Fiber nonlinearity mitigation by PAPR reduction in coherent optical OFDM systems via biased clipping OFDM

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A new method incorporating biased clipping orthogonal frequency division multiplexing (OFDM) is presented, which mitigates fiber nonlinear effects in a long-haul coherent optical OFDM (CO-OFDM) system. Under the scheme of the method, the wanted signal carried by odd subcarriers is orthogonal to clipping noise and a Mach-Zehnder modulator (MZM) performs the optimal OFDM signal up-converter from the radio frequency (RF) domain to the optical domain. Analysis and simulation results show that fiber nonlinear effects can be effectively mitigated by reducing the peak-to-average power ratio (PAPR) in biased clipping CO-OFDM system. The nonlinearity threshold (NLT) is improved by 5 dB with a reach of 240 km. With a fiber length up to 800 km, system Q value is improved by approximately 2.3, 1.2, and 0.6 dB at a chromatic dispersion of 6, 12, and 16 ps/(nm·km), respectively. Additionally, system Q reaches the maximum when direct currect (DC) bias is equal to the mean value of the OFDM waveform.

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Coherent optical orthogonal frequency division multiplexing (CO-OFDM) system, combined with coherent detection, multi-carrier modulation technology, and digital signal processing[1,2], is considered as a promising technology for future applications in the field of long-haul optical transmission[3,4]. However, nonlinearity causes severe degradation in CO-OFDM systems[5].

Recently, a number of methods have been proposed to mitigate the nonlinear effect in CO-OFDM systems, including partial carrier filling (PCF), which adds zeroes between every two data subcarriers[6]. However, the resulting improvement is limited. There are several efficient methods based on fiber nonlinearity compensation, e.g., fiber nonlinearity compensation implemented by periodic dispersion maps[7]. To achieve better performance, digital back-propagation has also been applied[8]. However, these methods are very complicated and have a high degree of computational complexity.

It is well known that signal clipping is an effective technique to reduce the peak-to-average power ratio (PAPR) of an OFDM symbol. Clipping is a nonlinear operation, which may produce additional unwanted noise and increase bit error rate (BER). Fortunately, if only odd subcarriers are carrying data, then clipping noise is orthogonal to the wanted signal. The algorithm is only suitable for an optical intensity modulation/direct detected (IM/DD) system[9]. In order to use the clipping algorithm in CO-OFDM, a new method combining signal clipping and direct currect (DC) bias is employed. The results are as follows: (i) signal clipping reduces the PAPR while the wanted signal carried by odd subcarriers is orthogonal to clipping noise, and (ii) DC bias performs optimal linear modulation for optical Mach-Zehnder modulator (MZM) up-converter from the radio frequency (RF) domain to the optical domain for clipping an OFDM signal.

Figure 1 is the diagram of the biased clipping CO-OFDM (BC-CO-OFDM) system, which is similar to the conventional CO-OFDM system, except for some overstriking modules. In the transmitter, the OFDM signal is clipped by setting the negative values to zero. The BC-CO-OFDM system not only uses signal clipping to remove the nonzero values and adopts an odd subcarrier to eliminate the clipping noise, but also introduces DC bias for better modulation. It has been shown that the optimum operation bias point for the MZM in the CO-OFDM system is a zero bias point, and the OFDM signal incurs minimal Q penalty from the up-conversion[10,11].

Therefore, moving the nonzero clipping OFDM signal to adapt to optimal linear modulation for MZM zero bias point is necessary. At the receiver, with the even subcarriers discarded, equalization can be performed easily by transmitting training series and pilot tunes[12−14].

The transmitter uses an inverse fast Fourier transform (IFFT) to generate sampled OFDM waveform, which can be expressed as

$$x(n)=\sum_{k=0}^{N-1}X(k)\exp\Big(-\mathrm{j}\frac{2\pi}{N}kn\Big),\qquad(1)$$

where $X(k)$ is the transmitted information symbol for the kth subcarrier in an OFDM symbol and N is the number of subcarriers. At the receiver, fast Fourier transform (FFT) is used to recover the data, which can be expressed as

$$X(m)=\frac{1}{N}\sum_{n=0}^{N-1}x(n)\exp\Big(-\mathrm{j}\frac{2\pi}{N}nm\Big).\qquad(2)$$

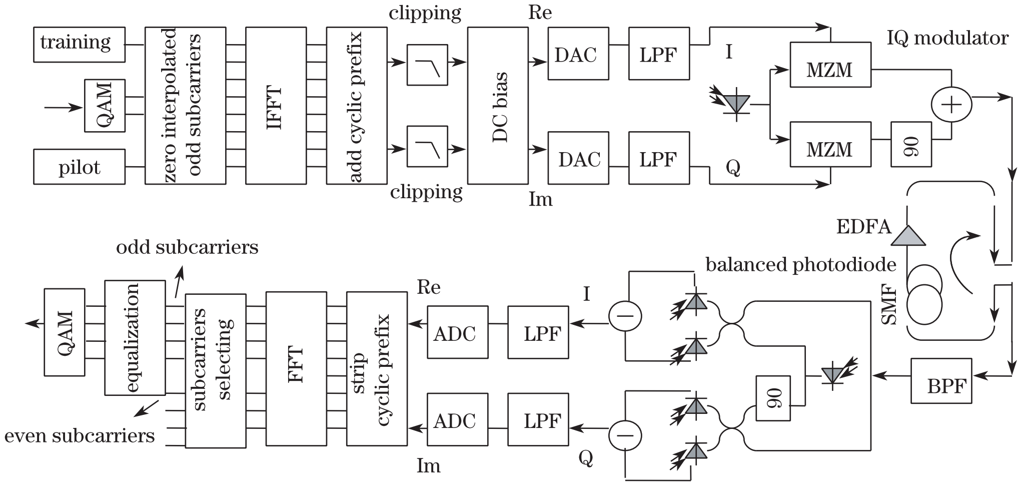

Fig. 1. Conceptual diagram of the BC-CO-OFDM system. LPF: low-pass filter; I: in-phase; Q: quadrature; EDFA: Er-doped fiber amplifer; SMF: single-mode fiber; BPF: band-pass filter; QAM: quadrature amplitude modulation.

The odd subcarriers, which have the property of $x(n+N/2)$=–$x(n)$, are used. Thus, $x(n)$ can be divided into two parts as

$$X(m)=\frac{1}{N}\sum_{\substack{n=0,\\ x(n)\geqslant 0}}^{N/2-1}\left\{x(n)\mathrm{e}^{-\mathrm{j}\frac{2\pi}{N}nm}+x\left(n+\frac{N}{2}\right)\mathrm{e}^{-\mathrm{j}\frac{2\pi}{N}(n+\frac{N}{2})m}\right\}+\frac{1}{N}\sum_{\substack{n=0,\\ x(n)<0}}^{N/2-1}\left\{x(n)\mathrm{e}^{-\mathrm{j}\frac{2\pi}{N}nm}+x\left(n+\frac{N}{2}\right)\mathrm{e}^{-\mathrm{j}\frac{2\pi}{N}(n+\frac{N}{2})m}\right\}. \quad (3)$$

With some modifications, Eq. (3) can be further expressed as

$$X(m)=\frac{2}{N}\cdot\sum_{\substack{n=0,\\ x(n)\geqslant 0}}^{N/2-1}x(n)\mathrm{e}^{-\mathrm{j}\frac{2\pi}{N}nm}+\frac{2}{N}\cdot\sum_{\substack{n=0,\\ x(n)<0}}^{N/2-1}x(n)\mathrm{e}^{-\mathrm{j}\frac{2\pi}{N}nm}. \quad (4)$$

Considering that the OFDM signal is clipped at zero, then only the first term in the first summation and the second term in the second summation in Eq. (4) are nonzero, which can be given as

$$X_{\mathrm{c}}(m)=\frac{1}{N}\sum_{\substack{n=0,\\ x(n)\geqslant 0}}^{N/2-1}x(n)\exp\left(-\mathrm{j}\frac{2\pi}{N}nm\right)+\frac{1}{N}\sum_{\substack{n=0,\\ x(n)<0}}^{N/2-1}x\left(n+\frac{N}{2}\right)\exp\left[-\mathrm{j}\frac{2\pi}{N}\left(n+\frac{N}{2}\right)m\right]. \quad (5)$$

The component of $X_{\mathrm{c}}(m)$ produced by the odd subcarriers is expressed as

$$X_{\mathrm{c,odd}}(m)=\frac{1}{N}\sum_{\substack{n=0,\\ x(n)\geqslant 0}}^{N/2-1}x(n)\exp\left(-\mathrm{j}\frac{2\pi}{N}nm\right)+\frac{1}{N}\sum_{\substack{n=0,\\ x(n)<0}}^{N/2-1}x(n)\exp\left(-\mathrm{j}\frac{2\pi}{N}nm\right)=\frac{1}{2}X(m). \quad (6)$$

The component of $X_{\mathrm{c}}(m)$ produced by the even subcarriers is given as

$$X_{\mathrm{c,even}}(m)=\frac{1}{N}\sum_{\substack{n=0,\\ x(n)\geqslant 0}}^{N/2-1}x(n)\exp\left(-\mathrm{j}\frac{2\pi}{N}nm\right)-\frac{1}{N}\sum_{\substack{n=0,\\ x(n)<0}}^{N/2-1}x(n)\exp\left(-\mathrm{j}\frac{2\pi}{N}nm\right). \quad (7)$$

Comparison between Eqs. (4) and (6) shows that the BC-OFDM results in the amplitude of data carried by odd subcarriers are half of their original value.

Monte Carlo simulations are conducted to verify the performance of the BC-CO-OFDM system. The data rate is 10 Gb/s with quadrature amplitude modulation (QAM) modulation, the total number of subcarriers is 256, and the optical carrier is centered at 193.1 THz. A total of 128 OFDM symbols containing 32768 pseudorandom bits are used for each system Q simulation, among which 8 symbols of training sequence are used for chromatic dispersion equalization. The MZM modulator bias point for the coherent system is π. The long-haul fiber link comprises 80-km spans of single-mode fiber (SMF) without any dispersion compensation. The fiber loss is compensated by an erbium-doped optical fiber amplifier (EDFA) with a gain of 16 dB (with noise figure of 6 dB).

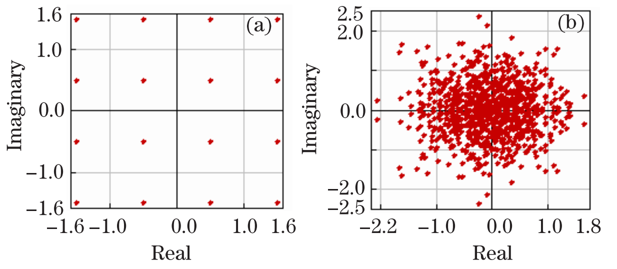

Fig. 2. Electrical signal constellations in BC-CO-OFDM system. (a) Odd component and (b) even component.

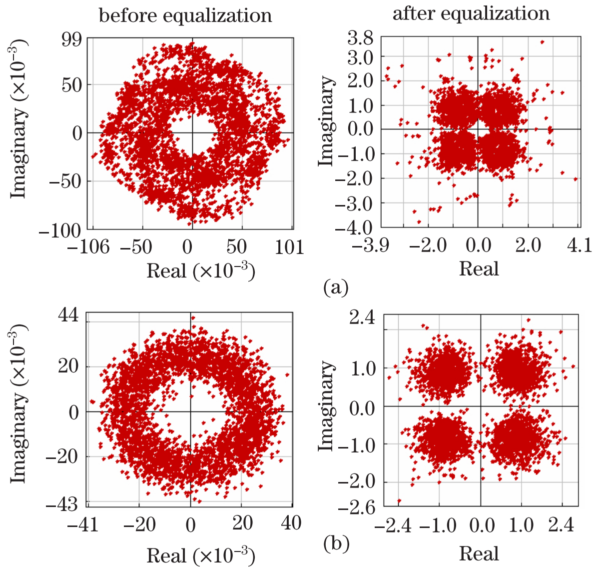

Fig. 3. Constellations before and after equalization in (a) CO-OFDM and (b) BC-CO-OFDM systems.

The fiber nonlinearity coefficient is 2.6×10^{-20} m^2/W with fiber loss of 0.2 dB/km. The system Q value is evaluated through the subcarrier symbol spread in the constellation diagram[15].

Figure 2 shows the electrical signal constellations of the 16 QAM modulation. After BC-OFDM, the constellation points of the odd subcarriers are converted to $\{\pm0.5, \pm0.5j\}$, $\{\pm1.5, \pm1.5j\}$, $\{\pm0.5, \pm1.5j\}$, and $\{\pm1.5, \pm0.5j\}$. The amplitude of each data carried on odd subcarriers is shown to be exactly half of their original value. The simulation results accord with Eq. (6).

Figure 3 illustrates the electrical signal constellations. The phase noise is caused by fiber nonlinearity induced inter-carrier interference (ICI). Figure 3(a) plots the constellation spread of amplitudes and phases in a conventional CO-OFDM system. Figure 3(b) shows that the constellations of the QAM symbols are tightly grouped in a BC-CO-OFDM system.

Figure 4 plots system Q value versus factor m for a number of fiber distances, where $m = V_{\rm dc}/V_{\rm mean}$, $V_{\rm dc}$ is the value of the DC bias, and $V_{\rm mean}$ is the mean value of the OFDM waveform. The performance of a BC-CO-OFDM system reaches the maximum value when m=1 for different fiber lengths.

Figure 5 illustrates the system Q value for various optical input powers with a fiber link of 240 km and at fiber chromatic dispersion of 16 ps/(nm·km). By utilizing BC-CO-OFDM system, the nonlinearity threshold (NLT) increases from –9 to –4 dBm. At a launch power of –4 dBm, the system Q value is improved by approximately 2.5 dB compared with a conventional CO-OFDM system. The performance of a BC-CO-OFDM system is worse than that of a conventional CO-OFDM system at the beginning of transmission because of its lower optical launch power. An additional reason is the reduction of the constellation size at the receiver by half.

Figure 6 shows the system Q value as a function of fiber link up to 800 km at a fiber chromatic dispersion of 6 ps/(nm·km) and optical launch power of –4 dBm. At the beginning of transmission, system performance is mainly influenced by amplified spontaneous emission (ASE) noise and thus, signal clipping may lead to poor performance. With the increase in fiber length, nonlinearity becomes the dominant factor in system performance. Therefore, BC-OFDM can effectively improve the nonlinearity tolerance of the system. When transmitted beyond 260 km, the BC-CO-OFDM system Q value is larger than that required for a conventional

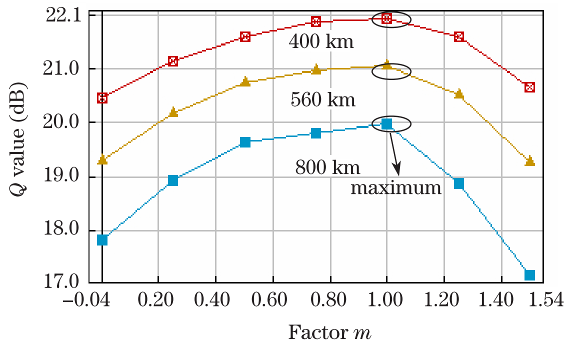

Fig. 4. System Q value versus DC bias.

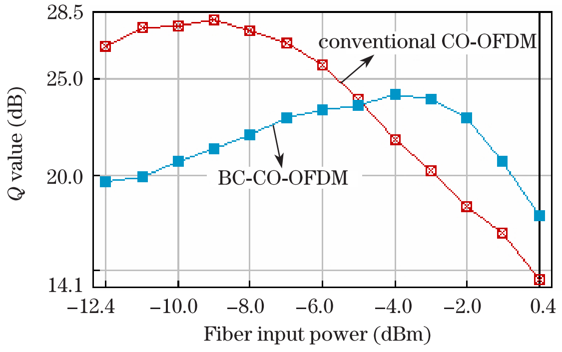

Fig. 5. System Q value versus optical input power.

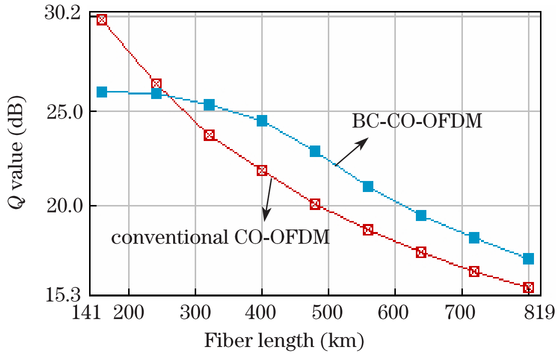

Fig. 6. System Q value versus fiber length at fiber chromatic dispersion of 6 ps/(nm·km).

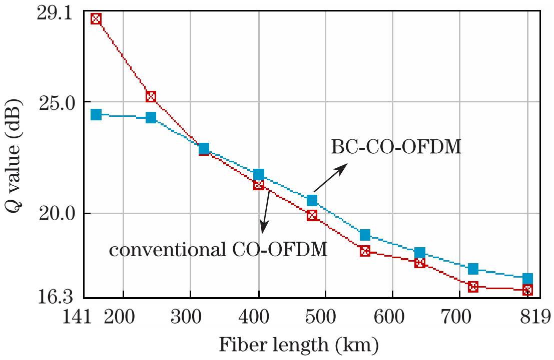

Fig. 7. System Q value versus fiber length at fiber chromatic dispersion of 12 ps/(nm·km).

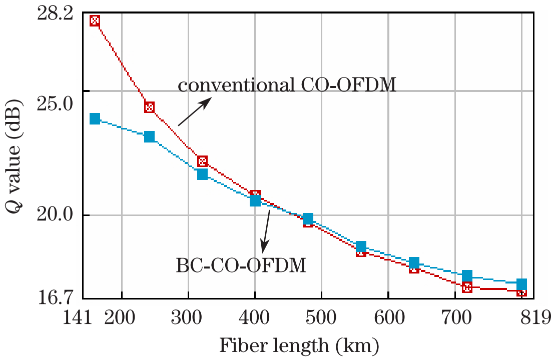

Fig. 8. System Q value versus fiber length at fiber chromatic dispersion of 16 ps/(nm·km).

CO-OFDM system. At the length of 800 km, the Q value is improved by 2.3 dB.

Figure 7 illustrates the system Q value versus fiber link at a fiber chromatic dispersion of 12 ps/(nm·km) and optical launch power of –4 dBm. When transmitted beyond 320 km, the system performance of BC-CO-OFDM is more comprehensive than that required for a CO-OFDM system. At the length of 800 km, the Q value is improved by 1.2 dB. Since fiber chromatic dispersion can mitigate the nonlinear effect, the improvement of nonlinearity tolerance is less pronounced compared with chromatic dispersion at 6 ps/(nm·km).

The simulation is also extended to a fiber chromatic dispersion of 16 ps/(nm·km) and optical launch power of –4 dBm, as shown in Fig. 8. It is evident that the BC-OFDM remains very effective. When transmitted beyond 450 km, the system Q value is larger than that required for a CO-OFDM system. At the length of 800 km, the Q value is improved by approximately 0.6 dB. The improvement is less pronounced because of greater chromatic dispersion at 16 ps/(nm·km).

The simulation results above show that the nonlinearity tolerance of a CO-OFDM system is improved by signal biased clipping. However, after clipping, the smaller constellation size may produce more phase noise from the fiber. Because of the orthogonal relationship between every two subcarriers, we consider the impact of phase noise induced by chromatic dispersion as the main parameter, which could be effectively removed by single equalization as illustrated in Ref. [16]. Therefore, the phase noise induced by changes in constellation variety is negligible.

In conclusion, a new technique using BC-OFDM method in CO-OFDM system to mitigate fiber nonlinear effects is presented. Analysis and simulation results show that the NLT is improved by approximately 5 dB at a reach of 240 km. The results also confirm that fiber dispersion can reduce fiber nonlinear penalty. However, further study is needed to investigate the effects of biased clipping in terms of combating fiber nonlinearity in BC-CO-OFDM system.

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