Single-FFT Receiver With Pairwise Maximum Likelihood for Layered ACO-OFDM

Jianfeng Li, *Member, IEEE*, Xiaoshuang Liu, *Member, IEEE*, Yahao Ren, and Zhitong Huang

***Abstract*—A single Fourier transform (FFT) receiver with pairwise maximum likelihood (ML) is proposed for layered asymmetrically clipped optical orthogonal frequency division multiplexing (LACO-OFDM). To improve the single-FFT receiver, the pairwise ML detection is made in time domain after a layer diversion in LACO-OFDM. With only one FFT block, the proposed receiver has a low complexity. Simulation results show that the proposed receiver has the better bit error ratio (BER) performance than the conventional iterative scheme for the LACO-OFDM system with 2 layers in additive white Gaussian noise (AWGN) channel. Furthermore, it is proved that compared with the conventional iterative receiver, the proposed receiver is less sensitive to the clipping distortion. As the nonlinearity increased, the proposed scheme can outperform the conventional iterative solution in nonlinearity channel for LACO-OFDM in visible light communications.**

***Index Terms*—Layered asymmetrically clipped optical orthogonal frequency division multiplexing (LACO-OFDM), pairwise maximum likelihood, nonlinearity channel, visible light communications.**

I. Introduction

Visible light communication (VLC) is a typical intensity modulation/direct detection (IM/DD) system, in which the input electrical current to a light emitting diode (LED) must be nonnegative and real-valued [1]. There are some unipolar techniques such as on-off keying (OOK) [2], *M*-ary pulse-amplitude modulation (*M*-PAM) [3], direct current biased optical orthogonal frequency division multiplexing (OFDM) (DCO-OFDM) [4], asymmetrically clipped optical OFDM (ACO-OFDM) [5], and Flip-OFDM [6]. ACO-OFDM without DC bias is a power efficient scheme. However, in ACO-OFDM only odd subcarriers are modulated, which leads to the loss of half of the spectral efficiency.

To improve the spectral efficiency, some superposition optical OFDM techniques have been proposed. Dissanayake *et al*. have proposed asymmetrically clipped DC biased optical OFDM (ADO-OFDM), in which odd subcarriers are modulated for ACO-OFDM and even subcarriers are also modulated for DCO-OFDM [7]. The ACO-OFDM and DCO-OFDM frames are superimposed in time domain and transmitted simultaneously. Unfortunately a DC bias is also required for ADO-OFDM. Ranjha *et al*. have proposed a similar method called hybrid ACO-OFDM (HACO-OFDM), in which even subcarriers are modulated by *M*-PAM [8]. Tsonev *et al*. have proposed a technique named enhanced unipolar OFDM (eU-OFDM) to improve the spectral efficiency of U-OFDM, in which multiple U-OFDM frames are superimposed in time domain [9]. Similar superposition techniques have been introduced such as spectral and energy efficient OFDM (SEE-OFDM) [10], layered ACO-OFDM (LACO-OFDM) [11], augmented spectral efficiency discrete multi-tone (ASE-DMT) [12], layered asymmetrically clipped optical single-carrier frequency-division multiplexing (LACO-SCFDM) [13], and interleaved discrete-Fourier-transform-spread LACO-OFDM [14]. Lowery has given a performance comparison for superposition optical OFDM techniques, which shows that LACO-OFDM is the most efficient technique with a given spectral efficiency [15]. However, in these superposition optical OFDM systems, multiple layers are distinguished and recovered by the iteration of inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT), which may increase the complexity for the receiver. In our previous work, a receiver with single-FFT has been proposed to decrease the complexity for LACO-OFDM systems [16]. In the proposed receiver, layers are recovered by a layer division in time domain without IFFT/FFT pairs. It has been shown that the single-FFT receiver is a low complexity design. However, without the iterative detection, the single-FFT receiver may have the interference between layers of LACO-OFDM, which leads to $1 \sim 3$ dB signal to noise ratio (SNR) penalty in additive white Gaussian noise (AWGN) channel.

To enhance the performance for the single-FFT receiver, in this paper, a pairwise maximum likelihood (ML) detection is proposed in LACO-OFDM. The pairwise ML detection is a very simple method, which has been developed by Asadzadeh *et al*. for ACO-OFDM systems [17], which can improve the single-FFT receiver for LACO-OFDM systems. With the pairwise ML detection, half of the samples in time domain are forced to zeros, and the noise is reduced by half theoretically. Simulation results compare the performance of the proposed scheme with the conventional technique in AWGN and amplitude clipping channel.

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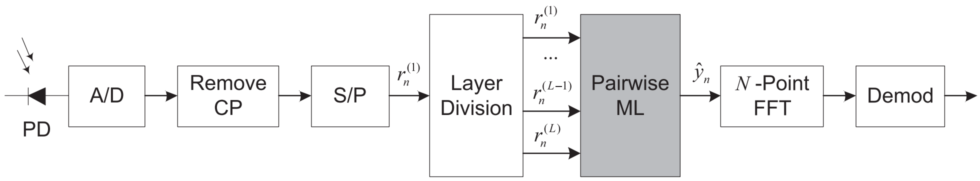

Fig. 1. Block diagram of proposed receiver for the LACO-OFDM based VLC system.

The rest of this paper is organized as follows. In Section II, the pairwise ML receiver with single FFT is proposed. In Section III, the simulation results and discussion are presented. Finally, a conclusion is drawn in Section IV.

II. Proposed Receiver

In the transmitter of LACO-OFDM, subcarriers are divided into subgroups to construct different layers. For Layer l, the k-th subcarrier signal in frequency domain is

$$X_k^{(l)} = \begin{cases} X, & k \in K_{\text{ACO}}^{(l)}, \\ 0, & \text{otherwise}, \end{cases} \tag{1}$$

where $K_{\text{ACO}}^{(l)}$ denotes the data-carrying subcarrier for Layer l, which can be given by [18]

$$K_{\text{ACO}}^{(l)} = \left\{1 \times 2^{l-1}, 3 \times 2^{l-1}, 5 \times 2^{l-1}, \ldots, N - 2^{l-1}\right\}. \tag{2}$$

In LACO-OFDM, $X_k^{(l)}$ has Hermitian symmetry in frequency domain: $X_k^{(l)} = X_{N-k}^{(l)*}$. After the operation of IFFT, the LACO-OFDM signal for Layer l in time domain is

$$x_{\text{ACO},n}^{(l)} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k^{(l)} \exp\left(\frac{j2\pi nk}{N}\right), \quad n = 0, 1, \ldots, N-1. \tag{3}$$

The negative parts of $x_{\text{ACO},n}^{(l)}$ can be clipped without loss of information:

$$\left\lfloor x_{\text{ACO},n}^{(l)} \right\rfloor_C = \begin{cases} x_{\text{ACO},n}^{(l)}, \; x_{\text{ACO},n}^{(l)} \geq 0 \\ 0, \; x_{\text{ACO},n}^{(l)} < 0 \end{cases}, n = 0, 1, \ldots, N-1, \tag{4}$$

where $\lfloor \cdot \rfloor_{\text{C}}$ denotes the operator of negative clipping at zero. All layers of $\lfloor x_{\text{ACO},n}^{(l)} \rfloor_{\text{C}}$ can be combined as

$$x_{\text{LACO},n} = \sum_{l=1}^{L} \left\lfloor x_{\text{ACO},n}^{(l)} \right\rfloor_{\text{C}}, \quad n = 0, 1, \ldots, N-1, \tag{5}$$

where L is the number of layers for LACO-OFDM.

The proposed receiver for LACO-OFDM systems is depicted in Fig. 1. In VLC systems, a photodiode (PD) is generally used to convert the received intensity of incident light into electrical signal. After cyclic prefix (CP) removal, analog-to-digital (A/D) conversion and serial-to-parallel (S/P) conversion, the received signal $r_n^{(1)}$ is input into a layer division to distinguish different layers. In the layer division, different layers are separated by the

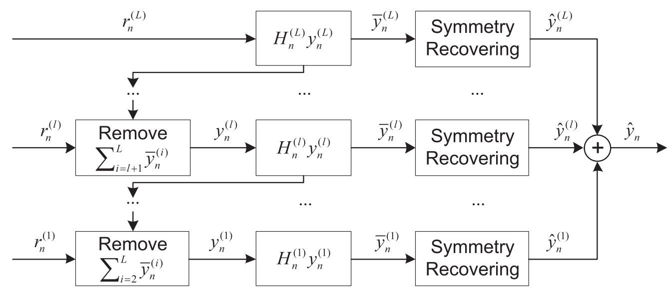

Fig. 2. Block diagram of the proposed pairwise ML for LACO-OFDM.

operation of symmetry recovering, which can be written as [16]

$$\widehat{y}_n^{(l)} = \begin{cases} r_n^{(l)} - r_{n+N/2^l}^{(l)}, & \bmod\,(n, N/2^{l-1}) < N/2^l \\ r_{n+N/2^l}^{(l)} - r_n^{(l)}, & \bmod\,(n, N/2^{l-1}) \geq N/2^l \end{cases}, \tag{6}$$

for $n = 0, 1, \ldots, N - N/2^l - 1$, where $\widehat{y}_n^{(l)}$ is Layer l ACO-OFDM signal after the layer division, $r_n^{(l)}$ is the superposed layer from Layer l to Layer L and mod($\cdot$, N) is the modulo N operator. The higher layer will be

$$r_n^{(l+1)} = r_n^{(l)} - \left\lfloor \widehat{y}_n^{(l)} \right\rfloor_{\text{C}}, \quad n = 0, 1, \ldots, N-1. \tag{7}$$

With the iteration loop of Eq. (6) and Eq. (7), we can have the received signal from $r_n^{(1)}$ to $r_n^{(L)}$, which are input to the proposed pairwise ML.

Fig. 2 shows the proposed pairwise ML for LACO-OFDM. The highest layer ($l = L$) has the following equation: $r_n^{(L)} = y_n^{(L)}$, which is directly input to the pairwise ML detector according to Eq. (9) and Eq. (10). Layer l ($l < L$) signal $y_n^{(l)}$ is given by

$$y_n^{(l)} = r_n^{(l)} - \sum_{i=l+1}^{L} \overline{y}_n^{(i)}, \quad n = 0, 1, \ldots, N-1, \tag{8}$$

where $\overline{y}_n^{(l)}$ denotes Layer l signal after the pairwise ML according to Eq. (11). The ML detector for Layer l signal ($1 \leq l \leq L$) can be written as

$$H_n^{(l)} = \begin{cases} 1, \left(y_n^{(l)} > y_{n+N/2^l}^{(l)}\right), & \bmod\,(n, N/2^{l-1}) < N/2^l \\ 0, \left(y_n^{(l)} \leq y_{n+N/2^l}^{(l)}\right), & \bmod\,(n, N/2^{l-1}) < N/2^l \end{cases} \tag{9}$$

for $n = 0, 1, \ldots, N - N/2^l - 1$ and

$$H^{(l)}_{n+N/2^l} = 1 - H^{(l)}_n, \quad \bmod\ (n, N/2^{l-1}) \ge N/2^l, \quad (10)$$

for $n = 0, 1, \ldots, N - N/2^l - 1$. Layer l signal $y^{(l)}_n$ follows a pairwise clipping as

$$\bar{y}^{(l)}_n = H^{(l)}_n y^{(l)}_n, \quad n = 0, 1, \ldots, N - 1. \quad (11)$$

After the pairwise clipping, half of samples of ACO-OFDM are clipped at zero while others are unaltered, by which the noise power can be reduced by half theoretically [19]. Layer l ACO-OFDM signal $\hat{y}^{(l)}_n$ with asymmetry is given by

$$\hat{y}^{(l)}_n = \begin{cases} \bar{y}^{(l)}_n - \bar{y}^{(l)}_{n+N/2^l}, & \bmod\ (n, N/2^{l-1}) < N/2^l \\ \bar{y}^{(l)}_{n+N/2^l} - \bar{y}^{(l)}_n, & \bmod\ (n, N/2^{l-1}) \ge N/2^l \end{cases}, \quad (12)$$

for $n = 0, 1, \ldots, N - N/2^l - 1$. After the operation of symmetry recovering according to Eq. (12), all layers of ACO-OFDM after the pairwise ML can be combined:

$$\hat{y}_n = \sum_{l=1}^{L} \hat{y}^{(l)}_n. \quad (13)$$

Then, a single FFT block is enough to realize demodulation.

In the single-FFT receiver, the complexity of layer division is $\sum_{l=1}^{L} \mathrm{O}(N) + 2\sum_{l=1}^{L-1} \mathrm{O}(N)$, which has been illustrated in [16]. In the proposed pairwise ML, there are L–1 iterations of N-point subtraction for the operation of removal, and L iterations of N-point multiplication are required for the pairwise clipping. The operation of symmetry recovering with N-point requires L iterations as well. The complexity for the layer division and pairwise ML can be written as $3\sum_{l=1}^{L} \mathrm{O}(N) + 3\sum_{l=1}^{L-1} \mathrm{O}(N)$, which can be reducible to $\mathrm{O}(LN)$. Besides, A N-point FFT block is used, which has the complexity of $\mathrm{O}(N\log_2 N)$. It mainly determines the complexity of the receiver. Therefore, the complexity of the proposed receiver can be written as

$$C = \mathrm{O}(N\log_2 N) + 3\sum_{l=1}^{L} \mathrm{O}(N) + 3\sum_{l=1}^{L-1} \mathrm{O}(N) = \mathrm{O}(N\log_2 N) + \mathrm{O}(LN). \quad (14)$$

III. Numerical Results

Simulation results are presented in this section. LACO-OFDM systems with 2, 3 and 4 layers in AWGN and amplitude clipping channel are studied. Bit error ratio (BER) performances of the proposed receiver and its conventional counterpart are evaluated in terms of the bit energy to noise power ratio E_b/N_0. The total number of subcarriers N is set to 1024. The subcarriers are modulated by M-ary quadrature amplitude modulation (M-QAM).

Fig. 3 illustrates the BER performance of LACO-OFDM with the proposed receiver (pro), the conventional iterative receiver (con) [11] and the single-FFT receiver (sin) [16] in AWGN channel. In the conventional LACO-OFDM, the subcarrier power for Layer l P_l is allocated by $P_1 = P_2 = P_3 = P_4$. In the single-FFT based LACO-OFDM system, P_l is loaded with $8P_1 = 4P_2 = 2P_3 = P_4$ [16]. The power allocation for the proposed scheme is shown in Table I. With strategies in Table I, different layers in LACO-OFDM have almost the same BER performance for the proposed receiver to achieve the lowest BER. For example, in Fig. 4, with the power allocation of $P_2 = 1.7P_1$ and $P_3 = 1.4P_2$, each layer in the LACO-OFDM of 16-QAM and 3 layers has almost the same BER performance for the proposed receiver. As shown in Fig. 3, with the pairwise ML, some SNR gain will be available for the receiver with single-FFT. Compared with the single-FFT receiver in [16], the proposed receiver can have the SNR gain of 1.5 dB, 1.1 dB, and 0.8 dB at 7% forward error correction (FEC) limit (BER $= 3.8 \times 10^{-3}$) for LACO-OFDM of 2, 3 and 4 layers respectively. The interference between layers increases with the number of layers, which causes the SNR gain to be lower for the LACO-OFDM with more layers. It is surprising that for the LACO-OFDM of 2 layers, the performance of the proposed receiver outperforms the conventional iterative solution.

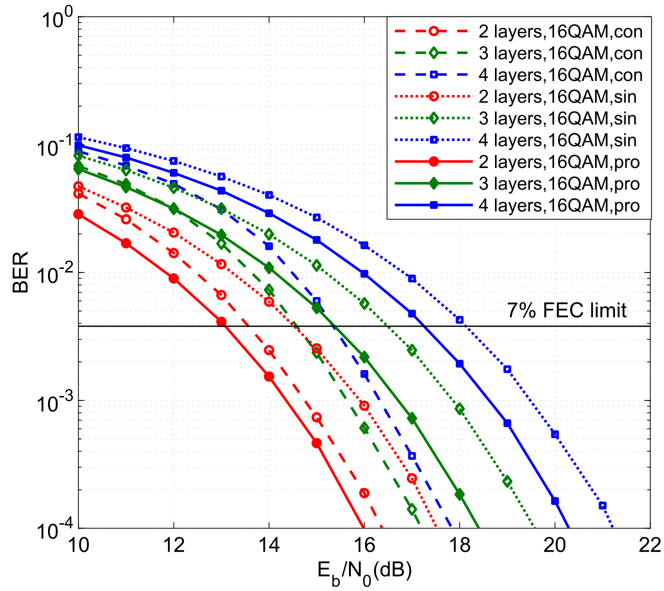

Fig. 3. BER performance of LACO-OFDM with 16QAM for the conventional iterative receiver, the single-FFT receiver and the proposed receiver.

TABLE I
List of Parameters for Fig. 3, Fig. 4, Fig. 5 and Fig. 6

Layers	M-QAM	Power allocation for the proposed scheme
2	4QAM	$P_2 = 1.45P_1$
	16QAM	$P_2 = 1.45P_1$
	64QAM	$P_2 = 1.45P_1$
3	4QAM	$P_2 = 1.7P_1$, $P_3 = 1.4P_2$
	16QAM	$P_2 = 1.7P_1$, $P_3 = 1.4P_2$
	64QAM	$P_2 = 1.7P_1$, $P_3 = 1.4P_2$
4	16QAM	$P_2 = 1.8P_1$, $P_3 = 1.72P_2$, $P_4 = 2.6P_2$

Fig. 5 and Fig. 6 show the BER performance of LACO-OFDM of 2 and 3 layers. The proposed receiver has the SNR gain of 1 dB, 1.5 dB, and 1.7 dB at 7% FEC limit for the LACO-OFDM with 4QAM, 16QAM and 64QAM, comparing with the single-FFT receiver. Compared with the conventional iterative scheme

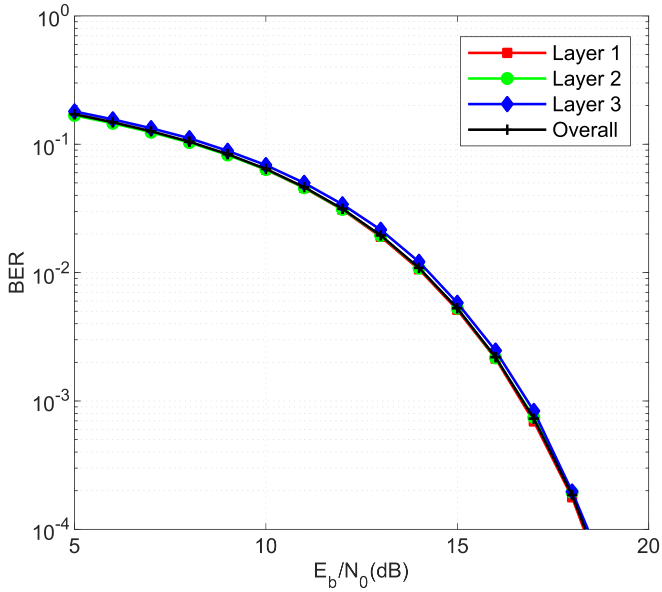

Fig. 4. BER performance of each layer in LACO-OFDM with 3 layers and 16-QAM for the proposed receiver.

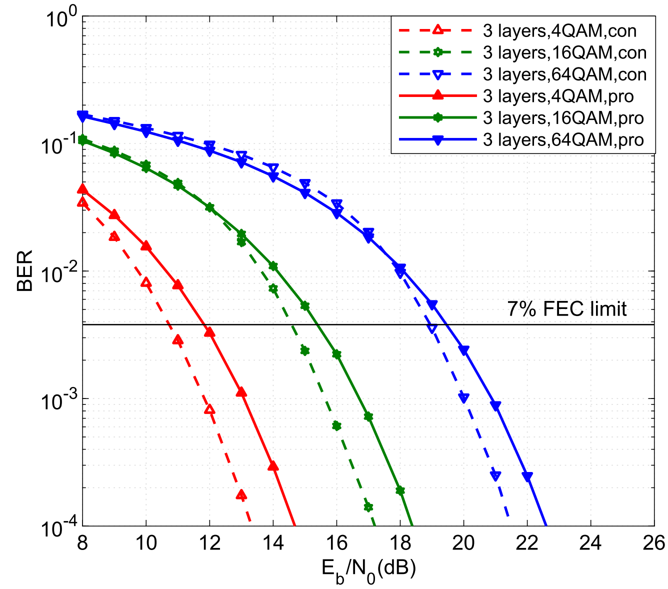

Fig. 6. BER performance comparison of the conventional iterative and proposed receiver with 3 layers.

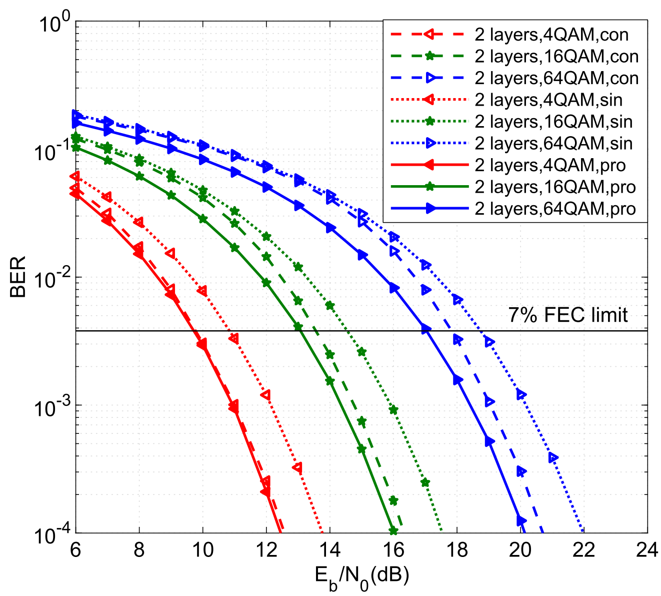

Fig. 5. BER performance of LACO-OFDM with 2 layers for the conventional iterative receiver, the single-FFT receiver and the proposed receiver.

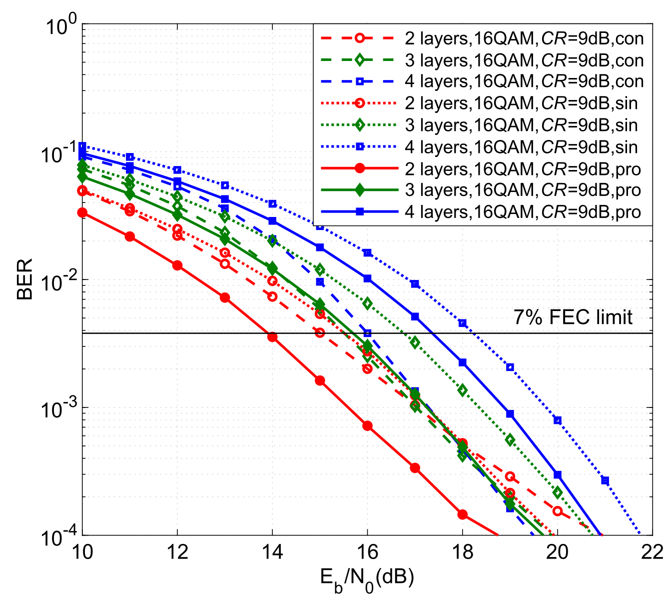

Fig. 7. BER performance of LACO-OFDM of 2, 3 and 4 layers with 16QAM for *CR* = 9 dB.

with 2 layers, the proposed receiver has 0.5 dB and 0.8 dB SNR gain at 7% FEC limit for 16QAM and 64QAM. However, as shown in Fig. 6, there are 0.4 dB $\sim$ 1.1 dB SNR degradations at 7% FEC limit for the proposed scheme. With the order of modulation *M* increasing, the BER performance gap is getting smaller.

OFDM systems always have a high peak to average power ratio (PAPR). LACO-OFDM has this disadvantage as well [13], [14]. The simplest method for the PAPR reduction is amplitude clipping. Therefore, the amplitude clipping channel is considered in this paper. For the LACO-OFDM signal $x_{\mathrm{LACO},n}$ in the transmitter, the amplitude clipping is given by

$$\overline{x}_{\mathrm{LACO},n} = \begin{cases} x_{\mathrm{LACO},n}, & \text{if } x_{\mathrm{LACO},n} < A, \\ A, & \text{otherwise}, \end{cases} \tag{15}$$

where $\overline{x}_{\mathrm{LACO},n}$ denotes the LACO-OFDM signal after the amplitude clipping, and A is the maximum peak amplitude of $\overline{x}_{\mathrm{LACO},n}$. The clipping ratio is defined as [20]

$$CR = 20\log_{10}\left(\frac{A}{\delta}\right) \text{ dB}, \tag{16}$$

where $\delta = \sqrt{\delta^2}$. δ^2 denotes the power of $x_{\mathrm{LACO},n}$. The smaller *CR* means the higher clipping distortion.

TABLE II
LIST OF PARAMETERS FOR FIG. 7, FIG. 8, FIG. 9 AND FIG. 10

Layers	*M*-QAM	*CR*	Power allocation for the proposed scheme
2	16QAM	9.0 dB	$P_2 = 0.9P_1$
3	4QAM	6.0 dB	$P_2 = 0.9P_1$, $P_3 = 1.4P_2$
		7.0 dB	$P_2 = 1.2P_1$, $P_3 = 1.4P_2$
	16QAM	8.0 dB	$P_2 = 0.9P_1$, $P_3 = 1.4P_2$
		9.0 dB	$P_2 = 1.3P_1$, $P_3 = 1.4P_2$
	64QAM	10.0 dB	$P_2 = 1.5P_1$, $P_3 = 1.4P_2$
		11.0 dB	$P_2 = 1.1P_1$, $P_3 = 1.4P_2$
4	4QAM	5.0 dB	$P_2 = 0.7P_1$, $P_3 = 1.72P_2$, $P_4 = 2.6P_2$
		6.0 dB	$P_2 = 1.0P_1$, $P_3 = 1.72P_2$, $P_4 = 2.6P_2$
	16QAM	7.5 dB	$P_2 = 0.8P_1$, $P_3 = 1.72P_2$, $P_4 = 2.6P_2$
		8.0 dB	$P_2 = 1.1P_1$, $P_3 = 1.72P_2$, $P_4 = 2.6P_2$
		9.0 dB	$P_2 = 1.5P_1$, $P_3 = 1.72P_2$, $P_4 = 2.6P_2$
	64QAM	9.5 dB	$P_2 = 1.2P_1$, $P_3 = 1.72P_2$, $P_4 = 2.6P_2$
		10.0 dB	$P_2 = 1.4P_1$, $P_3 = 1.72P_2$, $P_4 = 2.6P_2$

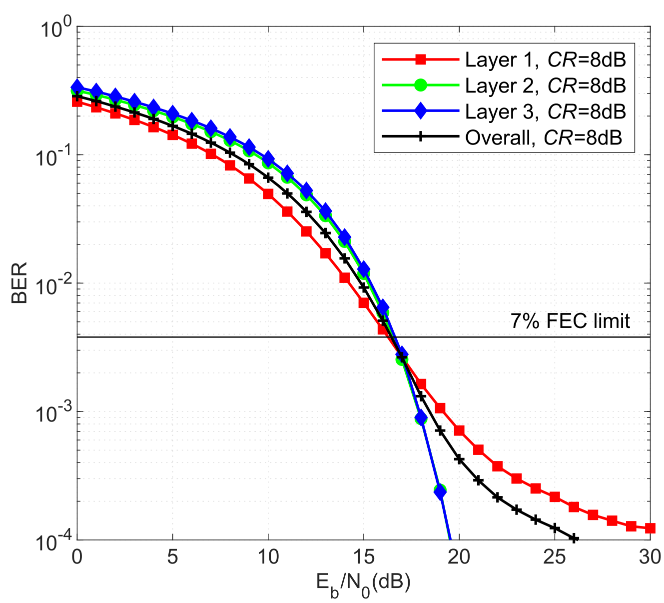

Fig. 8. BER performance of each layer in LACO-OFDM with 3 layers, 16QAM and $CR = 8$ dB for the proposed receiver.

Fig. 7 depicts the BER performance of LACO-OFDM with 16QAM in amplitude clipping channel. *CR* is set to 9 dB. In the conventional iterative scheme, the same power is still loaded on each layer. In the single-FFT receiver, P_l is allocated with $P_2 = 0.9P_1$ for 2 layers, $P_2 = 1.3P_1$, $P_3 = 2P_2$ for 3 layers and $P_2 = 1.5P_1$, $P_4 = 2P_3 = 4P_2$ for 4 layers. The power allocation for the proposed scheme is shown in Table II. With strategies in Table II, different layers in LACO-OFDM have almost the same BER performance at 7% FEC limit for the proposed receiver. For example, as shown in Fig. 8, with the power allocation of $P_2 = 0.9P_1$ and $P_3 = 1.4P_2$, each layer in LACO-OFDM of 16-QAM and 3 layers ($CR = 8$ dB) has almost the same BER at 7% FEC limit ($E_b/N_0 = 16.5$ dB). In Fig. 7, compared with the single-FFT receiver, there are still SNR gains of 1.5 dB (2 layers), 1.1 dB (3 layers), and 0.8 dB (4 layers) at 7% FEC limit for the proposed scheme, which illustrates the proposed receiver is insensitive to the clipping distortion. However, for the conventional iterative receiver, the nonlinear distortion in Layer 1 may be introduced into higher layers, which leads to the performance degradation [16]. Therefore, as shown in Fig. 6, the proposed scheme with 2 layers provides 1 dB SNR gain at 7% FEC limit compared to the conventional iterative receiver. With 3 layers the proposed receiver has almost the same BER performance as the conventional iterative receiver.

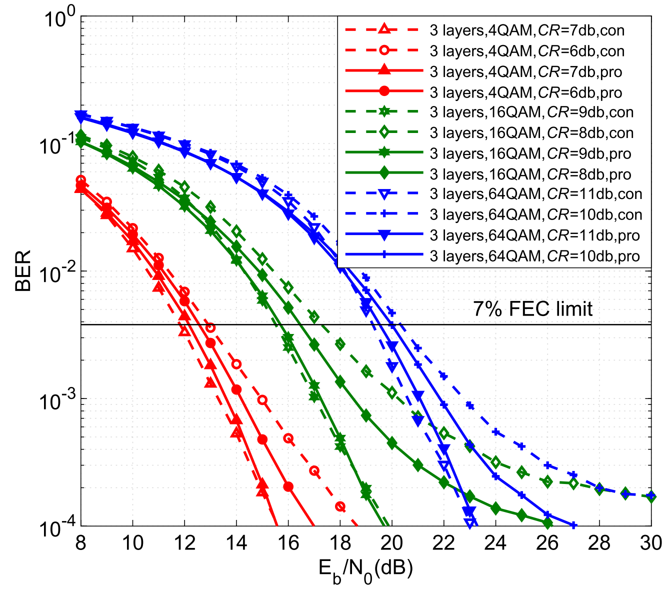

Fig. 9. BER performance comparison of the proposed and conventional iterative scheme with 3 layers at different clipping levels.

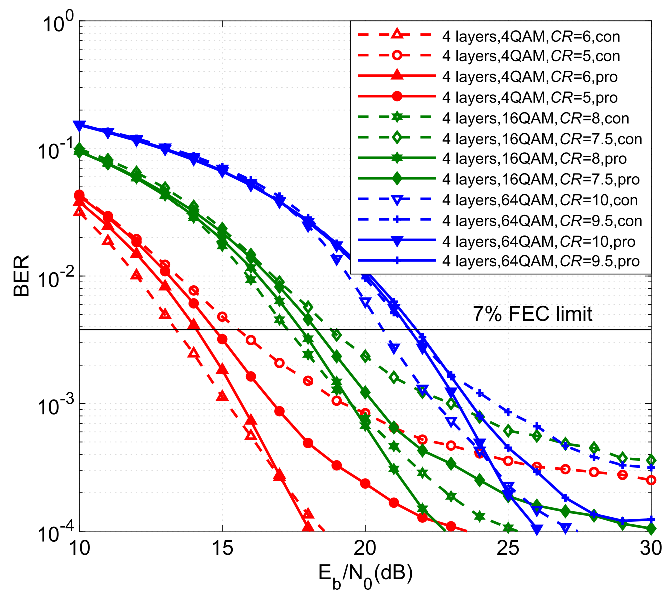

Fig. 10. BER performance comparison of the proposed and conventional iterative scheme with 4 layers at different clipping levels.

Fig. 9 and Fig. 10 show the BER performance of LACO-OFDM of 3 and 4 layers at different clipping levels. As shown in Fig. 9, the BERs of the proposed receiver gradually approach the BERs of the conventional iterative scheme as the *CR* decreases. The proposed scheme with 3 layers and 4QAM has nearly the same performance as the conventional iterative receiver for *CR* = 7 dB. When *CR* is reduced to 6 dB, the BER performance of the proposed scheme outperforms the conventional iterative results. LACO-OFDM systems with 16QAM and 64QAM have the similar performance. Similar results are achieved for LACO-OFDM of 4 layers, as shown in Fig. 10. Therefore, the proposed scheme has better performance for LACO-OFDM with the less *CR*.

IV. Conclusion

In this paper, a single-FFT receiver with pairwise ML is proposed for LACO-OFDM systems. In the single-FFT receiver without pairwise ML, there is 1$\sim$3 dB SNR penalty in AWGN channel. With the pairwise ML, some SNR gain can be available. The pairwise ML is a simple method. And the complexity of the proposed receiver is $\mathrm{O}(N\log_2 N) + \mathrm{O}(LN)$. Simulation results show that in AWGN channel the proposed receiver has 0.5 dB $\sim$ 1.7 dB SNR gain at 7% FEC limit compared with the single-FFT receiver. It's important to note that for LACO-OFDM of 2 layers, the BER performance of the proposed scheme outperforms the conventional iterative solution. Moreover, compared with the conventional iterative receiver, the proposed receiver is less sensitive to the clipping distortion in the amplitude clipping channel. As shown in Fig. 7 and Fig. 8, along with the nonlinearity increasing, the proposed scheme will have the better performance than the conventional iterative results. Therefore, the receiver proposed will be a good candidate for LACO-OFDM systems with less layers or high nonlinearity.

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