then calculate the values of modulation symbols carried by the received signal Y_l of each subcarrier according to formula (4) and formula (5), in which $s_l = R(s_l) + j * I(s_l)$, $u_1 = R(Y_l)$, $u_2 = I(Y_l)$, and $R(\cdot)$ represents retrieving the real part, $I(\cdot)$ represents getting the imaginary part, $\min(\cdot)$, $\max(\cdot)$, round$(\cdot)$ represent the minimum, maximum and round values, respectively. It is unnecessary to search modulation symbols when using HL algorithm. So the computational complexity can be greatly reduced, especially in the condition of high order modulation.

$$R(s_l) = \min[\max(2\text{round}(\frac{u_1+1}{2}) - 1, -N_1 + 1), N_1 - 1] \tag{4}$$

$$I(s_l) = \min[\max(2\text{round}(\frac{u_2+1}{2}) - 1, -N_2 + 1), N_2 - 1] \tag{5}$$

3 The Constructed Index Bits Mapping Method

The constructed index bits mapping method includes the Backward Selection mode and the Padding ‘1’ mode. The main idea is described as follows: a total of m information bits enter the OFDM-IM transmitter for the transmission of each OFDM block, these m bits are split into g groups each containing p bits, i.e., $m = pg$. Select the first p_1 bits of the incoming p bits and convert the value of p_1 into a decimal number Z. Then, we compare the value of Z with $C(n,k) - 2^{p_1} - 1$. According to the results of the comparison, the algorithm decides to choose one of the two modes, Backward Selection or Padding ‘1’. The block diagram of the transmitter is given in Fig. 2.

(1) **Backward Selection:**
If $0 \leq Z \leq C(n,k) - 2^{p_1} - 1$, select one more bit after the first p_1 bits, so the index bits become a length of $p_1 + 1$ bits sequence, then take the next step according to the (p_1+1)-th bit. This is called Backward Selection.
  (a) If the (p_1+1)-th bit is ‘0’, the index value Z^I is equal to Z.

(b) If the $(p_1 + 1)$-th bit is ‘1’, the index value Z^I is equal to $Z + 2^{p_1}$.

(2) **Padding ‘1’:**
If $Z > C(n, k) - 2^{p_1} - 1$, padding ‘0’ or ‘1’ after p_1 bits, then the index bits of p_1 turn into $p_1 + 1$ bits. The index value Z^I is equal to Z. This is called Padding ‘1’.

We take $p_1 = 2, n = 4, k = 2$ as an example for each subblock, which is shown in Table 1. If the numeric value in the active subcarrier is ‘1’, it indicates that the corresponding subcarrier is activated, and ‘0’ indicates that the subcarrier is not activated.

Table 1. Constructed index bits mapping method when $p_1 = 2, n = 4, k = 2$

Index bit	Z	$C(n,k)$ $-2^{p_1} - 1$	Backward Selection or Padding ‘1’	Constructed index bits	Index value Z^I	Sequences J	Active subcarrier
00	0	1	Backward Selection	000	0	{1, 0}	[1, 1, 0, 0]
				001	4	{3, 1}	[0, 1, 0, 1]
01	1	1	Backward Selection	010	1	{2, 0}	[1, 0, 1, 0]
				011	5	{3, 2}	[0, 0, 1, 1]
10	2	1	Padding ‘1’	101	2	{2, 1}	[0, 1, 1, 0]
11	3	1	Padding ‘1’	111	3	{3, 0}	[1, 0, 0, 1]

If the $p_1 = 2$ information bits of the data stream are ‘00’, its decimal value is 0, that is, $Z = 0$. And $C(n, k) - 2^{p_1} - 1 = 6 - 2^2 - 1 = 1$, so $0 \leq Z \leq C(n, k) - 2^{p_1} - 1$ is derived, according to the algorithm, the one more bit after the first p_1 bits of the data stream will be selected. The ‘0’ or ‘1’ should be padded into the sequence after original index bits to form the new index bits sequence, which we named the Constructed Index Bits: If the subsequent bit is ‘0’, the $Z^I = 0$ is obtained by converting the new index bits ‘000’ into decimal form; If the subsequent bit is ‘1’, the $Z^I = 4$ is obtained by converting the new index bits ‘001’ to decimal plus 2^{p_1}, then $Z^I = Z + 2^{p_1} = 4$.

If the two information bits of the data stream are ‘10’, its decimal value is 2. $C(n, k) - 2^{p_1} - 1 = 6 - 2^2 - 1 = 1, 2 \geq 1$. Therefore, according to the algorithm, the information bit ‘1’ will be padded after the original index bits ‘10’, we get a new index bits ‘101’. Then the new index bits sequence ‘101’ is converted to the decimal form 2, that is $Z^I = 2$.

Each subblock adopts the bit-padding technique mentioned above, in the meantime a total of p_2 bits are sent to the M_A mapper and M_B mapper.

$$p_2 = k \log_2 M_A + (n - k) \log_2 M_B \qquad (6)$$

where M_A and M_B represent the modulation order. It is clear that the length of subcarrier indices of each OFDM-IM subblock are equal after bit-padding process, meanwhile the number of bits which carried in each subblock will be $p = (p_1 + 1) + p_2$ or $p = p_1 + p_2$. Because of Backward Selection, the former is 1 larger than the latter.

According to the value of Z^I, we use the combinational method to obtain the corresponding SAP as shown in formula (2) [5]. Among them, $c_k > \ldots > c_1 \geq 0$, which c_k represents the position corresponding to the activation of the subcarrier in each subblock. The number of active subcarriers satisfies $C(c_k,k) \leq Z^I$ and $C(c_{k-1},k-1) \leq Z^I - C(c_k,k)$, *etc*. Then the serial number of active subcarriers finally is $J+1$, $J = \{c_k,\ldots,c_1\}$.

$$Z^I = C(c_k,k) + \ldots + C(c_2,2) + C(c_1,1) \tag{7}$$

As an example, when $n=4, k=2, C(4,2)=6$, the algorithm, which finds the lexicographically ordered sequences for all possibilities, can be explained as follows: start by choosing the maximal c_k that satisfies $C(c_{k-1},2) \leq 5$ and then choose the maximum c_{k-1} that satisfies $C(c_{k-1},1) \leq 5 - C(c_k,2)$ and so on. The following sequences J can be calculated as:

$$\begin{aligned}
5 &= C(3,2) + C(2,1) \rightarrow J = \{3,2\} \\
4 &= C(3,2) + C(1,1) \rightarrow J = \{3,1\} \\
3 &= C(3,2) + C(0,1) \rightarrow J = \{3,0\} \\
2 &= C(2,2) + C(1,1) \rightarrow J = \{2,1\} \\
1 &= C(2,2) + C(0,1) \rightarrow J = \{2,0\} \\
0 &= C(1,2) + C(0,1) \rightarrow J = \{1,0\}
\end{aligned} \tag{8}$$

4 Results and Discussion

4.1 Transmission Efficiency

The number of data bits carried in each subblock of traditional OFDM-IM and the proposed BPDM-OFDM are as below:

OFDM-IM:

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

BPDM-OFDM:

a. Backward Selection:

$$p = (p_1 + 1) + p_2 = \lfloor \log_2 C(n,k) \rfloor + 1 + k \log_2 M_A + k \log_2 M_B$$

b. Padding ‘1’:

$$p = p_1 + p_2 = \lfloor \log_2 C(n,k) \rfloor + k \log_2 M_A + k \log_2 M_B$$

The comparison of the number of transmission data bits in each subblock between BPDM-OFDM and OFDM-IM systems for $n = 4, k = 2$ are shown in Table 2.

Table 2. Comparison of the number of data bits at $n = 4, k = 2$

Modulation mode	OFDM-IM	BPDM-OFDM (Backward Selection)	BPDM-OFDM (Padding '1')
BPSK	4	7	6
QPSK	6	11	10

Spectrum efficiency is calculated with $\rho = \frac{g(p_1 + p_2)}{N + L}$.with BPSK, the spectrum efficiency of OFDM-IM is 0.89 bit/Hz, and the spectrum efficiency of BPDM-OFDM is 1.56 bit/s/Hz or 1.33 bit/s/Hz; With QPSK modulation, the spectrum efficiency of OFDM-IM is 1.33 bit/Hz, and the spectrum efficiency of BPDM-OFDM is 2.45 bit/s/Hz or 2.22 bit/s/Hz. From the comparison it can be concluded that BPDM-OFDM system obtains higher spectrum efficiency.

4.2 Complexity Analysis

The total computational complexity of the detectors of OFDM-IM and BPDM-OFDM systems, in terms of real multiplications, are shown in Table 3.

Table 3. Complexity analysis

Model	Detection algorithm	Complexity	Example: $n, k, M = (4, 2, 4)$
OFDM-IM	ML	$\mathrm{O}(2CM^k)$	196
BPDM-OFDM	ML	$\mathrm{O}(6n^2 M_A M_B)$	1536
	LLR+ML	$\mathrm{O}(6nM_A + 6n(M_A + M_B))$	288
	LLR-HL	$\mathrm{O}(9n + 6n(M_A + M_B))$	228

In Table 3, $C = 2^{p_1}$ is the total number of active subcarrier index combinations, and $M_A = M_B = M$ is the order of modulation.

As shown in Table 3, the complexity of ML detection algorithm increases quadratically with the number of subcarriers N, and increases linearly with modulation order. When the transmitting terminal is equipped with dozens or even hundreds of subcarriers, the detection complexity of ML detector will be so large that makes it become impractical. In our proposed LLR-HL algorithm, the posterior probability is used to judge the dual-mode modulation constellation space. HL algorithm which can directly calculates modulation symbol is used to replace the full-search ML detection, so the LLR-HL detection algorithm can greatly reduce the complexity of detection and eliminate the problem that the complexity increases exponentially with N.

4.3 BER Analysis

In this subsection, simulation is carried out under AWGN channel and frequency-selective channel for the BPDM-OFDM with QPSK modulation and OFDM-IM with 16QAM modulation to ensure they have the same spectrum efficiency. In all simulations, we assumed the following system parameters: $N = 128$, $n = 4$, $k = 2$ and $L = 16$. The comparison of BER performance between OFDM-IM and BPDM-OFDM systems using different detection algorithms are shown in Figs. 3, 4 and 5.

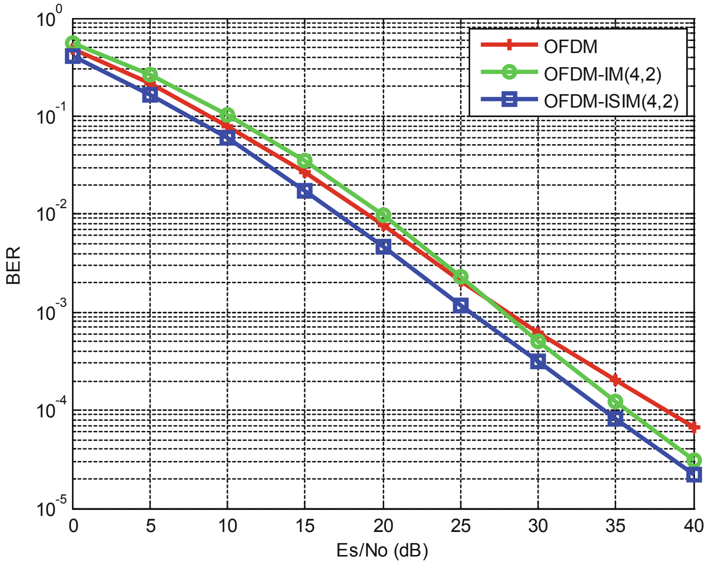

Fig. 3. Performance comparison of OFDM-IM with/without interleaving

As shown in Fig. 3, under BPSK modulation, the OFDM-IM with subcarrier interleaving (OFDM-ISIM) has obvious advantages over OFDM-IM and OFDM at medium to high SNR. At a BER value of 10^{-3}, the performance gap between OFDM-ISIM and OFDM-IM is about 7 dB. Therefore, we employ the subcarrier

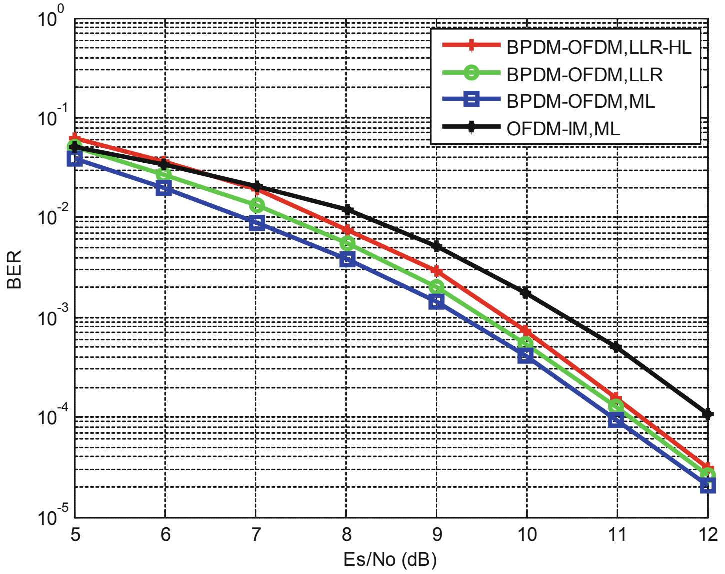

Fig. 4. Performance comparison of BPDM-OFDM over AWGN channel

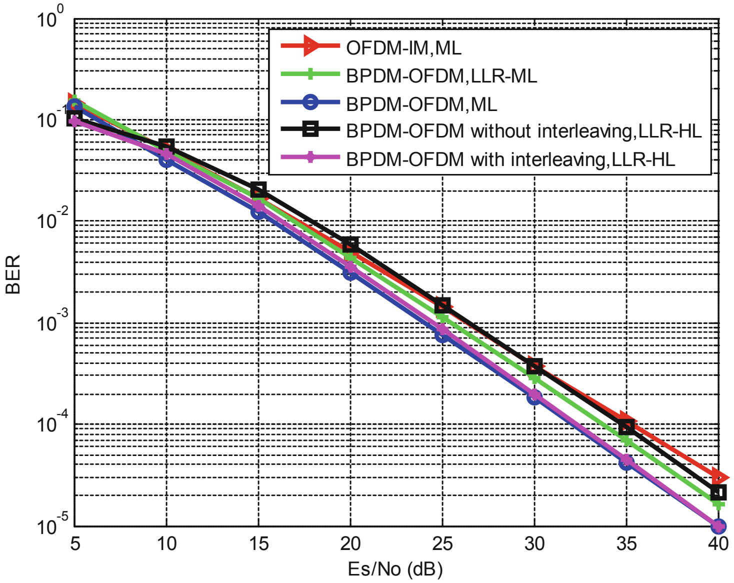

Fig. 5. Performance comparison of BPDM-OFDM over frequency-selective channels

interleaving to BPDM-OFDM, and the BER performance between BPDM-OFDM with/without interleaving is shown in Fig. 5.

As shown in Fig. 4, the proposed BPDM-OFDM achieves approximately 1 dB better than the BER performance of OFDM-IM when using the ML detection. When the LLR detection is used, there is about 0.1 dB performance loss comparing to the ML detection in the low SNR region. Considering the complexity of LLR detection is still high, the LLR-HR detection method is also compared. The BER performance of the proposed LLR-HL detection scheme is very close to that of the LLR detection. As we explained before, LLR uses the posterior probability to reduce the detector's search times, and LLR-HL can directly calculate the modulation symbols according to the real part and imaginary part of the received information after the modulation constellation diagram is decided. Although the LLR-HL detection exhibites a slight BER performance loss compared to ML detection, it achieves a great decrease in computational complexity.

As shown in Fig. 5, the performance of BPDM-OFDM is about 2 dB at the BER 10^{-3},which shows better performance than that of OFDM-IM. The reason is that under the same spectrum efficiency, BPDM-OFDM adopts QPSK modulation while OFDM-IM adopts 16QAM modulation with higher order. At a BER value of 10^{-3}, the LLR-HL algorithm without interleaving in BPDM-OFDM exhibits about 2 dB loss with ML algorithm. However, the BER performance of LLR-HL detection algorithm could reach the similar performance of ML detection with the interleaving technique.

5 Conclusion

In this paper, a novel BPDM-OFDM scheme has been presented based on dual-mode modulation with bit-padding and subcarrier interleaving techniques. The BPDM-OFDM system is proposed for exploiting all of the possible SAPs to convey data in order to improve transmission efficiency and BER performance in contrast with the traditional OFDM-IM system. A low complexity LLR-HL detection algorithm instead of ML detection is employed, which reduces the detection complexity distinctly. It is shown via computer simulation that the performance of BPDM-OFDM outperforms the traditional OFDM-IM. In follow-up research work, the lower order modulation method in OFDM-IM can be studied to further improve the system error performance and spectral efficiency [14]. The Gray-coded index mapping method was already reported to be used to reduce the index error rate of dual-mode system [14]. The structure of the dual-mode system has yet to be further improved.

Declarations

Availability of Data and Materials

Algorithm 1 Iteration LLR-HL Calculation for BPDM-OFDM

Require: Received signal Y_n, channel coefficient H_n, noise energy N_0, constellation sets M_A, M_B, $M = N_1 \times N_2$, and their sizes of OFDM subblock l, number of subcarriers modulated by mapper A per subblock k;

Ensure: γ_n is LLR of n-th subcarrier;

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$\Delta_1 = -\frac{1}{N_0}|Y_n - H_n S_A(j)|^2$
$\Delta_2 = -\frac{1}{N_0}|Y_n - H_n S_B(q)|^2$
for ( $j = 2; j \le M_A; j++$ ) do
    $T_1 = -\frac{1}{N_0}|Y_n - H_n S_A(j)|^2$
    $T_2 = \max\{\Delta_1, T_1\} + f(|\Delta_1 - T_1|)$
    $\Delta_2 = T_2$
end for
for ( $q = 2; j \le M_B; q++$ ) do
    $T_1 = -\frac{1}{N_0}|Y_n - H_n S_B(q)|^2$
    $T_2 = \max\{\Delta_2, T_1\} + f(|\Delta_2 - T_1|)$
    $\Delta_2 = T_2$
end for
$\gamma_n = \ln(k) - \ln(n-k) + \Delta_1 - \Delta_2$
return $\gamma_n$
If $\gamma_n > 0$ $D = \frac{H_n \times Y_n}{\|H_n\|^2}$
    Else $D = \frac{W}{(1+\sqrt{3}) \times \exp(-j \times \pi \times 0.75)}$
$u_1 = real(D), u_2 = imag(D)$
$R(s_l) = \min[\max(2round(\frac{u_1+1}{2}) - 1, -N_1 + 1), N_1 - 1]$
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References

1. Cheng, X., Zhang, M., Wen, M., Yang, L.: Index modulation for 5G: striving to do more with less. IEEE Wirel. Commun. **25**(2), 126–132 (2018)
2. Basar, E., Wen, M., Mesleh, R., Di Renzo, M., Xiao, Y., Haas, H.: Index modulation techniques for next-generation wireless networks. IEEE Access **5**, 16693–16746 (2017)
3. Abu-Alhiga, R., Haas, H.: Subcarrier-index modulation OFDM. In: 2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications, Tokyo, pp. 177–181 (2009)
4. Başar, E.: Multiple-input multiple-output OFDM with index modulation. IEEE Signal Process. Lett. **22**(12), 2259–2263 (2015)
5. Başar, E., Aygölü, Ü., Panayırcı, E., Poor, H.V.: Orthogonal frequency division multiplexing with index modulation. IEEE Trans. Signal Process. **61**(22), 5536–5549 (2013)
6. Siddiq, A.I.: Low complexity OFDM-IM detector by encoding all possible subcarrier activation patterns. IEEE Commun. Lett. **20**(3), 446–449 (2016)
7. Wen, M., Zhang, Y., Li, J., Basar, E., Chen, F.: Equiprobable subcarrier activation method for OFDM with index modulation. IEEE Commun. Lett. **20**(12), 2386–2389 (2016)
8. Yang, Y., Aissa, S.: Bit-padding information guided channel hopping. IEEE Commun. Lett. **15**(2), 163–165 (2011)
9. Mao, T., Wang, Q., Wang, Z.: Generalized dual-mode index modulation aided OFDM. IEEE Commun. Lett. **21**(4), 761–764 (2017)
10. Zheng, B., Chen, F., Wen, M., Ji, F., Yu, H., Liu, Y.: Low complexity ML detector and performance analysis for OFDM with in-phase/quadrature index modulation. IEEE Commun. Lett. **19**(11), 1893–1896 (2015)
11. Rajashekar, R., Hari, K.V.S., Hanzo, L.: Reduced-complexity ML detection and capacity-optimized training for spatial modulation systems. IEEE Trans. Commun. **62**(1), 112–125 (2014)
12. Başar, E.: OFDM with index modulation using coordinate interleaving. IEEE Wirel. Commun. Lett. **4**(4), 381–384 (2015)
13. Nambi, S.A., Giridhar, K.: Lower order modulation aided BER reduction in OFDM with index modulation. IEEE Commun. Lett. **22**(8), 1596–1599 (2018)
14. Li, X., Wang, H., Guan, N., Lai, W.: A dual-mode index modulation scheme with gray-coded pairwise index mapping. IEEE Commun. Lett. **22**(8), 1580–1583 (2018)