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Performance of coherent detection for FTN-DFTs-OFDM signal using receiver-side quadrature duobinary shaping

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ABSTRACT

In this paper we investigate Faster-than-Nyquist Discrete-Fourier-Transform spread Orthogonal Frequency Division Multiplexing (FTN-DFTs-OFDM) signaling which combines the features of both single carrier FTN and OFDM system. By introducing the quadrature duo-binary (QDB) filtering at the receiver side, the transmitted OFDM signal can be packed in a sub-Nyquist spacing, which improves the spectral efficiency (SE) compared to conventional detection schemes. Maximum a posteriori (MAP) and maximum likelihood sequence estimation (MLSE) criteria have been both used and compared to find an optimal equalization scheme for combating FTN multiplexing at transmitter side and QDB filtering at receiver side. The simulations result show that by applying QDB filtering at the receiver side, the back-to-back (BTB) required optical signal noise ratio (OSNR) at bit error rate (BER) of 1×10^{-2} is reduced by 1.5-dB for 20-GHz spaced 128-Gb/s polarization-division-multiplexed quadrature-phase-shift-keying (PDM-QPSK) signal, achieving a SE of 6.4-b/s/Hz.

1. Introduction

For meeting the ever-increasing bandwidth demand, improving the spectral-efficiency (SE) of optical fiber transmission has been one of the most important pursuit for recent years' studies on single mode fiber transmission areas. Various methods have been considered for such purpose, including increasing the order of modulation formats, applying bandwidth efficient modulation and multiplexing techniques (such as single carrier Nyquist wavelength-division multiplexing (WDM) and orthogonal frequency–division multiplexing (OFDM)) etc. [1–3]. Among these studies, both single carrier based Nyquist WDM and multi-carrier OFDM have been attracting large quantity of attention by applying a close-to-symbol-rate channel spacing.

To further increase the SE, Faster-than-Nyquist (FTN) firstly proposed by Mazo in 1975 draws increasing concern recently, which aims to increase the SE further by breaking the limitation of Nyquist rule and applying a sub-Nyquist channel spacing [4,5]. For reducing the serious inter channel interference (ICI) induced by the sub-Nyquist spacing, the signal is strongly filtered by low-pass filter (LPF) before being multiplexed in the frequency domain. However, for further increasing the SE of conventional optical OFDM signal, such direct FTN filtering seems unreasonable since the subcarriers are orthogonally distributed in the optical frequency and direct filtering in the frequency domain would unavoidably remove the data on the edge subcarriers.

Recently, a FTN Discrete-Fourier-Transform spread OFDM (FTN-DFTs-OFDM) scheme has been proposed to further increase the SE of OFDM without removing part of the signal [6]. As an enhanced OFDM scheme, DFTs is first introduced to improve the tolerance of fiber nonlinearity [7–10]. At the same time, the DFTs processing makes it feasible to reduce the bandwidth of OFDM through direct frequency domain filtering without removing data unrecoverable.

In [6], the partial response filtering is adopted in the Tx DSP only to narrow the bandwidth of OFDM signal and reduce the inter-sub-band interference (ISBI). In [11,12], the receiver-side partial response filtering has been conducted at single carrier based FTN condition. With the partial response filtering at receiver, the mature constant modulus algorithm (CMA) and Viterbi-Viterbi phase estimation can be used without any modification. And the partial response filtering after channel estimation can suppress the noise at higher frequency and improve the signal-to-noise ratio (SNR). With these factors considered, we investigate FTN-DFTs-OFDM system by applying a quadrature duobinary (QDB) filtering at receiver [11–13].

In this paper, the FTN-DFTs-OFDM employing QDB filtering and maximum a posteriori (MAP) or maximum-likelihood-sequence estimation (MLSE) at receiver is demonstrated compared without QDB filtering [14–16]. The numerical results show that the perfor-

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mance has a 1.5-dB OSNR improvement by using QDB filtering. At the same time, 1000 km transmission simulations show that 2-dBm is the optimal launch power.

2. The principle of FTN-DFTs-OFDM scheme

The FTN-DFTs-OFDM generation scheme is shown in Fig. 1(a). The pseudo random binary sequence (PRBS) is split into 3 sub-bands and mapped into quadrature-phase-shift-keying (QPSK) signals. After transformed by M-point DFT, all sub-bands are filtered by 5th order super-Gaussian low-pass filters and mapped into an L-point Inverse-Discrete-Fourier-Transform (IDFT) (L > 3 M) with part of adjacent sub-band spectrum overlapped. In this way, the bandwidth of signals can be reduced directly. With Cyclic Prefix (CP) added, the generated OFDM symbols are sent out using a polarization multiplexed IQ modulated optical Mach-Zehnder modulator (MZM). The spectrum of conventional DFTs-OFDM and FTN-DFTs-OFDM are respectively shown in Fig. 1(b) and (c) for an intuitive comparison. For generating the FTN-DFTs-OFDM symbols, orthogonal relations are still satisfied for subcarriers that are located in different sub-bands without introducing inter-subcarrier interference. The interferences only occur between adjacent sub-bands, and the amount of interference depends on the bandwidth of LPF and the spacing between sub-bands. In other words, the interferences between sub-bands depends on the ratio of bandwidth compression. When multiplexed for different wavelength channels, the FTN condition can be reached without ICI introduced. The difference of conventional DFTs-OFDM from FTN-DFTs-OFDM is that there is no low-pass filtering and spectrum overlapping between sub-bands. In addition, guard bands are inserted between sub-bands to ensure no ISBI introduced.

The receiver side DSP of FTN-DFTs-OFDM is shown in Fig. 2(a). With the optical signal detected by coherent receiver, CP is cut off at first. After L-point DFT converting the signals into frequency domain, chromatic dispersion (CD) is compensated. With de-multiplexed into different sub-bands, the signal is converted back to time domain by M-point IDFT processing. CMA is employed for polarization de-multiplexing and channel estimation. Next, carrier recovery is performed with Viterbi-Viterbi algorithm [17]. The QDB filter realized by a delay-&-add operation with two equal weight taps, as shown in Fig. 2(b) [13,18]. Finally, MLSE/MAP is implemented to compensate the residual ISI and calculate the bit error rate (BER).

As a linear equalizer, CMA has a relatively much flat amplitude response. For the information signals, the excess gain near the edges of the Nyquist band benefit the compensation of the aggressive pre-filtering at the transmitter. However, the in-band noise having the same spectral components is likewise amplified together with the information signal, which bringing to a decrease of the signal-noise ratio (SNR) [11]. So, a QDB filter is adopted after CMA to suppress the high-frequency noise component without degrading the signal quality. At the same time, the QDB filtering can shorten the ISI memory length and reduce the pressure of MLSE/MAP algorithm [17].

According to the optimal reception theory, the optimal detection process is not to reconstruct the original waveform of transmitted signals but to estimate the transmitted sequence [15]. MLSE and MAP are two optimal candidates which could simulate the ISI generation process in the channel and select the most likely sequence. Both of them are nonlinear detector.

The principle of MLSE is to maximize the probability $p(\overline{Y}|\overline{A})$, which means the probability of receiving sequence $\overline{Y}$, when the sequence $\overline{A}$ is transmitted [14]. We assume that the noise is independent, even though the adjacent symbols are correlated. In this way, the total probability can be given by the product of the individual probabilities:

$$p(\overline{Y}|\overline{A}) = \prod_{k=o}^{\infty} p(y_k|\overline{A}) \quad (1)$$

where k is the time index of received sample sequence. Then, the Viterbi algorithm (VA) is employed to solve the Eq. (1) [14].

For MAP, the decision procedure is to maximize the posterior probability [15,16]

$$p(\overline{A}|\overline{Y}) = \prod_{k=0}^{\infty} p(a_k|\overline{Y}) \quad (2)$$

With Bayes' Law used, Eq. (2) can be divided as:

$$p(a_k|\overline{Y}) = \sum_{a_k} \cdots \sum_{a_{k+L}} p(a_k a_{k+1} \cdots a_{k+L}, Y_1 \cdots Y_{k+L}) \quad (3)$$

$$p(a_k \cdots a_{k+L}, Y_1 \cdots Y_{k+L}) = P(a_{k+L}) p(Y_{k+L}|a_k \cdots a_{k+L}) \times \sum_{a_{k-1}} p(a_{k-1} a_k \cdots a_{k+L-1}, Y_1 \cdots Y_{k+L-1}) \quad (4)$$

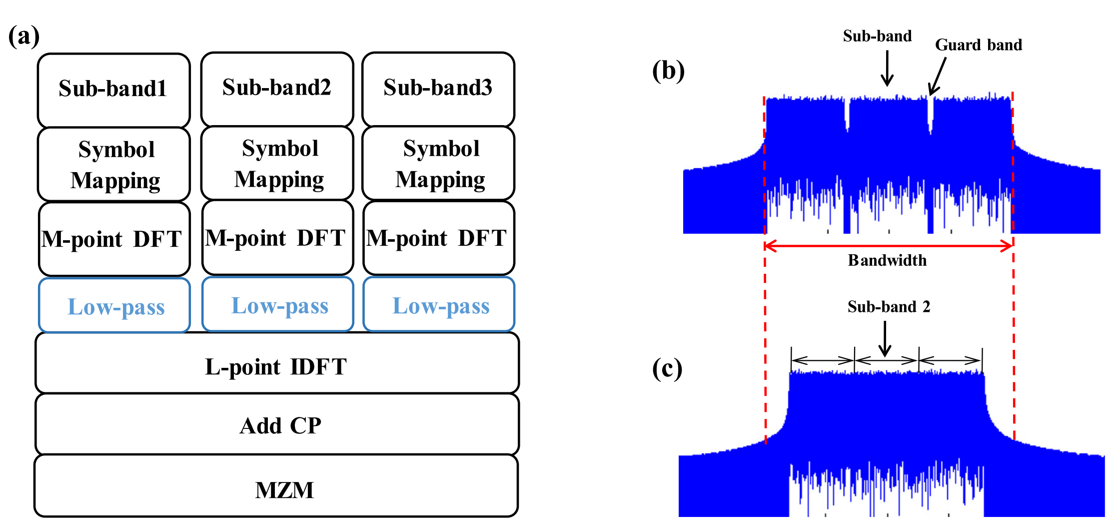

Fig. 1. (a) The generation scheme of FTN-DFTs-OFDM; (b) the spectrum of conventional DFTs-OFDM; (3) the spectrum of FTN-DFTs-OFDM.