SSMI cancellation in direct-detection optical OFDM with novel half-cycled OFDM

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Abstract: Half-cycled DDO-OFDM transmission and reception was successfully demonstrated to resist SSMI without spectra efficiency reduction for the first time. The receiver sensitivity was improved by 2 and 1.5 dB in QPSK and 16QAM OFDM with 40-km SSMF-28 transmission, respectively.

References and links


1. Introduction

Optical orthogonal frequency division multiplexing (OFDM) has attracted lots of attention due to its high spectral efficiency (SE) and robustness to transmission impairments enabled by digital signal processing (DSP) [1–8]. Based on configurations of optical receivers, the implementation of optical OFDM systems has two categories: direct-detected optical OFDM (DDO-OFDM) [1–6,9,10] and coherent optical OFDM (CO-OFDM) [7,8]. Due to the advantages of simple and cost-effective configuration, the DDO-OFDM system tends to be applied in access network for short reach.
In a typical DDO-OFDM system, OFDM signal will be interfered by subcarrier–subcarrier mixing interference (SSMI) after square-law detection via the photodiode (PD) in the receiver [1–3,6]. As reported in [1,2], the frequency guard-band was proposed to prevent SSMI from OFDM signal. Another scheme which was called interleaved OFDM was applied in the DDO-OFDM to eliminate the impact of SSMI by inserting data only in even subcarriers [3]. Both these schemes can effectively mitigate the distortions introduced by SSMI, while the system SE will be decreased to half. In order to maintain high SE, the bit interleaver and turbo code techniques are proposed to combat the SSMI in the 64-ary quadrature-amplitude-modulation (64QAM) DD-OFDM system with 100-km fiber transmission [6]. These techniques can mitigate the SSMI effectively, but the SE will still be degraded due to the utilization of turbo code. Moreover, the complexity due to forward-error-correction (FEC) decoding will limit their applications. The bit-loading technique can adaptively adjust the data modulation format to adapt the signal to noise (SNR) distribution obtained by the training sequence [8], and it can also be applied to eliminate the impairment induced by SSMI. System calibration should be done first before the communication links with bit-loading technique are established, and half-cycled scheme in this paper is more practical in the real-system to resist the SSMI without any calibration. In this paper, for the first time, a novel half-cycled DDO-OFDM transmission and reception system was proposed and successfully demonstrated to resist SSMI without SE reduction. The receiver sensitivity was improved by 2 and 1.5 dB in QPSK and 16QAM OFDM with 40-km standard single-mode fiber-28 (SSMF-28) transmission, respectively.

2. Principle and experimental setup

Figure 1(a) shows the concept of three different kinds of OFDM signal in DDO-OFDM. The first one is traditional OFDM signal, for which after square-law detection with PD the SSMI will be distributed in the whole OFDM signal band, and the bit-error ratio (BER) performance of signal will be seriously degraded. The second one is guard-band enabled OFDM signal proposed in [1,2], for which the SSMI will locate only in the guard-band and the BER performance can be improved with half reduced SE. The third one is interleaved OFDM signal [3], and the data was only modulated onto the even subcarriers. The SSMI will be distributed only in the odd subcarriers, and data only modulated on the even subcarriers is immune to the SSMI. In the SSMI cancellation scheme with the interleaved OFDM signal, the OFDM symbol will exhibit symmetric in the time domain when data only modulated onto the even/odd subcarriers, and based on this theory we proposed the half-cycled DDO-OFDM.

![Fig. 1. (a) Concept of three different types of DDO-OFDM, (b) structure of proposed half-cycled DDO-OFDM, and (c) combination of two parallel half-cycled OFDM symbols.](image)

The inverse Fourier transform (IFFT) size during the OFDM modulation in this paper is $N$ and the time length of one OFDM symbol is $T$. After IFFT, the OFDM signal can be expressed as

$$s(t) = \sum_{k=0}^{N-1} c_k \exp(j2\pi f_k t) \quad (1 \leq t \leq T).$$

(1)
in which \( k \) represents the index of subcarriers, and \( f_k \) is the frequency of the \( k \)th subcarrier given as

\[
f_k = k\Delta f = \frac{k}{T}.
\]  

In the time domain, the first half and second half of one OFDM symbol can be expressed as

\[
s(t_1) = \sum_{k=0}^{N-1} c_k \exp(j2\pi f_k t) \quad (1 \leq t_1 \leq T/2).
\]  

\[
s(t_2) = \sum_{k=0}^{N-1} c_k \exp(j2\pi f_k t) \quad (T/2 + 1 \leq t_2 \leq T).
\]  

As \( t_2 = t_1 + T/2 \), the second half can be expressed as

\[
s(t_1 + T/2) = \sum_{k=0}^{N-1} c_k \exp(j2\pi f_k (t_1 + T/2))
\]

\[
= \sum_{k=0}^{N-1} c_k \exp(j2\pi f_k t_1 + jk\pi)
\]

\[
= \sum_{k=0}^{N-1} c_k (\cos k\pi + j\sin k\pi) \exp(j2\pi f_k t_1)
\]

\[
= \sum_{k=0}^{N-1} c_k \cos k\pi \exp(j2\pi f_k t_1) \quad (1 \leq t_1 \leq T/2).
\]  

In order to further simplify the formula, the index for sub-carriers is from \( 0 \) to \( N-1 \), and the index of even and odd subcarriers can be expressed as \( m \) and \( n \), respectively. The first half and second half of one OFDM symbol can be expanded as

\[
s(t_1) = \sum_{n=0}^{N-1} c_n \exp(j2\pi f_n t_1) + \sum_{m=0}^{N-1} c_m \exp(j2\pi f_m t_1) \quad (1 \leq t_1 \leq T/2).
\]  

\[
s(t_2) = s(t_1 + T/2)
\]

\[
= \sum_{k=0}^{N-1} c_k \cos k\pi \exp(j2\pi f_k t_1)
\]

\[
= \sum_{n=0}^{N-1} c_n \cos n\pi \exp(j2\pi f_n t_1) + \sum_{m=0}^{N-1} c_m \cos m\pi \exp(j2\pi f_m t_1)
\]

\[
= \sum_{n=0}^{N-1} -c_n \exp(j2\pi f_n t_1) + \sum_{m=0}^{N-1} c_m \exp(j2\pi f_m t_1) \quad (1 \leq t_1 \leq T/2).
\]  

In the interleaved OFDM scheme, subcarriers with even index are reserved without data mapping to resist SSMI, which means \( c_m \) are set to be “0”s. Thus, the first half and second half of one OFDM symbol can be simplified as

\[
s(t_1) = \sum_{n=0}^{N-1} c_n \exp(j2\pi f_n t_1) \quad (1 \leq t_1 \leq T/2).
\]  

\[
s(t_2) = \sum_{n=0}^{N-1} -c_n \exp(j2\pi f_n t_1)
\]

\[
= -s(t_1) \quad (t_2 = T/2 + t_1).
\]
From Eqs. (8) and (9), we can find that the first half and second half in one OFDM symbols demonstrate the inverted amplitude in the time-domain, and the second half was cut during the transmission. By this way the time length used to convey data transmission was shortened to \( T/2 \), and the second half of the symbol can be replaced with an independent “new first half” carrying additional data. Thus the data rate is doubled and the SE will maintain the same as traditional OFDM signal after this process.

Figure 1(b) shows the structure of proposed half-cycled DDO-OFDM. First, data is modulated only onto even subcarriers just the same as the interleaved OFDM signal in the frequency domain, and then IFFT is applied to realize OFDM modulation. After IFFT the period of one OFDM symbol is \( T \), while the first half and the second half demonstrate the inverted amplitude in the time-domain. The second half is cut during the transmission and thus the time length used to convey data transmission is shortened to \( T/2 \), while the SE maintains the same as traditional OFDM signal after this process even only odd subcarriers are filled with data. After electrical-to-optical (E/O) and optical-to-electrical (O/E) conversion, as the fiber link can be regarded as an approximate time invariant system, the second half OFDM symbol can be recovered by half cycled of the first half OFDM symbol. And then FFT is applied to realize OFDM demodulation, and after demodulation the SSMI is distributed in the odd subcarriers. In the proposed half-cycled DDO-OFDM, the cancellation of SSMI can be implemented without SE decrease. Figure 1(c) shows the combination of two half cycled OFDM symbol with parallel processing. After IFFT two different half cycled OFDM symbols discarded the second half of OFDM symbols in the time domain and two parallel remaining parts of symbols are combined to be a new symbol within a period of \( T \), which is the length of traditional OFDM symbol. After this processing, two different half-cycled OFDM symbols are transmitted within a period of \( T \). If the length of cyclic prefix (CP) after OFDM modulation is also cut half during the half cut in time domain, and the total capacity of system still maintain the same as traditional OFDM system. The main drawback of the half-cycled scheme compared to the traditional OFDM symbol is that the resistance of ISI induced by CD of fiber is limited as the length of CP is cut half. While in the access networks with direct-direction the span is usually not very long, this drawback is not very critical.

Figure 2 shows the experimental setup of half-cycled DDO-OFDM. In this paper, a double-side band (DSB) DDO-OFDM system is applied to verify the novel half-cycled OFDM. At the transmitter, an external cavity laser (ECL) at 1557.04\,\text{nm} with less than 100-kHz linewidth and maximum output power of 14.5\,dBm is modulated by intensity Mach-Zehnder modulator (MZM) driven by an electrical baseband OFDM signal. The OFDM signal is generated by an arbitrary waveform generator (AWG) with a 12-GSa/s sample rate. Here the FFT size for OFDM generation is 256, in which 200 subcarriers are employed with 100 conveying data in the positive frequency bins, the first subcarrier is set to zero for DC-bias and the rest 55 null subcarriers at the edge are reserved for oversampling. 4/16-QAM is taken on all the 100 information-bearing subcarriers. An 8-sample CP is added to the 256 samples, giving 264 samples per one OFDM symbol. In the traditional OFDM signal transmission scheme, 264 samples are transmitted in one OFDM symbol, while only 132 samples including 128 data samples and 4-sample CP are transmitted in the half-cycled OFDM scheme. One training sequence (TS) is inserted between every 160 OFDM data...
symbols to realize synchronization and obtain the channel response. The raw total bit rate in the system is 9.1 and 18.2 Gb/s for 4-QAM and 16-QAM transmission, respectively. One low pass filter (LPF) with 5-GHz bandwidth is used to filter aliasing products after digital to analog convertor (DAC) before injected into MZM. For optical OFDM modulation, the switching voltage is 3.4 V and MZM is biased at 1.9 V at its quadrature point. The generated signal is injected into Erbium-doped fiber amplifier (EDFA) to adjust the launched power to 8 dBm into fiber. The optical spectrum with 0.02-nm resolution is shown as an inset in the Fig. 2, and the optical carrier to signal ratio in this experiment is 20 dB. After 40-km SSMF-28 transmission, the OOFDM signal is filtered by a 0.33-nm bandwidth tunable optical filter (TOF) to block the out-of-band amplified spontaneous emission (ASE) noise from EDFA. An optical attenuator (ATT) is applied to adjust the received optical power for sensitivity measurement and then O/E conversion is implemented via an optical receiver with 3-dB bandwidth of 10 GHz. The converted electrical signal is captured by a real-time oscilloscope and then processed offline with a sample rate of 40 GSa/s. The resolution of the DAC in AWG and ADC in real-time oscilloscope respectively used at the transmitter and receiver are both 8 bits. The captured signal is then further processed with the offline DSP. The offline DSP procedure contains synchronization, half-cycled operation in time domain, CP removal, FFT, channel estimation with intra-symbol frequency-domain averaging (ISFA), one-tap equalization, 4-QAM or 16-QAM de-mapping and BER calculation. The BER is obtained by direct error counting with 320000 bits. The electrical spectra of traditional and half-cycled OFDM signal are shown in the Figs. 3(a) and 3(b), respectively.

3. Experimental results

In the experiment, three types of OFDM signals including traditional OFDM signal [4–6,9,10], interleaved OFDM [3] and half-cycled OFDM signal were tested. The lengths of traditional and interleaved OFDM are the same in the time domain while the length of half-cycled OFDM is reduced to half. In order to verify the effectiveness of SSMI cancellation by half-cycled operation, 4-QAM and 16-QAM OFDM signal were both demonstrated in this paper. In the receiver of interleaved OFDM signal, the second half of one OFDM symbol was also copied from the first half to compare the performance with half-cycled OFDM signal.
In the 4-QAM OFDM transmission, the BER versus received optical power was measured. The curves of the optical back to back (OBTB) and after 40-km SSMF-28 transmission are shown in the Figs. 4(a) and 4(b), respectively. The BER performance demonstrates that the receiver sensitivity was improved by 2 dB both at OBTB and after 40-km SSMF-28 transmission after SSMI cancellation with half-cycled OFDM compared to traditional OFDM signal. The difference between half-cycled OFDM and interleaved OFDM can be ignored, which proves that half-cycled OFDM is really practical. The constellations of three types of OFDM signal when the received optical power is −11 dBm at OBTB and after 40-km SSMF-28 are inserted in Figs. 4(a) and 4(b), respectively.

In the 16-QAM OFDM transmission, the BER versus received optical power was also measured. The curves of the OBTB and after 40-km SSMF-28 transmission are shown in the Figs. 5(a) and 5(b), respectively. The receiver sensitivity was improved by 1.5 dB both at OBTB and after 40-km SSMF-28 transmission after SSMI cancellation with half-cycled OFDM compared to traditional OFDM signal. The constellations of three types of OFDM signal when the received optical power is −6 dBm at OBTB and after 40-km SSMF-28 are inserted in Figs. 5(a) and 5(b), respectively. The receiver sensitivity improvement with QPSK modulation format is slightly higher than that with 16QAM modulation format. The OFDM signal is vulnerable to the synchronizations timing errors, as timing errors will introduce the Inter-Carrier-Interference (ICI) and Inter-OFDM Symbol-Interference (ISI) [11]. The accuracy of synchronization for traditional OFDM signal is higher than that for half-cycled OFDM signal, as the number of samples used to calculate the synchronization with TS for traditional OFDM signal is larger than that for half-cycled OFDM signal. QPSK-OFDM signal is robust to the ISI and ICI induced by synchronizations timing errors, while 16QAM-OFDM signal is much more vulnerable to this impairment, so the improvement of receiver sensitivity with QPSK modulation format is slightly higher than with that 16QAM modulation format. The error rate versus payload index of traditional and half-cycled 16-QAM OFDM after 40-km SSMF-28 when the received optical power is −7 dBm are shown in the Figs. 6(a) and 6(b), respectively. The number of samples used for error ratio calculation is more than 1000. In the tradition OFDM the number of data modulated subcarriers is 100 while for the half cycled OFDM the number is 50 with just only half symbol length. The error rate was significantly declined after SSMI cancellation with half-cycled technique.
4. Conclusions

Half-cycled technique was successfully demonstrated to overcome SSMI without SE reduction. In this scheme, two half cycled OFDM symbols with parallel processing are combined after the second half of each OFDM symbol in the time domain is discarded in the transmitter. After this processing, two different half-cycled OFDM symbols are transmitted within the same period as traditional OFDM symbol and the total capacity of system still maintain the same as traditional OFDM system. The receiver sensitivity was improved by 2 and 1.5 dB in QPSK and 16QAM OFDM with 40-km SSMF-28 transmission, respectively.

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