An Energy Sequencing Based Partial Maximum Likelihood Detection Method for Space-Frequency Joint Index Modulation System

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Abstract. In this paper, an energy sequencing based partial Maximum Likelihood (ML) detection algorithm is proposed for the complex characteristics of receiver detection in space-frequency joint index modulation system. This algorithm can solve the problems of high complexity from ML detection and poor Bit Error Rate (BER) performances by Minimum Mean Square Error (MMSE) detection. The major idea of the proposed algorithm is to demodulate the activated sub-carrier sequence number, antenna sequence number and constellation symbol step by step, where the sub-carrier sequence number is equalized with MMSE and the energy value of each sub-carrier is calculated and sorted. And the P value is set as the number of candidate sub-carriers. Finally, the sequence numbers of alternative sub-carriers, antenna serial numbers and constellation symbols are detected by ML. Simulation results show that the proposed algorithm can reduce both search range of traditional ML methods and the complexity according to the selection of P value. For example, when $P = 3$, the BER can be reduced to 10^{-4} at the SNR of 20 dB in the proposed algorithm.

Keywords: Maximum Likelihood (ML) · Space-Frequency joint index modulation · Bit Error Rate (BER) · Minimum Mean Square Error (MMSE)

1 Introduction

Traditional information transmission resources in spatial domain, frequency domain and time domain can no longer satisfy the growing demand for high-speed data transmission in 5G. Therefore, the combination of both spatial and frequency domain information sounds like a better idea, however, the dramatically increased numbers of

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antennas and sub-carriers have been causing new challenges at the receiver side. In order to solve aforementioned problems, Index Modulation (IM) technology makes a good use of the indexes of transmission medium, such as transmit antennas, sub-carriers, time slots or linear block codes, to modulate information bits by some kinds of mapping rules [1]. Due to the small power consumption of the transmission index bits, IM exploits a feasible trade-off between Spectral Efficiency (SE) and Energy Efficiency (EE), or in other words, the diversity gain and multiplexing gain. IM technology mainly includes Spatial Modulation (SM) and sub-carrier index modulation, both of which use IM to diminish interference and introduce index bits to compensate for the loss of SE. The difference in between is that SM is applied to select antennas, while sub-carrier index modulation is used for selecting sub-carriers. SM is a Multiple-Input Multiple-Output (MIMO) transmission method, which considers the transmitting antennas as a spatial constellation point to carry additional information bits [2]. By activating only one antenna at each time instant, SM system is insensitive to Inter-Channel Interference (ICI) and can suppress the requirement of Inter-Antenna Synchronization (IAS) [3]. Meanwhile, both the detection complexity and the cost of Radio-Frequency (RF) chain are reduced [4]. Thus, SM is regarded as a competitive successor to conventional MIMO techniques. Orthogonal Frequency Division Multiplexing with Index Modulation (OFDM-IM) [5] is an extension of sub-carrier index in SM concept in multi-carrier systems. Under certain conditions, the OFDM-IM scheme has also been proposed to provide higher throughput and better BER performance than plain OFDM. The OFDM-IM scheme also provides an interesting trade-off between complexity, SE and performance by changing the number of active sub-carriers [6].

In this paper, a new space-frequency joint index modulation system, SM-OFDM-IM, that combines SM with OFDM-IM is created [7]. This system combines antenna index in spatial domain and sub-carrier index in frequency domain. However, the receiver has much more strict requirements for channel independence, synchronization and poor real-time performance, and the symbol information that needs to be detected changes with it. In this system, the receiver requires to detect the antenna index bits, sub-carrier index bits and modulation bits. Therefore, it is an important content for index modulation to design a detection algorithm with low complexity and excellent BER performance. At present, there are very few detection algorithms like this proposed SM-OFDM-IM system. In [8], based on Sequential Monte Carlo (SMC) theory and extracts samples at sub-block level, a low complexity detection algorithm is proposed to achieve approximately optimal BER performance. The computational complexity is greatly reduced. But the algorithm only detects the sequence number of the active sub-carriers and constellation symbols, not the sequence number of the active antenna. A low complexity LLR detection algorithm for OFDM-IM system is proposed in [9]. Because the computational complexity of calculating the log likelihood ratio of each bit is extremely high due to the dependence between the sub-carriers caused by the sub-carrier index modulation. Simulation results show that the proposed algorithm achieves near-optimal BER performance with low computational complexity. However, the algorithm can not be directly applied to the proposed system.

Based on the research of signal detection algorithm in SM-OFDM-IM system, an energy sequencing based partial ML detection algorithm is proposed for the characteristics of the receiver. This algorithm reduces the search range of ML and can achieve the compromise between complexity and BER performance. The main contribution of this algorithm is to demodulate the active sub-carrier serial number, antenna sequence number and constellation symbol in sequence.

2 System Model

SM-OFDM-IM system is a combination, that not only SM, but also sub-carrier index modulation are applied to OFDM. The transmitted information is mapped to different combinations of transmit antennas, sub-carriers and modulation respectively, which reflects the flexibility of the implementation of SM-OFDM-IM system. The system model of SM-OFDM-IM is shown in Fig. 1. The active antenna is selected according to the antenna index bits, and the OFDM-IM modulation is carried out on the activated antennas. According to the sub-carrier index bits, some dedicated sub-carriers are chosen and activated. And corresponding constellation symbols are modulated on these sub-carriers. The reverse operation will be implemented at the receiver. Consider a SM-OFDM-IM system with n_t transmit antennas, one transmit RF chain and n_r receive antennas. The N sub-carriers are divided into G sub-carrier blocks of $n = N/G$. Binary bit stream is divided into three parts. The first part is used for sub-carrier index, which modulates $\lfloor \log_2 C_n^k \rfloor$ bits to determine a set of k active sub-carriers for transmission out of n available ones, and the sub-carrier configuration is (n, k), where $\lfloor x \rfloor$ is the greatest integer smaller than x and C_n^k represents the binomial coefficient. In second part, every $\lfloor \log_2 n_t \rfloor$ bits are used for choose 1 out of n_t transmit antennas. In third part, $k \log_2 M$ bits are modulated using $M - \mathrm{QAM}$ modulation to form the constellation symbol. Therefore, $\lfloor \log_2 C_n^k \rfloor + \lfloor \log_2 n_t \rfloor + k \log_2 M$ bits are transport at the transmitter, and the SE of SM-OFDM-IM in terms of bits per channel use (bpcu) is

$$R = \lfloor \log_2 C_n^k \rfloor + \lfloor \log_2 n_t \rfloor + k \log_2 M \ (bpcu) \tag{1}$$

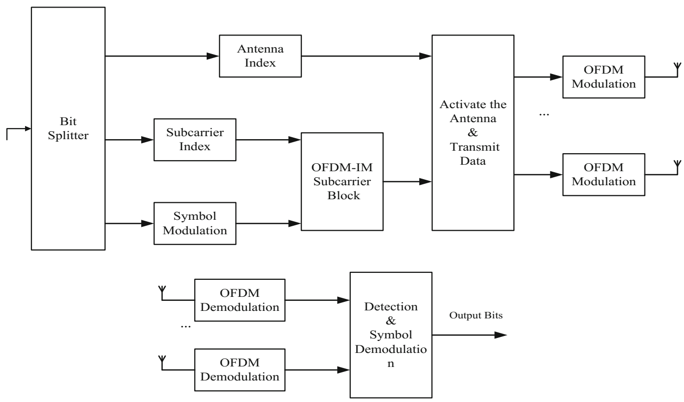

Fig. 1. System model of SM-OFDM-IM

According to the above description, the frequency domain form of the transmit signal $S_g \in C^{n_t \times n}$ of the g-th sub-block can be given by

$$\begin{aligned} S_g &= [s_1^g, s_2^g, \cdots, s_n^g] \\ &= \begin{bmatrix} s_{1,1}^g \cdots s_{1,n}^g \\ \vdots \\ s_{n_t,1}^g \cdots s_{n_t,n}^g \end{bmatrix}, g = 1, \cdots, G \end{aligned} \tag{2}$$

where its elements $S_{i,j}^g \in \{0, S\}, i = 1, 2, \cdots, n_t, j = 1, 2, \cdots, n$ represents the transmitted symbol at the j-th frequency in group g on antenna i, and S is the constellation set of $M - QAM$.

It is assumed that the wireless channels remain constant in the transmission of an SM-OFDM-IM symbol, the frequency domain received signal of SM-OFDM-IM is obtained as

$$y_j^g = H_j^g s_j^g + n_j^g \tag{3}$$

where $H_j^g \in C^{n_r \times n_t}$ is the frequency domain channel matrix at the j-th sub-carrier frequency of group g, whose elements follow i.i.d $CN(0,\ 1)$, y_j^g, $n_j^g \in C^{n_r \times 1}$ represents the received signal and frequency domain additive white Gaussian noise samples with variance σ^2 at the j-th sub-carrier frequency of group g. The system signal-to-noise ratio (SNR) is defined as $P_s/N_0 = 1/N_0$, where $P_s = 1$ is the normalized transmit power.

At the receiver, using the ML principle decodes the symbol, formula can be written as

$$[\hat{i},\ \hat{n},\ \hat{m}] = \underset{X \in \Lambda}{\arg\min} \|y - Hs\|_F^2 \tag{4}$$

where Λ denotes all possible transmit signal vector combinations.

3 A Partial Maximum Likelihood Detection Method

In the SM-OFDM-IM system, active antenna sequence numbers, sub-carrier serial numbers and constellation symbols should be detected at the receiver. However, the traditional detection methods of sole SM and OFDM-IM systems are not applicable. Therefore, both the joint detection and stepwise detection are proposed in the dedicated detection algorithms of SM-OFDM-IM system. In [10], the proposed Energy Detection (ED) algorithm for frequency-domain index modulation systems can achieve a bit error rate of 10^{-4} when SNR is 40 dB. But the performance becomes worse when it is applied to SM-OFDM-IM system directly, and the BER is always around 10^{-2}. On this basis, an energy order based partial ML detection algorithm is proposed in this paper.

The detection algorithm is listed as follows:

The received signal is detected in units of each sub-block. It is assumed that the g-th received sub-block is y_g, with the dimension of $n_t \times n$.

First, MMSE equalization. MMSE belongs to the linear detection algorithm. More precisely, it is based on the improved result of Zero Forcing (ZF) detection algorithm. It considers the effect of noise on the detection, so the weight matrix is designed as:

$$G_{MMSE} = (H^H H + \sigma^2 I)^{-1} H^H \tag{5}$$

Where σ^2 is the noise variance, and I is the $n_t \times n$ identity diagonal matrix. According to (5), the signal after the MMSE equilibrium is

$$\begin{aligned} \tilde{X}_{MMSE} &= G_{MMSE}\, y_g \\ &= \left(H^H H + \sigma^2 I\right)^{-1} H^H \times y_g \\ &= \tilde{S} + (H^H H + \sigma^2 I)^{-1} H^H \times N \\ &= \tilde{S} + \tilde{N}_{MMSE} \end{aligned} \tag{6}$$

where $\tilde{N}_{MMSE} = N \times G_{MMSE} = (H^H H + \sigma^2 I)^{-1} H^H \times N$.

Second, calculating the energy value of the signal after equalization, that is $E_{\tilde{X}_{MMSE}} = \left\|\tilde{X}_{MMSE}\right\|_2^2$, $\hat{E}_{\tilde{X}_{MMSE}}$ is obtained by summing the energy value of the estimated signal on each sub-carrier. And then was sorted by the size in terms of $\hat{E}_{\tilde{X}_{MMSE}}$, that is $[e_1, e_2, \cdots, e_N] = \arg sort(\hat{E}_{\tilde{X}_{MMSE}})$. It is believed that the sub-carrier with the highest energy is most likely to be activated sub-carrier.

Thirdly, the complexity of energy detection is low, but its detection performance is poor due to interference between multiple antennas and Gaussian noise. Therefore, we need to select P $(P = 1, 2, \cdots, n)$ sub-carrier sequence number with higher energy as candidate sub-carrier sequence number. If $P = 2$, select the two sub-carriers with top 2 highest energy value as candidate sub-carriers.

Fourth, the candidate sub-carrier sequence numbers, antenna sequence numbers and constellation symbols are used for ML detection, $D = \left\|y_g - H_g \tilde{x}_g\right\|_F^2 \cdot \tilde{x}_g$ is the transmission symbol for the g-th sub-block estimated according to above steps. Considered that the combination of minimum Euclidean distance is the final detection result. The complexity of the algorithm varies with the value of P.

Finally, $g = g + 1$, repeat above steps and get the detection results of all sub-blocks.

In this detection algorithm, the energy detection is applied to reduce the traversal range of sub-carriers, and then the partial ML detection is carried out on this basis, which narrows the traversal range of ML and reduces the complexity. For the above algorithm, it is very important to determine the order of energy value of the estimated signal. In order to further reduce the complexity, the cost function can be changed to ZF criterion, that is ZF-ML, instead of the MMSE that used in above paper. The simulation results will be compared in Sect. 4.

4 Numerical Results

In this section, the BER performance of the proposed SM-OFDM-IM system, the OFDM and the OFDM-IM scheme are compared by computer simulations under Gaussian noise, as described below.

In order to ensure that OFDM, OFDM-IM and SM-OFDM-IM have the same SE, the simulation parameters of OFDM-IM and SM-OFDM-IM systems are presented in Table 1. The BER performance is given in Fig. 2. Figure 3 is a comparison of Peak Average Power Ratios (PAPR) between OFDM and OFDM-IM systems.

Table 1. OFDM-IM and SM-OFDM-IM systems parameters

Parameters	Vaules of OFDM-IM	Vaules of SM-OFDM-IM
Number of transmit antennas (n_t)	1	2
Number of receive antennas (n_r)	1	2
Number of sub-carriers (N)	128	64
Length of cyclic prefix	32	16
Number of sub-block (G)	64	32
Sub-carrier configuration	(2, 1)	(2, 1)
Simulation channel	Rayleigh fading channel	Rayleigh fading channel
Modulation mode	BPSK	QPSK

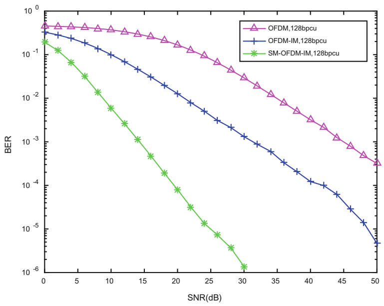

Fig. 2. BER of OFDM, OFDM-IM, SM-OFDM-IM systems

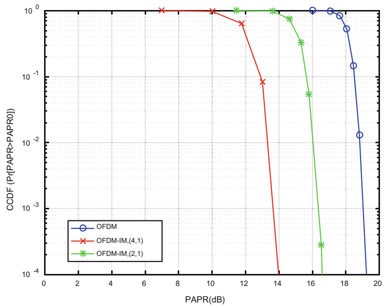

Fig. 3. PAPR of OFDM and OFDM-IM systems

From Fig. 2, at a BER value of 10^{-3}, it can be observed that the SM-OFDM-IM system achieves approximately 30 dB and 15 dB better BER performance than the OFDM and OFDM-IM at the same spectrum efficiency, respectively. This is due to the fact that SM-OFDM-IM adds sub-carrier index and antenna index to transmit data. While the other sub-carriers and antennas remain silent, the sparsity of frequency domain data reduces the sensitivity of the system to frequency offset and the influence of inter-carrier interference on transmission performance. In spatial domain, only one antenna is activated and inter-antenna interference is thereby avoided. SM-OFDM-IM can reduce the SE because of the silence of some sub-carriers and some antennas, and the introduction of index bit information can make up for the transmitting rate. As the result, SM-OFDM-IM is a more promising multi-carrier system than OFDM because of its unique system setting and more flexible parameter configuration.

From Fig. 3, it can be observed that OFDM-IM system have lower PAPR values than conventional OFDM systems under the same number of sub-carriers and the same modulation order. The smaller the number of active sub-carriers is, the lower the PAPR value of OFDM-IM system is.

On the basis of SM-OFDM-IM system model, the impact of different detection methods on BER are compared in this section. The BER performance of the proposed detector, the ML detector and ZF-ML detector with $n_t = 4$, $n_r = 4$, $N = 128$ and the sub-carrier configuration is (4, 1) for BPSK constellations are presented in Fig. 4. And the BER performance with different sizes of P is given in Fig. 5.

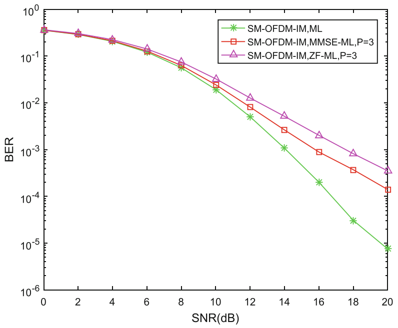

Fig. 4. BER of SM-OFDM-IM system of different detection methods

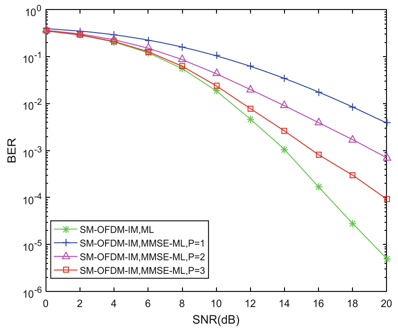

Fig. 5. BER of SM-OFDM-IM system of different P values

As shown in Fig. 4, the proposed detection algorithm achieves almost 2 dB better BER performance than ZF-ML at the BER value of 10^{-3}. This is because MMSE takes the effect of noise into account. But compared with the ML detection method, the proposed method reduced the complexity at the cost of a lost of about 4 dB BER performance at the value of 10^{-4} due to the smaller search range.

According to the introduction in Sect. 3, the BER performance of SM-OFDM-IM system varies with P values. As shown in Fig. 5, the higher of P values, the larger the search ranges, the higher the complexity and the better the BER performance will be achieved. When P = 4, that is the ML detection, the BER performance is the best and the complexity is highest.

The computational complexity in terms of the complex multiplications performed per sub-block for different detectors is given in Table 2.

Table 2. A total multiplicative computational complexity of different detectors

Different type of decoders	Computational complexity
ML	$(\frac{(n+n_r)n_t}{2}\log_2\frac{n}{2}+n_r n_t^2)M^{nn_t}\sim o(M^{nn_t})$
Proposed partial ML	$10n_t^2 n_r+11nn_t+n_t+(\frac{(n+n_t)n_r}{2}\log_2\frac{n_t}{2}+n_r n_t^2)M^{Pn_t}\sim o(M^{Pn_t})$
ZF-ML	$10n_t^2 n_r+11nn_t+(\frac{(n+n_t)n_r}{2}\log_2\frac{n_t}{2}+n_r n_t^2)M^{Pn_t}\sim o(M^{Pn_t})$

As expected, the calculation complexity of the proposed energy sequencing based partial ML is rather low compared with that of the ML detector. This can be explained that the proposed detector narrows the range of ML by introducing energy ordering. The complexity of the algorithm is slightly higher than that of ZF-ML due to the difference of the weight matrix.

5 Conclusion

In this paper, simulation results has proved that the BER performance of SM-OFDM-IM system outperforms OFDM-IM and OFDM. Then, an energy sequencing based partial ML detection algorithm is proposed for the complex characteristics of the receiver in SM-OFDM-IM system and solved problems of traditional detection methods. The major idea of the algorithm is to demodulate the activated sub-carrier serial numbers, antenna sequence numbers and constellation symbols step by step. The sequence number of sub-carriers is equalized with MMSE, and the energy value of each sub-carrier is obtained, and the number of candidate sub-carriers is set as P value. Then the sequence numbers of partial sub-carriers, antenna serial numbers and constellation symbols are detected by ML. The simulation results show that the proposed algorithm can reduce the search range of traditional ML and reduce the complexity of the algorithm according to the selection of P.

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