DOI:10.3969/j.issn.1673-5188.2017.03.008
http://kns.cnki.net/kcms/detail/34.1294.TN.20170904.0922.002.html, published online September 4, 2017

Layered ACO-FOFDM for IM/DD Systems

GUO Mengqi, ZHOU Ji, TANG Xizi, and QIAO Yaojun
(Beijing University of Posts and Telecommunications, Beijing 100876, China)

Abstract

We propose a layered asymmetrically clipped optical fast orthogonal frequency division multiplexing (ACO-FOFDM) scheme for intensity-modulated and direct-detected (IM/DD) systems. Layered ACO-FOFDM can compensate the weakness of conventional ACO-FOFDM in low spectral efficiency. For FOFDM system, the utilization of discrete cosine transform (DCT) instead of fast Fourier transform (FFT) can reduce the computational complexity without any influence on bit error rate (BER) performance. At transmitter, the superposition of multiple layers is performed in frequency domain, and the iterative receiver is used to recover transmitted signals by subtracting the clipping noise of each layer. We compare the BER performance of the proposed layered ACO-FOFDM system and DC-offset FOFDM (DCO-FOFDM) system with optimal DC-bias at the same spectral efficiency. Simulation results show that in terms of optical bit energy to noise power ratio, the layered ACO-OFDM system has 1.23 dB, 2.77 dB, 3.67 dB and 0.78 dB improvement at the forward error correction (FEC) limit compared with DCO-FOFDM system when the spectral efficiencies are 1 bit/s/Hz, 2 bits/s/Hz, 3 bits/s/Hz and 4 bits/s/Hz. The layered ACO-FOFDM system with zero DC-bias is more suitable for adaptive system, so this system also has potential for application in IM/DD systems.

Keywords

FOFDM; ACO-FOFDM; DCT; spectral efficiency; IM/DD

1 Introduction

The demand for system capacity increases rapidly in optical communication systems. As a multicarrier modulation format, orthogonal frequency division multiplexing (OFDM) has been widely investigated to meet the capacity demand. Its superiorities in high spectral efficiency and robustness against chromatic dispersion and polarization-mode dispersion make it more suitable for high-speed optical communication systems [1]–[4]. Intensity-modulated and direct-detected (IM/DD) technique has been applied in data center interconnections, passive optical network and indoor optical wireless communications due to its advantages in low cost and simple structure [5]–[7]. Therefore, IM/DD optical OFDM system is an attractive technique for both high-speed and short-range optical transmission systems.

The signal transmitted in IM/DD OFDM system must be real and positive. To obtain a real signal, Hermitian symmetry is needed to constrain the input constellations of inverse fast Fourier transform (IFFT). DC-offset OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM) systems are most commonly used to generate positive signals [8], [9]. The performance of DCO-OFDM strongly depends on DC-bias. If the DC-bias is not large enough, the negative values are clipped to zero, which leads to clipping distortion. If the DC-bias is larger than the negative peaks, the system can be inefficient in optical power. The optimal DC-bias depends on the constellation size, which makes DCO-OFDM system not suitable for adaptive system. For ACO-OFDM system, only odd subcarriers are used to carry the signal, zero DC-bias is applied and clipping noise falls on even subcarriers. Although zero DC-bias can reduce the optical power, half of the subcarriers are useless, which results in the spectral efficiency of ACO-OFDM system to be half of that of DCO-OFDM system.

To improve spectral efficiency of ACO-OFDM system, different types of schemes have been proposed. Asymmetrically clipped DC biased optical OFDM (ADO-OFDM) system transmits ACO-OFDM on odd subcarriers and DCO-OFDM on even subcarriers simultaneously, but the even subcarriers still need DC-bias [10]. Hybrid ACO-OFDM uses ACO-OFDM on odd subcarriers and pulse-amplitude-modulation discrete-multitone (PAM-DMT) on even subcarriers, but the real components of even subcarriers are useless [11]. Asymmetrically and symmetrically clipping optical OFDM (ASCO-OFDM) uses two frames of ACO-OFDM with the useful signal on odd subcarriers and one frame of flip-OFDM with the useful signal on even subcarriers [12], which has the same spectral efficiency as Hybrid ACO-OFDM. Afterwards, to improve the spectral efficiency further the superposition of more than two layers are proposed. Layered ACO-OFDM [13] and enhanced asymmetrically clipped optical OFDM (eACO-OFDM) [14] overlap multiple layers with ACO-OFDM in time domain. In ACO-OFDM system, the scaling factors are used to adjust the average power for each layer, which improves the bit error rate (BER) performance at the cost of implementation complexity. Spectrally and energy efficient OFDM (SEE-OFDM) [15] and augmented spectral efficiency discrete multitone (ASE-DMT) [16] overlap multiple layers in frequency domain instead of time domain, which is easier for implementation. SEE-OFDM system employs superposition of multiple layers with ACO-OFDM. ASE-

This work was supported in part by National Natural Science Foundation of China under Grant Nos. 61427813 and 61331010, and in part by ZTE Industry-Academia-Research Cooperation Funds.

DMT uses PAM-DMT on imaginary components of all the subcarriers and layered ACO-OFDM on the remaining real components.

Fast OFDM (FOFDM) based on discrete cosine transform (DCT) has been studied in IM/DD optical communication systems [17]– [19]. In IM/DD system, the transmitted signal should have real values. For fast Fourier transform (FFT) based OFDM system, Hermitian symmetry is needed to generate real signals, but in DCT-based FOFDM system, the real transformation does not need Hermitian symmetry any more, and the one-dimensional modulation has lower computational complexity. For FOFDM system, the interval between subcarriers is half of that in OFDM system. However, the positive frequency of FOFDM system has corresponding image on negative frequency, so the M-PAM FOFDM system has the same spectral efficiency as M^2quadrature-amplitude-modulation (QAM) OFDM system.

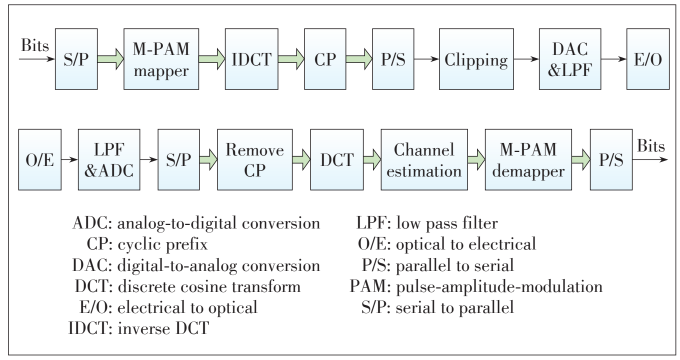
In this paper, we first propose layered FOFDM for IM/DD systems. The superposition of multiple layers is performed in frequency domain, and the iterative receiver is used to subtract the clipping noise of each layer. The spectral efficiency improvement of layered asymmetrically clipped optical fast orthogonal frequency division multiplexing (ACO-FOFDM) system is compared with conventional ACO-FOFDM system and the computational complexity superiority of layered ACO-FOFDM system is investigated. The hard decision is used in the iterative receiver to improve the BER performance. Compared with the DC-offset FOFDM (DCO-FOFDM) system with optimal DC-bias and the same spectral efficiency, layered ACO-FOFDM has better BER performance in terms of optical bit energy to noise power ratio.

The rest of this paper is organized as follows. We discuss the principle of ACO-FOFDM in Section 2. Section 3 describes the detail structures of transmitter and receiver of layered ACO-FOFDM system. In Section 4, we analyze the spectral efficiency, computational complexity and BER performance of layered ACO-FOFDM system. The conclusions are drawn in Section 5.

2 Principle of ACO-FOFDM in Optical Transmission System

FOFDM system based on DCT has been investigated in detail in [19]. Compared with ACO-OFDM, ACO-FOFDM has the same spectral efficiency, power efficiency and BER performance but with lower computational complexity for digital signal processing [18], [19]. **Fig. 1** shows the block diagram of ACO-FOFDM transmitter and receiver. Different from the conventional ACO-OFDM system based on FFT, ACO-FOFDM system uses inverse DCT (IDCT) at the transmitter and DCT at the receiver. The N-point IDCT and DCT are defined as

$$x_n = \sqrt{\frac{2}{N}}\sum_{k=0}^{N-1} W_k X_k \cos\left(\frac{\pi(2n+1)k}{2N}\right), 0 \leqslant n \leqslant N-1, \quad (1)$$



▲**Figure 1. Block diagram of ACO-FOFDM transmitter and receiver.**

$$X_k = \sqrt{\frac{2}{N}} W_k \sum_{n=0}^{N-1} x_n \cos\left(\frac{\pi(2n+1)k}{2N}\right), 0 \leqslant k \leqslant N-1, \quad (2)$$

where $W_k = \begin{cases} \frac{1}{\sqrt{2}}, & k=0 \\ 1, & k=1,2,\cdots,N-1 \end{cases}$.

Since IDCT is a real transform, when the real-valued frequency domain M-PAM signal X inputs IDCT, the generated time domain signal is also real-valued. The M-PAM signal X only consists of odd components, which can be expressed as $X=[0,X_1,0,X_3,...,X_{N-1}]$.

After IDCT, cyclic prefix (CP) is added to eliminate the intersymbol interference (ISI) after transmission. Then, parallel to serial conversion is performed and all the negative parts of time-domain signal are clipped at zero level. The clipped FOFDM symbol $[X_n]_c$ can be described as

$$[x_n]_c = \begin{cases} x_n, & x_n > 0 \\ 0, & x_n \leqslant 0 \end{cases}, \quad 0 \leqslant n \leqslant N-1, \quad (3)$$

If only odd subcarriers are used to carry the signal, the negative parts of the time domain signal can be clipped at zero level without loss of information. The only influence is the amplitudes of the received signal on odd subcarriers decrease to half of the original values, and all the clipping noises fall into the even subcarriers. After digital-to-analog conversion (DAC) and low pass filter (LPF), the analog electrical signal is modulated to the optical carrier.

At the receiver, the generated electrical signal passes through the LPF and performs analog-to-digital conversion (ADC), the digital signal processing is the reverse process of the transmitter. At last, signal on odd subcarriers is extracted for BER detection.

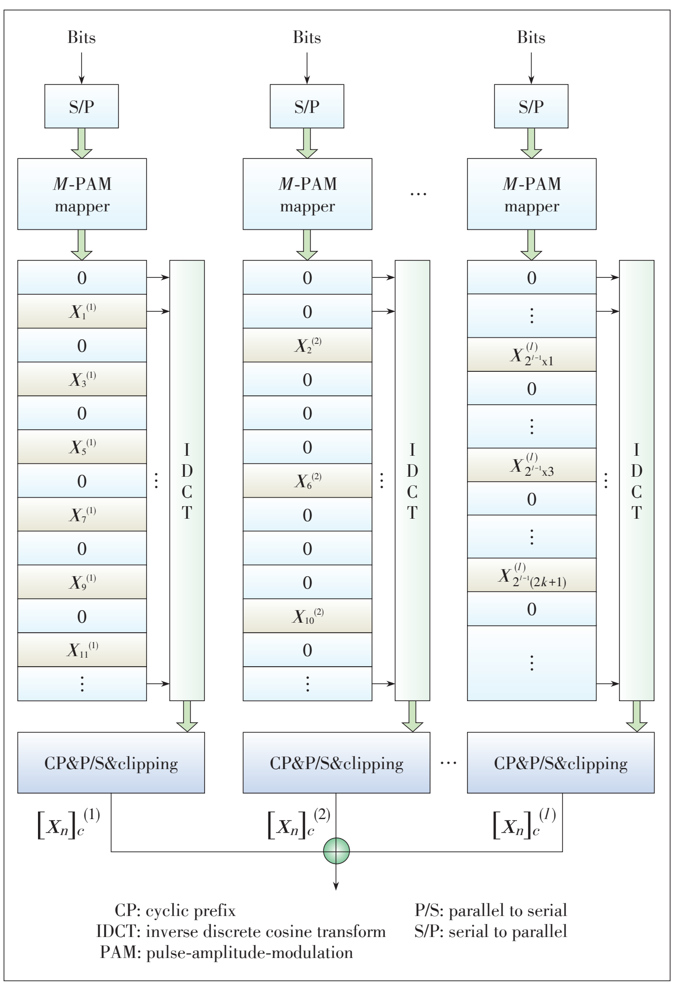
3 Layered ACO-FOFDM System

In this section, the principles of transmitter and receiver of the proposed layered ACO-FOFDM system are described in detail. L represents the total number of layers and l represents the l-th layer in the proposed system.

3.1 Transmitter

At transmitter, the superposition of multiple layers can be performed in time domain [13], [14] or frequency domain [15], [16]. In this paper, the superposition is performed in frequency domain, which is easier for implementation than that in time domain. **Fig. 2** shows the transmitter block diagram of layered ACO-FOFDM. At Layer 1, only odd subcarriers are used to carry the signal (index $2k+1$, k=0,1,2,...,$N/2^1-1$), the clipping noise falls on the even subcarriers, which is the same as conventional ACO-FOFDM system. The odd subcarriers of the remaining unused subcarriers at Layer 1 are used in Layer 2 (index $2(2k+1)$, k=0,1,2,...,$N/2^2$-1), and the clipping noise falls on the even subcarriers of the remaining unused subcarriers of Layer 1. The rest layers can be done in the same manner that odd subcarriers of the remaining unused subcarriers are utilized in each layer. At the l-th layer, only the $2^{l-1}(2k+1)$(k = 0,1, 2,...,$N/2^l$-1) subcarriers are utilized to carry the signal, and the clipping noise of the l-th layer only influences the layers higher than l (i.e., Layer l+1 to Layer L). It is not difficult to get the original transmitted signal of each layer at receiver if the clipping noise of its previous layers is eliminated.

Although at Layer $l+1$, half number of subcarriers are used as that at Layer l, all the layers can perform N-point IDCT. The advantages of frequency domain superposition are that a repeater is not needed as in the time domain superposition, and that obtaining chips to conduct IDCT with the same order N is easier than obtaining chips with different IDCT orders in hardware implementation. Moreover, the computational complexity of IDCT/DCT depends on the number of subcarriers with actual data, not just depends on the number of order N. Therefore, the subcarriers without data do not increase the computational complexity. After N-point IDCT, the signal performs adding CP, parallel to serial conversion and zero clipping for each layer. The real and positive time-domain signals are added together at last.



▲**Figure 2. Transmitter block diagram of layered ACO-FOFDM.**

3.2 Receiver

The iterative receiver is used to recover transmitted signals from the layer l from low to high. The asymmetric clipping of the l-th layer at transmitter brings clipping noise, which can influence the layers with higher numbers. Only after the influence of lower layers is eliminated, can the signal at higher layers be recovered successfully. For easy to implement, two different structure types of receiver are introduced in this section, both of them can eliminate the clipping noise in frequency domain. Moreover, the soft decision and hard decision are described in this section. **Fig. 3** reveals two types of receiver structures with soft decision and hard decision.

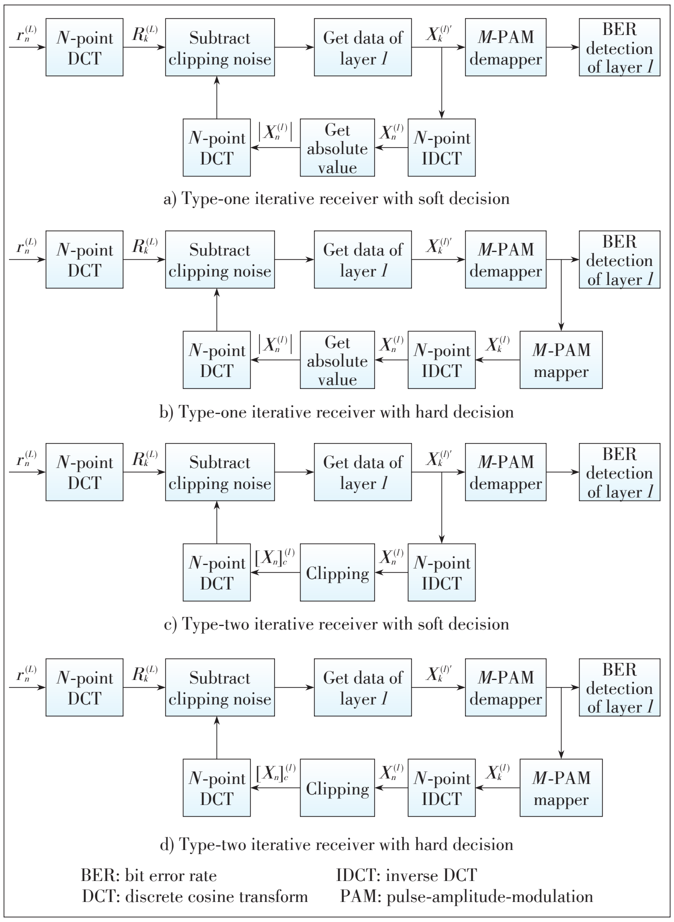
3.2.1 Type One

The first type of receiver can eliminate the influence of the l-th layer to the layers higher than l in frequency domain. For conventional ACO-OFDM system, the received signal on an odd subcarrier o can be represent as $X_o^{'}=\frac{1}{2}FFT(x_n)$ and the received signal on an even subcarrier e can be represent as $X_e^{'}=\frac{1}{2}FFT(|x_n|)$. The same results can be obtained in the ACO-FOFDM system as

$$X_o^{'}=\frac{1}{2}DCT(x_n)\ , \tag{5}$$

$$X_e^{'}=\frac{1}{2}DCT(|x_n|)\ . \tag{6}$$

Fig. 3a shows that after the additive white Gaussian noise (AWGN) channel, the signal on Layer 1 can be directly gotten from the odd subcarriers of $R_k^{(L)}$. Eqs. (5) and (6) reveal that the signal amplitude should double after DCT. Then, the signal $X_k^{(L)'}$ on Layer 1 can perform N-point IDCT, get the absolute value and perform N-point DCT, so the clipping noise on even



▲**Figure 3. Two different types of receiver structures with soft decision or hard decision.**

subcarriers of Layer 1 is obtained. Only the obtained clipping noise on even subcarriers of Layer 1 needs to be subtracted to get the signal on Layer 2. The rest layers can be done in the same manner. Only after the clipping noise of Layers 1 to l has been eliminated, can the signal on Layer l+1 be recovered successfully.

It should be noticed that the soft decision is applied in Fig. 3a, which means the noisy constellation values are used to reconstruct the clipping noise, while in Fig. 3b, an additional M-PAM mapper is needed so that the recovered bits are used to reconstruct the clipping noise. The determinate constellation positions are more accurate than noisy constellation positions to reconstruct the clipping noise, and this hard-decision method was proposed in [15]. The later simulation shows BER performance of the system with hard decision is better than the system with soft decision.

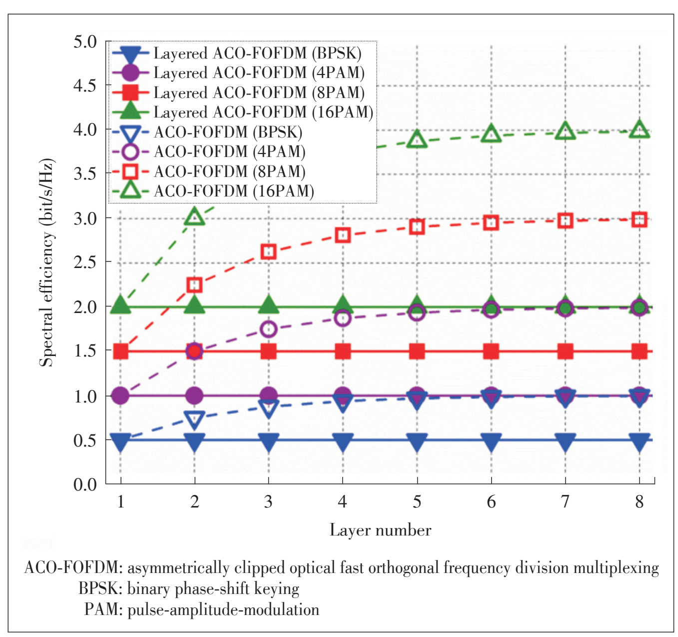
3.2.2 Type Two

Figs. 3c and 3d demonstrate the second type of receiver with soft decision and hard decision, respectively, which also eliminate the influence of the l-th layer to the layers higher than l in frequency domain. The principle can also be found in (5) and (6), and the received signal amplitude should be doubled after DCT. The signal on Layer 1 can be directly gotten from the odd subcarriers of $R_k^{(L)}$. Then, by soft decision the signal $X_k^{(L)'}$ on Layer 1 can perform N-point IDCT, while by hard decision the recovered bits on Layer 1 perform M-PAM mapper and N-point IDCT. After zero clipping and N-point DCT, the amplitude of the signal is doubled, so that the received signals on both odd and even subcarriers of Layer 1 are obtained. Then, we can subtract the obtained clipping noise on even subcarriers of Layer 1 to eliminate the influence of higher layers, and the rest layers can be done in the same manner.

4 Performance of Layered ACO-FOFDM System

4.1 Spectral Efficiency

Fig. 4 compares the spectral efficiency between the layered ACO-FOFDM and conventional ACO-FOFDM systems with BPSK, 4PAM, 8PAM and 16PAM. For conventional ACO-FOFDM system, half of subcarriers are used to carry the signal, which is the same as Layer 1 of the layered ACO-FOFDM system. Layer l+1 carries half number of data compared with Layer l, so the spectral efficiency increases with the increasing of the layer number, and the spectral efficiency converges to twice of that of conventional ACO-FOFDM system when the layer number is large enough. Moreover, in the layered ACO-OFDM system, Hermitian symmetry is needed to generate real-value signals. Therefore, to achieve the same spectral efficiency the size of the complex constellation in FFT-based layered ACO-OFDM system is M^2 while the size of the real constella-



▲**Figure 4. Spectral efficiency comparison between layered ACO-FOFDM system and conventional ACO-FOFDM system.**

tion in DCT-based layered ACO-FOFDM system is M.

4.2 Computational Complexity

As for computational complexity, **Table 1** reveals the comparison of real multiplications and real additions between N-point FFT and N-point DCT. The N-point FFT algorithm has $N\log_2 N-3N+4$ real multiplications and $3N\log_2 N-3N+4$ real additions, while the N-point DCT algorithm only has $\frac{N}{2}\log_2 N$ real multiplications and $\frac{3N}{2}\log_2 N-N+1$ real additions [20]. It is easy to see that the computational complexity of DCT algorithm is lower than that of FFT algorithm in layered ACO-OFDM system. This is the advantage of DCT-based layered ACO-FOFDM system. The multiplications of DCT occupy the most part of computational complexity, so we only considered the real multiplications at transmitter and receiver of the layered ACO-FOFDM system.

At transmitter, for layered ACO-FOFDM system with L layers, half of the subcarriers are utilized to carry the signal and the other half are zeros, so the computational complexity of Layer 1 is $\frac{N}{4}\log_2\frac{N}{2}$. Layer $l+1$ carries half of data compared Layer l, so the computational complexity increases with the increasing of layer number, which is the same as spectral efficiency. Finally, the computational complexity converges to twice of that of conventional ACO-FOFDM system when the layer number is large enough, which can be written as $\sum_{l=1}^{L}\frac{N}{4\times 2^{l-1}}\log_2\frac{N}{2\times 2^{l-1}}\leqslant(2-\frac{1}{2^{L-1}})\frac{N}{4}\log_2\frac{N}{2}$.

At receiver, the computational complexity of N-point DCT is $\frac{N}{2}\log_2 N$. However, for Layer l (l>1), an additional IDCT and an additional DCT are needed to eliminate the clipping noise. Layer 1 does not need to subtract the clipping noise, so the computational complexity for layer 1 is $\frac{N}{2}\log_2 N$, and for ACO-FOFDM system with L layers (L>1), the computational complexity is $\frac{N}{2}\log_2 N+2\sum_{l=1}^{L-1}\frac{N}{4\times 2^{l-1}}\log_2\frac{N}{2\times 2^{l-1}}\leqslant\frac{N}{2}\log_2 N+(4-\frac{1}{2^{L-3}})\frac{N}{4}\log_2\frac{N}{2}$. This result reveals the computational complexity increment of layered ACO-FOFDM receiver is no more than three times of conventional ACO-FOFDM system.

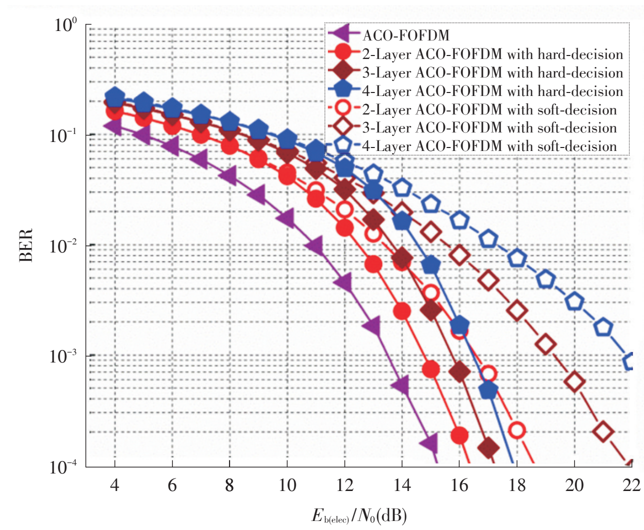
4.3 BER Performance

The advantage of hard decision over soft decision is revealed in **Fig. 5**. The 4-layer ACO-FOFDM with hard decision has nearly the same BER performance as 2-layer ACO-FOFDM with soft decision with a forward error correction (FEC) limit (BER=1×10^{-3}). The required $E_{b(elec)}/N_0$ (electrical bit energy to noise power ratio) to achieve the FEC limit for layered ACO-FOFDM systems with soft decision is far more than that with hard decision. As for hard decision, although the in-

▼**Table 1. Comparison of real multiplications and real additions between *N*-point FFT and *N*-point DCT**

	Real multiplications	Real additions
FFT	$N\log_2 N-3N+4$	$3N\log_2 N-3N+4$
DCT	$\frac{N}{2}\log_2 N$	$\frac{3N}{2}\log_2 N-N+1$

DCT: discrete cosine transform FFT: fast Fourier transform



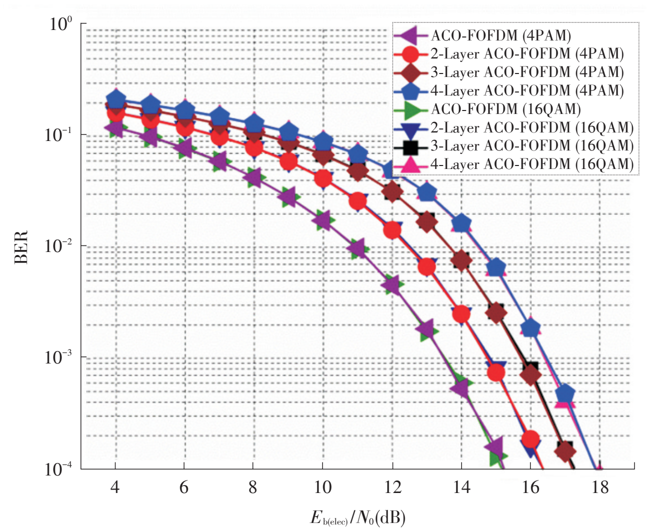
ACO-FOFDM: asymmetrically clipped optical fast orthogonal frequency division multiplexing
BER: bit error rate

▲**Figure 5. BER performance comparison between soft decision and hard decision in 4PAM layered ACO-FOFDM.**

correctly decoded bits in lower layers can be translated into distortions on all the subsequent layers, this error propagation effect becomes weaker with the increasing of $E_{b(elec)}/N_0$. The determinating constellation positions are more accurate than noisy constellation positions to reconstruct the clipping noise. Therefore, hard decision is used for iterative receiver of the layered ACO-FOFDM system.

Fig. 6 shows the BER performance comparison between 4PAM layered ACO-FOFDM system and 16QAM layered ACO-OFDM system in AWGN channel. With the same spectral efficiency, BER curves of M-PAM-modulated ACO-FOFDM and those of M^2-QAM-modulated ACO-OFDM coincide with each other, which have been demonstrated in [18]. This result is also suitable for the layered ACO-FOFDM and layered ACO-OFDM systems. With the same constellation size of each layer, the BER curves of M-PAM-modulated layered ACO-FOFDM and M^2-QAM-modulated layered ACO-OFDM coincide with each other when the same simulation parameters are adopted.

As demonstrated in **Fig. 7**, the BER performance of layered ACO-FOFDM system is compared with DCO-FOFDM system with optimal DC-bias in AWGN channel, and the spectral efficiencies range from 1 bit/s/Hz to 4 bits/s/Hz. Although the

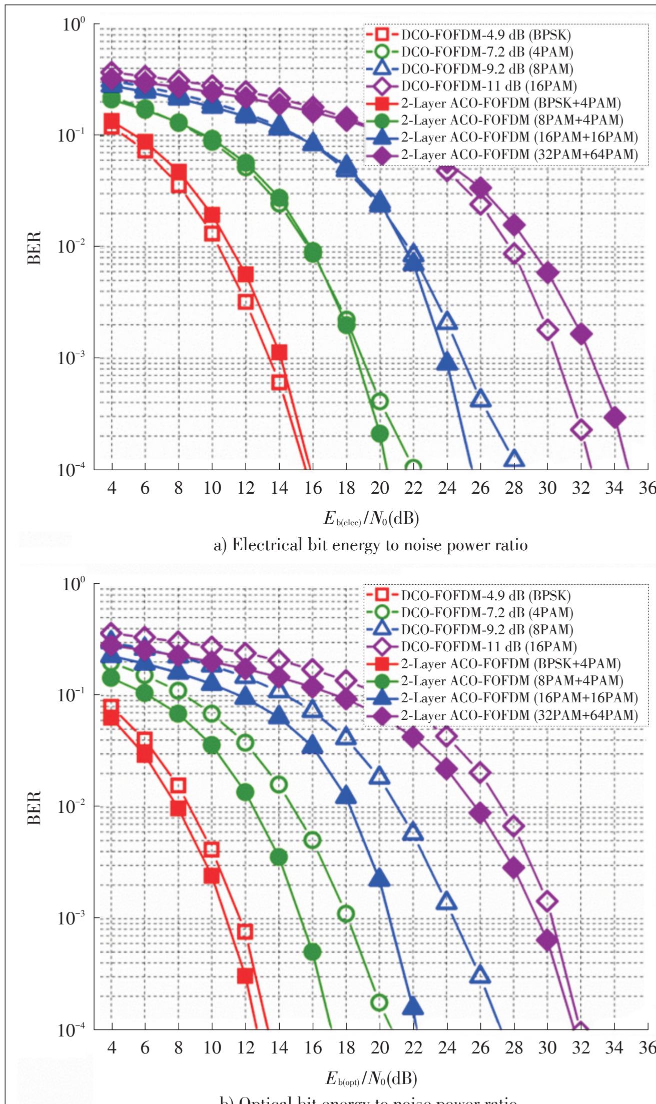


ACO-FOFDM: asymmetrically clipped optical fast orthogonal frequency division multiplexing
BER: bit error rate
PAM: pulse-amplitude-modulation
QAM: quadrature-amplitude-modulation

▲**Figure 6. BER performance for 4PAM layered ACO-FOFDM system and 16QAM layered ACO-OFDM system.**

spectral efficiency of DCO-FOFDM system is twice of that of the ACO-FOFDM system with the same constellation size, the performance of DCO-FOFDM strongly depends on the DC-bias [8]. If the DC-bias is not large enough, the negative values are clipped to zero, which leads to clipping distortion. If the DC-bias is larger than the negative peaks, the system can be inefficient in optical power. To obtain the optimal BER performance of DCO-FOFDM system, we use 4.9 dB, 7.2 dB, 9.2 dB and 11 dB DC-biases for BPSK, 4PAM, 8PAM and 16PAM as investigated in [19]. The disadvantage of DCO-FOFDM is different proper DC biases should be found for different systems. For the layered ACO-FOFDM system, if all the layers use the same constellation size, its spectral efficiency can never be the same as that of DCO-FOFDM system because the infinite number of layers are required for layered ACO-FOFDM system. Therefore, we use 2-layer ACO-FOFDM system with different constellation sizes for layers to obtain the same spectral efficiency as DCO-FOFDM system. The average signal power applied to each layer is proportion to the number of bits transmitted in each layer. The constellation size combination mode with relatively good BER performance is chosen. Moreover, the optimal combination mode of layer number and constellation size can be used in the future work to achieve better BER performance.

Figs. 7a and 7b reveal the BER performance of 2-layer ACO-FOFDM system and DCO-FOFDM system with optimal DC-bias in terms of $E_{b(elec)}/N_0$ (electrical bit energy to noise power ratio) and $E_{b(opt)}/N_0$ (optical bit energy to noise power ratio). For the conversion from electrical bit energy to noise power ratio to optical bit energy to noise power ratio, the average optical power is set to unity [8]. In Fig. 7a, the BER performance



ACO-FOFDM: asymmetrically clipped optical fast orthogonal frequency division multiplexing
BER: bit error rate
BPSK: binary phase-shift keying
DCO-FOFDM: DC-offset fast orthogonal frequency division multiplexing
PAM: pulse-amplitude-modulation

▲**Figure 7. BER performance comparison between layered ACO-FOFDM system and DCO-FOFDM system with the same spectral efficiency. The spectral efficiencies are set to 1 bit/s/Hz, 2 bits/s/Hz, 3 bits/s/Hz and 4 bits/s/Hz. The optimal dc-biases of DCO-FOFDM system are 4.9 dB, 7.2 dB, 9.2 dB and 11 dB for BPSK, 4PAM, 8PAM and 16PAM [18].**

of 2-layer ACO-FOFDM system is only a little bit better than that of DCO-FOFDM system when the spectral efficiency is 2 bits/s/Hz or 3 bits/s/Hz, and its BER performance is worse than that of DCO-FOFDM system when the spectral efficiency is 1 bit/s/Hz or 4 bits/s/Hz. The superiority of 2-layer ACO-FOFDM system is apparent in terms of optical bit energy to noise power ratio, it has 1.23 dB, 2.77 dB, 3.67 dB and 0.78 dB improvement at FEC limit compared with DCO-FOFDM system when the spectral efficiencies are 1 bit/s/Hz, 2 bits/s/

Hz, 3 bits/s/Hz and 4 bits/s/Hz. Consequently, the layered ACO-FOFDM system also has potential for application in IM/DD systems.

5 Conclusions

This paper proposes a layered ACO-FOFDM scheme based on DCT for IM/DD systems. The conventional ACO-FOFDM system only uses odd subcarriers to carry the signal, which leads to low spectral efficiency. For the layered ACO-FOFDM system, the superposition of signal on different layers is performed in frequency domain at transmitter to increase the spectral efficiency. The average signal power applied to each layer is proportion to the number of bits transmitted in each layer. At receiver, the iterative receiver is used to recover transmitted signal from low-to-high layers, and hard decision is applied to improve the BER performance. In the layered ACO-FOFDM system, the spectral efficiency converges to twice of that of conventional ACO-FOFDM system when the layer number is large enough. For the same spectral efficiency, the layered ACO-FOFDM system based on DCT has the same BER performance but lower computational complexity compared with the layered ACO-OFDM system based on FFT. Simulation results demonstrate that the proposed layered ACO-FOFDM system with zero DC-bias is more suitable for adaptive system, and also a promising scheme for application in IM/DD systems.

References

[1] J. Armstrong, "OFDM for optical communications," *Journal of Lightwave Technology*, vol. 27, no. 3, pp. 189–204, Feb. 2009. doi: 10.1109/JLT.2008.2010061.
[2] W. Shieh and I. Djordjevic, *OFDM for optical communications*. New York, USA: Academic Press, 2009.
[3] J. Zhou, Y. Yan, Z. Cai, Y. Qiao, and Y. Ji, "A cost-effective and efficient scheme for optical OFDM in short-range IM/DD systems," *IEEE Photonics Technology Letters*, vol. 26, no. 13, pp. 1372–1374, Jul. 2014. doi: 10.1109/LPT.2014.2325602.
[4] J. Zhou, Y. Qiao, Z. Cai, and Y. Ji, "An improved scheme for Flip-OFDM based on Hartley transform in short-range IM/DD systems," *Optics Express*, vol. 22, no. 17, pp. 20748–20756, Aug. 2014. doi: 10.1364/OE.22.020748.
[5] J. Wei, N. Eiselt, C. Sanchez, R. Du, and H. Griesser, "56 Gb/s multi-band CAP for data center interconnects up to an 80 km SMF," *Optics Letters*, vol. 41, no. 7, pp. 4122–4125, Sept. 2016. doi: 10.1364/OL.41.004122.
[6] J. Zhou and Y. Qiao, "Low-peak-to-average power ratio and low-complexity asymmetrically clipped optical orthogonal frequency-division multiplexing uplink transmission scheme for long-reach passive optical network," *Optics Letters*, vol. 40, no. 17, pp. 4034–4037, Sept. 2015. doi: 10.1364/OL.40.004034.
[7] O. González, R. Perez-Jimenez, S. Rodriguez, et al., "OFDM over indoor wireless optical channel," *IEE Proceedings-Optoelectronics*, vol. 152, no. 4, pp. 199–204, Aug. 2005. doi: 10.1049/ip-opt:20045065.
[8] J. Armstrong and B. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN," *IEEE Communications Letters*, vol. 12, no. 5, pp. 343–345, May 2008. doi: 10.1109/LCOMM.2008.080193.
[9] J. Armstrong and A. Lowery, "Power efficient optical OFDM," *Electronics Letter*, vol. 42, no. 6, pp. 370–372. Mar. 2006. doi: 10.1049/el:20063636.
[10] S. Dissanayake and J. Armstrong, "Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM in IM/DD Systems," *Journal of Lightwave Technology*, vol. 31, no. 7, pp. 1063–1072, Apr. 2013. doi: 10.1109/JLT.2013.2241731.
[11] B. Ranjha and M. Kavehrad, "Hybrid asymmetrically clipped OFDM-based IM/DD optical wireless system," *Journal of Optical Communications and Networking*, vol. 6, no. 4, pp. 387–396, Apr. 2014. doi: 10.1364/JOCN.6.000387.
[12] N. Wu and Y. Bar-Ness, "A novel power-efficient scheme asymmetrically and symmetrically clipping optical (ASCO)-OFDM for IM/DD optical systems," *EURASIP Journal on Advances in Signal Processing*, vol. 15, no. 1, pp. 1–10, Jan. 2015. doi: 10.1186/1687-6180-2015-3.
[13] Q. Wang, C. Qian, X. Guo, et al., "Layered ACO-OFDM for intensity-modulated direct-detection optical wireless transmission," *Optics Express*, vol. 23, no. 9, pp. 12382–12393, May 2015. doi: 10.1364/OE.23.012382.
[14] M. Islim, D. Tsonev, and H. Haas, "On the superposition modulation for OFDM-based optical wireless Communication," in *Proc. IEEE GlobalSIP 2015*, Orlando, USA, Dec. 2015, pp. 1022–1026. doi: 10.1109/GlobalSIP.2015.7418352.
[15] E. Lam, S. Wilson, H. Elgala, and T. Little. (2015, Octomber 28). *Spectrally and energy efficient OFDM (SEE-OFDM) for intensity modulated optical wireless systems* [Online]. Avaliable: http://arxiv.org/abs/1510.08172
[16] M. Islim and H. Haas, "Augmenting the spectral efficiency of enhanced PAM-DMT-based optical wireless communications," *Optics Express*, vol. 24, no. 11, pp. 11932–11949. May 2016. doi: 10.1364/OE.24.011932.
[17] E. Giacoumidis, A. Tsokanos, C. Mouchos, et al., "Extensive comparisons of optical fast-OFDM and conventional optical OFDM for local and access networks," *Journal of Optical Communications and Networking*, vol. 4, no. 10, pp. 724–733, Oct. 2012. doi: 10.1364/JOCN.4.000724.
[18] J. Zhou, Y. Qiao, Z. Cai, and Y. Ji, "Asymmetrically Clipped Optical Fast OFDM Based on Discrete Cosine Transform for IM/DD Systems," *Journal of Lightwave Technology*, vol. 33, no. 9, pp. 1920–1927. May 2015. doi: 10.1109/JLT.2015.2398441.
[19] J. Zhou, Y. Qiao, T. Zhang, et al., "FOFDM Based on Discrete Cosine Transform for Intensity-Modulated and Direct-Detected Systems," *Journal of Lightwave Technology*, vol. 34, no. 16, pp. 3717–3725, Aug. 2015. doi: 10.1109/JLT.2016.2586526.
[20] M. Vetterli and H. J. Nussbaumer, "Simple FFT and DCT algorithms with reduced number of operations," *Signal Processing*, vol. 6, no. 4, pp. 267–278, Aug. 1984. doi: 10.1016/0165-1684(84)90059-8.

Manuscript received: 2016-12-25

Biographies

GUO Mengqi (guomengqi@bupt.edu.cn) received her B.S. degree from Beijing University of Posts and Telecommunications, China in 2015. Currently, she is a Ph.D. candidate in School of Information and Communication Engineering and State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications. Her research interests include signal processing for optical orthogonal frequency division multiplexing systems.

ZHOU Ji (zhouji@bupt.edu.cn) received his B.S. degree in communication engineering from Beijing University of Posts and Telecommunications, China in 2012. Currently, he is a Ph.D. candidate in School of Information and Communication Engineering and State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications. His research interests include signal processing for optical orthogonal frequency division multiplexing systems and coherent optical communications.

TANG Xizi (tangxizi@bupt.edu.cn) received his B.S. degree from Beijing Technology and Business University, China in 2012. Currently, he is a Ph.D. candidate in School of Information and Communication Engineering and State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications. His research interests include signal processing for passive optical networks.

QIAO Yaojun (qiao@bupt.edu.cn) received his B.S. degree from Hebei Normal University, China in 1994, M.S. degree from Jilin University, China in 1997, and Ph.D. degree from Beijing University of Posts and Telecommunications (BUPT), China in 2000. He was with Lucent and Fujitsu from 2000 to 2007. In 2007, he joined BUPT, where he is currently a professor. His research interests include optical fiber communication system and network.