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Golay sequences coded coherent optical OFDM for long-haul transmission

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ABSTRACT

We propose to use binary Golay sequences in coherent optical orthogonal frequency division multiplexing (CO-OFDM) to improve the long-haul transmission performance. The Golay sequences are generated by binary Reed-Muller codes, which have low peak-to-average power ratio and certain error correction capability. A low-complexity decoding algorithm for the Golay sequences is then proposed to recover the signal. Under same spectral efficiency, the QPSK modulated OFDM with binary Golay sequences coding with and without discrete Fourier transform (DFT) spreading (DFTS-QPSK-GOFDM and QPSK-GOFDM) are compared with the normal BPSK modulated OFDM with and without DFT spreading (DFTS-BPSK-OFDM and BPSK-OFDM) after long-haul transmission. At a 7% forward error correction code threshold (Q^2 factor of 8.5 dB), it is shown that DFTS-QPSK-GOFDM outperforms DFTS-BPSK-OFDM by extending the transmission distance by 29% and 18%, in non-dispersion managed and dispersion managed links, respectively.

1. Introduction

Coherent optical orthogonal frequency-division multiplexing(CO-OFDM)has shown its capability in high-speed long-haul optical fiber transmission systems [1]. However, the nonlinear noise in CO-OFDM due to relatively high peak-to-average power ratio (PAPR) severely limits the transmission distance [1]. Several methods have been proposed to reduce the PAPR and hence fiber nonlinear effects over long-haul transmission [2–4]. However, these methods are inefficient when the transmission distance is more than 8000-km.

Recently, nonlinear noise cancellation or squeezing (NLNC or NLNS)methods have been proposed in both OFDM [5] and single-carrier [6,7] long-haul transmission systems. Due to the loss of 50% spectral efficiency, the QPSK format is selected in [5–7] to compare with the BPSK format in the demonstration. Through both simulation and experiment, it is shown that the Q^2factor of QPSK signal with nonlinear noise cancellation (or squeezing) is ~1.4–2 dB higher than BPSK signal after ~8000-km fiber transmission. However, both NLNC and NLNS require pre-equalization for chromatic dispersion (CD) to achieve a symmetric dispersion map, which reduces the flexibility of optical networks and in turn increases the computational complexity.

It has been proved in wireless OFDM that the PAPR of any binary Golay sequences is at most 3 dB [8]. However, the performances of Golay sequences coded OFDM have not been evaluated through nonlinear channels in both wireless and optical transmission systems. The main problem of Golay sequences is their low code rate at large code length and high modulation order. In this paper, for the first time, we propose to apply binary Golay sequences in CO-OFDM system with QPSK modulation to maintain good spectral efficiency and improve the long-haul transmission performance. We first construct QPSK codes based on binary Golay sequences. The Golay sequences are generated through the Reed-Muller codes, which have low PAPR and certain error correction capability [8]. In our scheme, the length of Golay sequences is 16 and the code rate is 0.5. Therefore, we cascade several Golay sequences in one OFDM symbol to achieve a larger subcarrier number. A low-complexity decoding algorithm for the QPSK codes is then proposed. With the same spectral efficiency, the QPSK modulated OFDM with Golay sequences coding with and without discrete Fourier transform (DFT) spreading (DFTS-QPSK-GOFDM and QPSK-GOFDM) are chosen to compare with the normal BPSK modulated OFDM with and without DFT spreading (DFTS-BPSK-OFDM and BPSK-OFDM) in a wavelength division multiplexing (WDM) polarization division multiplexing (PDM) long-haul transmission system. Through simulation, it is shown that DFTS-QPSK-GOFD Maintains the best performance after both non-dispersion managed (NDM) and dispersion managed (DM) transmission links. The performance of DFTS-QPSK-GOFDM surpasses DFTS-BPSK-OFDM by 29% and 18% in maximum transmission distances for NDM and DM links at 7% forward error correction(FEC) code threshold, respectively.

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2. Golay sequences coded OFDM

2.1. Construction of higher modulation order OFDM codes

It has been shown that the Golay sequences with length 2^m can be obtained from the summation of second-order cosets and first-order Reed-Muller codes [8]. Therefore, the binary Golay sequences of length 2^m is given by

$$\mathbf{G}(1,\,2,\ldots,\,2^m) = \sum_{k=1}^{m-1} x_{\pi(k)}x_{\pi(k+1)} + \sum_{k=0}^{m} c_k x_k \tag{1}$$

where $\boldsymbol{\pi}$ is a permutation of the elements[1, 2, ...,m]. The Boolean function x_i can be specified by a true table [8]. The modulated signals in the OFDM subcarriers are then given by

$$\mathbf{S}(1,\,2,\ldots,\,2^m) = \exp[\,j\pi\mathbf{G}(1,\,2,\ldots,\,2^m)] \tag{2}$$

where only BPSK modulation is considered in (2). It is because the generated Golay sequences in (2) are binary sequences. The higher order modulation can also be achieved based on the forms of (1) and (2), which is also shown in [8].

In (1), the first part in the right hand-side is the second-order cosets. For a certain m, there are $m!/2$ cosets generated in (1). Generally, w information bits are used to choose the cosets representative, where 2^w is the largest number no greater than $m!/2$. The second part in right hand-side of (1) is the (m+1) bits c_k(k is from 0 to m) mapping to first-order Reed-Muller codes with length 2^m. Therefore, we encode $[w+(m+1)]$ information bits into Golay sequences of length 2^m.

It is easy to see that the spectral efficiency of Golay sequences is very low, especially when m is very large. In order to solve this problem, we choose $m=4$, which means 8 ($w=3$) information bits are encoded into Golay sequences of length 16, corresponding to spectral efficiency of 0.5. We use $\mathbf{S_1}$ and $\mathbf{S_2}$ to represent two BPSK sequences in the form of (2). Then the generated QPSK sequences $\mathbf{S_Q}$ will have the same spectral efficiency as normal BPSK sequences (spectral efficiency of 1), which can be expressed as

$$\mathbf{S_Q} = \frac{\sqrt{2}}{2}\mathbf{S_1} + \frac{\sqrt{2}}{2}j\mathbf{S_2} \tag{3}$$

In (3), the length of QPSK sequences is 16, which is too small to be an OFDM symbol. In order to increase the length of QPSK sequences, we define $\mathbf{S_Q}$ in (3) as a sub-block and one OFDM symbol consists of several sub-blocks.

2.2. Decoding algorithm for the proposed QPSK sequences

The decoding algorithm for binary Reed-Muller codes has been reported in [8]. The algorithm can be modified to decode the binary Golay sequences in (1), where the second-order cosets are considered. In this paper, only 8 cosets are chosen in the generation of Golay sequences. Therefore, we can subtract each possible cosets from the received codeword to obtain 8 Reed-Muller codes for decoding. The best decoding result determines the coset representative. Considering that the real and imaginary parts of the QPSK sequences are two independent binary Golay sequences, the decoding algorithm for the proposed QPSK sequences in one OFDM symbol is summarized below.

1) Input the real part of the received signal **R** as a binary sequence **r** of length 16 in one sub-block after decision.
2) Subtract each possible cosets representative to obtain 8 binary sequences $\boldsymbol{r}_k\,(k=1,2,\ldots,8)$.
3) Decode the 8 sequences to get the corresponding decoded sequences $\boldsymbol{s}_k$ based on the Reed-Muller decoding algorithm [8].
4) Modulate each decoded sequence $\boldsymbol{s}_k$ based on (1) and (2) as $\mathbf{S}_k$.
5) The best decoded result $\hat{s}$ is chosen as the corresponding modulated sequence $\mathbf{S}_k$has the minimum Euler distance with the real part of the received signal **R**.
6) Repeat the steps (1) to (5) until both the real and imaginary parts of the received signal in all sub-blocks have been decoded.

3. Simulation setup

We carried out simulation investigation using Optisystem 13.0 [9]. The simulation setup consists of four WDM-PDM channels with 20-GHz channel spacing, and the original data at two polarizations are sampled at 32-GSa/s and mapped onto 128 subcarriers with QPSK or BPSK modulation in each channel. The DFT size is 256, resulting in a filling ratio of 2. The subband number is 2 for DFTS scheme as this achieves almost optimal performance [2]. We choose 4 samples as the cyclic prefix to avoid inter-symbol interference. The laser linewidth is set to be 100-kHz. The fiber link consists of several spans of DM or NDM sections. A DM section consists of 70-km standard single mode fiber (SSMF) and 10-km dispersion compensation fiber (DCF),while a NDM section consists of 80-km SSMF. The CD, polarization mode dispersion (PMD), attenuation coefficient, and nonlinearity coefficient for the SSMF and DCF are: D_{SSMF}=16 ps/nm/km, D_{DCF}=−112 ps/nm/km, α_{SSMF}=0.2 dB/km, α_{DCF}=0.6 dB/km, γ_{SSMF}=1.3 $\mathrm{w}^{-1}\,\mathrm{km}^{-1}$, γ_{DCF}=5.4 $\mathrm{w}^{-1}\,\mathrm{km}^{-1}$, D_{PMD}=0.5 ps $\mathrm{km}^{-1/2}$. An Erbium doped fiber amplifier is used to fully compensate the fiber loss with a noise figure of 6.0 dB. The CD in NDM transmission link is first compensated digitally at the receiver side before OFDM demodulation. We use 10 training symbols for every 200 data symbols for channel estimation and equalization. 4 pilot subcarriers are used in each OFDM symbols for common phase compensation. Therefore, the raw bitrate for the WDM-PDM channel is $32\mathrm{GSa/s}\times128/256\times1\mathrm{b/Sa}\times4\times2 = 128$ Gb/s. The total number of transmission bits in the simulation is 10^6. The Q^2 factor is derived directly from bit error rate (BER) based on the formula $\mathrm{Q}^2[\mathrm{dB}]=20\times\log_{10}(\sqrt{2}\,\mathrm{erfcinv}(2\times\mathrm{BER}))$ [7].

4. Simulation results and discussions

We first investigate and compare the complementary cumulative distribution function (CCDF) of (DFTS-)QPSK-GOFDM, (DFTS-) BPSK-OFDM, and normal QPSK-OFDM. As shown in Fig. 1, the PAPRs of QPSK-GOFDM and DFTS-BPSK-OFDM are similar. The PAPR of QPSK-GOFDM is lower than that of QPSK-OFDM, which proves low PAPR characteristic of Golay sequences. The DFTS-QPSK-GOFDM has the lowest PAPR value due to extra DFT spreading at the transmitter side [2–4].

Fig. 2 depicts the BER versus optical signal-to-noise ratio (OSNR)in the back-to-back case for the four schemes in single channel at bit rate

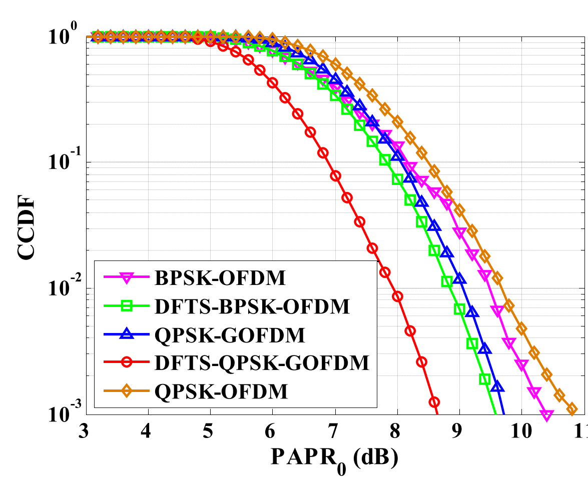

Fig. 1. CCDF for (DFTS-) QPSK-GOFDM, (DFTS-) BPSK-OFDM and QPSK-OFDM, respectively.