LDPC-Coded OFDM Transmission Over Graded-Index Plastic Optical Fiber Links

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***Abstract*—The possibility of 10-Gb/s transmission over graded-index plastic optical fiber (GI-POF) using the orthogonal frequency-division multiplexing (OFDM) and iteratively decodable codes is demonstrated by simulations. Several classes of low-density parity-check (LDPC) codes suitable for use in LDPC-coded OFDM transmission over GI-POF are presented as well. Several power efficient OFDM schemes are introduced.**

***Index Terms*—Graded-index plastic optical fiber (GI-POF), low-density parity-check (LDPC) codes, optical communications, orthogonal frequency-division multiplexing (OFDM).**

I. INTRODUCTION

THE graded-index plastic optical fiber (GI-POF) [1] is a robust, low-cost, easy-to-install medium, and provides relatively high-bandwidth [1]. Possible applications of POFs include gigabit-ethernet and uncompressed HDTV [2]. However, due to limited bandwidth-length product of GI-POF (about 3.45 GHz × 100 m, see [1]), the POFs impose serious bandwidth limitations for applications at 2.5 Gb/s and above. To counter the bandwidth problem, an adaptive multiple subcarrier system operating at 1 Gb/s with spectral efficiency of 6.3 b/s/Hz and employing either 256 quadrature-amplitude modulation (256-QAM) or 64-QAM has been proposed in [2]. Unfortunately, as shown in [3], the multiple subcarrier scheme is not a very spectrally efficient scheme because it requires the use of guard bands between neighboring subbands. The multiple subcarrier systems do not have a good mechanism to deal with intersymbol interference (ISI) introduced by limited bandwidth of a POF. Moreover, the multiple subcarrier scheme proposed in [2] is not a power efficient one, because it requires the use of dc bias large enough so that when added to the multiple subcarrier signal, the resulting signal is non-negative (to enable transmission over an intensity-modulation/direct-detection (IM/DD) link).

To improve the spectral efficiency and ISI tolerance due to chromatic dispersion of multiple subcarrier (multicarrier) scheme [2], we propose the use of orthogonal frequency-division multiplexing (OFDM) [3]–[5]. Due to orthogonality of subcarriers in OFDM, the partial overlapping of neighboring carriers is allowed, improving, therefore, the spectral efficiency significantly. Through the concept of cyclic extension, the overlapping of neighboring OFDM symbols is allowed, and by using a sufficient number of subcarriers, the ISI due to chromatic dispersion can be significantly reduced. Moreover, the pilot-aided channel estimation [3] can be used for chromatic dispersion compensation. To improve poor power efficiency of multiple subcarrier systems, we propose the use of single-sideband (SSB) transmission and clipped and unclipped OFDM (explained in Section II). Due to severe dispersion distortion of signals at 2.5 Gb/s and above, transmitted over GI-POFs, the powerful forward-error-correction (FEC) schemes are required. Several such FEC schemes based on girth-8 low-density parity-check (LDPC) codes are introduced as well.

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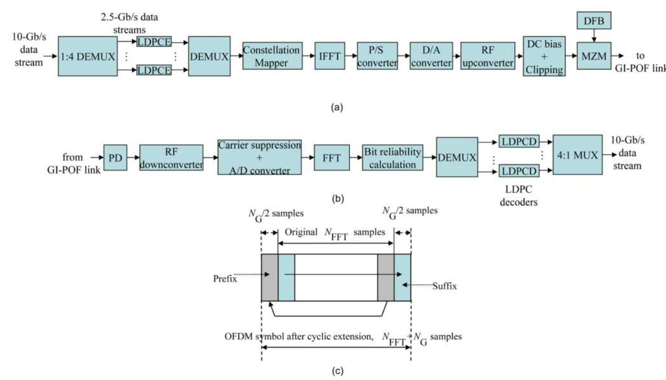

Fig. 1. (a) Transmitter configuration, (b) receiver configuration, and (c) OFDM symbol after cyclic extension. LDPCE: LDPC encoder; LDPCD: LDPC decoder; S/P: serial-to-parallel converter.

II. LDPC-CODED OFDM TRANSMISSION OVER GI-POF LINKS

The transmitter configuration, receiver configuration, and the OFDM symbol after cyclic extension are shown in Fig. 1(a), (b), and (c), respectively. An information-bearing stream at 10 Gb/s is demultiplexed into four 2.5-Gb/s streams, which are further encoded using identical LDPC codes. This step is determined by currently existing LDPC chips [7]. The outputs of LDPC encoders are demultiplexed and forwarded to the QAM mapper employing the Gray mapping rule. The QAM mapper signal points are used as the inputs to the inverse fast Fourier transform (IFFT) block. The OFDM symbol, shown in Fig. 1(c), is generated as follows: N_{QAM} input QAM symbols are zero-padded to obtain N_{FFT} input samples for IFFT, the N_G samples are inserted to create the guard interval, and the OFDM symbol is multiplied by the window function. The cyclic extension (introduced to preserve the orthogonality among subcarriers when the neighboring OFDM symbols partially overlap due to dispersion), illustrated in Fig. 1(c), is done by repeating the last $N_G/2$ samples of the effective OFDM symbol part (N_{FFT} samples) as the prefix, and repeating the first $N_G/2$ samples as the suffix. (For more details on OFDM an interested reader is referred to [3], [4].) After a digital–analog

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conversion and RF up-conversion, the RF signal is converted to optical domain using one of two possible options: 1) the OFDM signal directly modulates the distributed-feedback laser, and 2) the OFDM signal is used as RF input of the Mach–Zehnder modulator (MZM). The dc bias component is inserted to enable recovering the QAM symbols incoherently. In what follows, three different OFDM schemes are introduced. The first scheme is based on direct modulation, and shall be referred to as the "biased-OFDM" (B-OFDM) scheme. Because bipolar signals cannot be transmitted over an IM/DD link, it is assumed that the bias component is sufficiently large so that when added to the OFDM signal, the resulting sum is non-negative. The main disadvantage of the B-OFDM scheme is the poor power efficiency. To improve the power efficiency, we propose two alternative schemes. The first scheme, which we shall refer to as the "clipped-OFDM" (C-OFDM) scheme, is based on SSB transmission, and clipping of the OFDM signal after bias addition. The bias is varied to find the optimum one for fixed optical launched power. It was found that the optimum case is one in which $\sim$50% of the total electrical signal energy before clipping is allocated for transmission of a carrier. The second power-efficient scheme, which we shall refer to as the "unclipped-OFDM" (U-OFDM) scheme, is based on SSB transmission and employs $LiNbO_3$ MZM. To avoid distortion due to clipping, the information is imposed by modulating the electrical field (instead of IM employed in the B-OFDM and C-OFDM schemes) so that the negative part of the OFDM signal is transmitted to the photodetector. Distortion introduced by the photodetector, caused by squaring, is successfully eliminated by proper filtering. The receiver employs a p-i-n photodiode (PD) in a transimpedance amplifier (TA) configuration, whose output is given by

$$\begin{aligned} i(t) &= \mathsf{R}\left|(s_{\mathrm{OFDM}}(t)+b)*h(t)\right|^2 \\ &= \mathsf{R}\Big[\left|s_{\mathrm{OFDM}}(t)*h(t)\right|^2+\left|b*h(t)\right|^2 \\ &\qquad +2R_e\left\{(s_{\mathrm{OFDM}}(t)*h(t))\,(b*h(t))\right\}\Big] \end{aligned} \quad (1)$$

where $s_{\mathrm{OFDM}}(t)$ denotes the transmitted OFDM signal, b is the dc bias component, and R denotes the PD responsivity. With $h(t)$, we denoted the impulse response of the GI-POF, which was found to be Gaussian in [1]. The signal after RF down-conversion and appropriate filtering, can be written as

$$r(t) = [i(t)k_{\mathrm{RF}}\cos(\omega_{\mathrm{RF}}t)]*h_e(\tau)+n(t) \quad (2)$$

where $h_e(t)$ is the impulse response of the low-pass filter, $n(t)$ is electronic noise in the receiver (mostly due to TA thermal noise), commonly modeled as Gaussian, and k_{RF} denotes the RF down-conversion factor. Finally, after the analog–digital conversion and cyclic extension removal, the transmitted signal is demodulated by the FFT algorithm. The soft outputs of FFT demodulator are used to estimate the bit reliabilities that are fed to identical LDPC iterative decoders based on the sum-product algorithm. For the sake of illustration, let us consider the signal waveforms and power-spectral densities (PSDs) at various points in the OFDM system, as shown in Fig. 2. The bandwidth of the OFDM signal is set to B GHz, and the RF carrier to $0.75B$. With B, we denoted the aggregate data rate. The number of OFDM subchannels is set to 64, the OFDM sequence is zero-padded, and the FFT is calculated

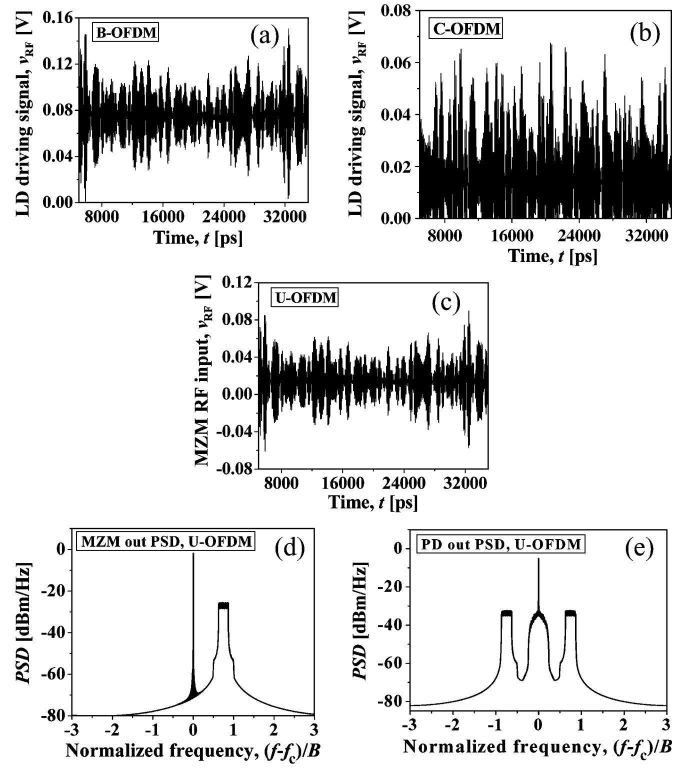

Fig. 2. Waveforms and PSDs of SSB QPSK-OFDM signal at different points during transmission for electrical SNR (per bit) of 6 dB. (f_c: optical carrier frequency; LD: laser diode.)

using 128 points. The guard interval is obtained by a cyclic extension of 2 × 16 samples. The average transmitted launched power is set to 0 dBm. The OFDM system parameters are carefully chosen such that the RF driver amplifier and MZM operate in linear regime [see Figs. 2(a)–(c)]. The laser driving signals for B-OFDM and C-OFDM, and MZM RF input signal for U-OFDM are given in Fig. 2(a)–(c), respectively. The PSD for an SSB QPSK-OFDM MZM output signal is shown in Fig. 2(d), and a photodetector output signal PSD is shown in Fig. 2(e). The transmitted QAM symbols are estimated by

$$\hat{X}_{i,k} = \left(h_i^*/|h_i|^2\right)e^{-j\theta_k}Y_{i,k} \quad (3)$$

where h_i is channel distortion introduced by chromatic dispersion, and θ_k is the corresponding phase shift of kth OFDM symbol. With $Y_{i,k}$, we denoted the received QAM symbol in the ith subcarrier of the kth OFDM symbol. To determine the channel coefficients it is enough just to pretransmit a short training OFDM sequence.

As already mentioned in Section I, POFs have limited bandwidth [1], [2], and introduce severe dispersion distortion of signals above 2.5 Gb/s transmitted over POFs. The powerful FEC schemes, much more powerful than those already proposed for use in long-haul transmission, would be required to enable 10-Gb/s transmission over POF links. Three such FEC schemes based on girth-8 LDPC codes are introduced in this section. The first class is the class of girth-8 *regular* LDPC codes designed based on the concept of mutually orthogonal Latin rectangles (MOLRs) [8]. The second class of the codes is the class of *irregular* girth-8 LDPC codes obtained from the combinatorial objects known as pairwise balanced designs

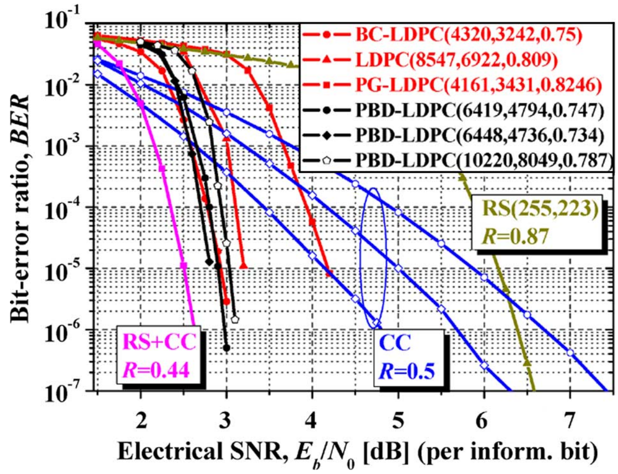

Fig. 3. Proposed LDPC codes against PG, RS, convolutional, and concatenation of convolutional and RS codes on an additive white Gaussian noise (AWGN) channel.

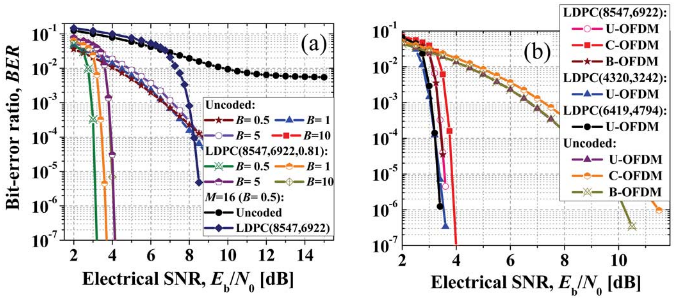

Fig. 4. BERs of LDPC-coded OFDM over GI-POF links [4 : 1 multiplexer output in Fig. 1(b)]. (left) comparison of different normalized bandwidths, and (right) comparison of different LDPC-coded OFDM schemes.

(PBDs) [8]. The third-class of codes is class of *regular* array (also known as block-circulant (BC) [9]) LDPC codes of girth-8. In Fig. 3, proposed LDPC codes are compared against a Reed–Solomon (RS) (255,223) code, convolutional codes (CC) (of constraint lengths 3, 5, and 7), and projective geometry (PG) girth-6 LDPC code (4161,3431) [6]. The proposed LDPC codes, both regular and irregular, significantly outperform other classes of codes. Notice that PBD-based irregular LDPC codes tend to outperform even the concatenation of convolutional (of rate $R = 1/2$) and RS (of rate 0.87) codes (denoted in Fig. 3 as RS + CC) of significantly lower code rate $(R = 0.44)$ at bit-error ratios (BERs) below 10^{-7}. As expected, irregular LDPC codes outperform regular LDPC codes.

III. Numerical Results and Conclusion

The results of simulations [at the output of a 4 : 1 multiplexer in Fig. 1(b)] for LDPC-coded OFDM are shown in Fig. 4 for different values of GI-POF normalized bandwidth B [the bandwidth is normalized with respect to the aggregate bit rate (10 Gb/s)]. For normalized bandwidths $B \geq 1$, the OFDM system parameters are selected as follows. The OFDM signal bandwidth is set to $0.25B$, the number of subchannels is set to $N_{\mathrm{QAM}} = 64$, FFT/IFFT is calculated in $N_{\mathrm{FFT}} = 128$ points, RF carrier frequency is set to $0.75B$, the bandwidth of optical filter for SSB transmission is set to $2B$, and the total averaged launched power is set to 0 dBm. The guard interval is obtained by cyclic extension of $N_G = 2 \times 16$ samples as explained earlier. For normalized bandwidth $B < 1$, all parameters are the same except for the RF carrier frequency set to $0.3B$. The results reported in Fig. 4 are given in terms of normalized OFDM signal bandwidth, so that they are applicable for a variety of OFDM systems having the same normalized bandwidth. Three classes of LDPC codes, as explained in Section II, are considered in simulations. The first class is the girth-8 *regular* LDPC code (8547,6922) of rate 0.81. The second class is *irregular* girth-8 LDPC code (6419,4794) of rate 0.75. The third class is girth-8 *regular* BC LDPC code (4320,3242) of rate 0.75. In simulations shown in Fig. 4 (left), the LDPC code of rate 0.81 is employed, and BER results for different GI-POF normalized bandwidths is reported for U-OFDM scheme. For normalized bandwidth $B = 0.5$ and QPSK-U-OFDM, the LDPC code of rate 0.81 provides the coding gain about 9 dB at BER of 10^{-6}; much larger coding gain is expected for lower BERs. The uncoded 16-QAM-U-OFDM exhibits the BER floor, while the LDPC-coded OFDM scheme is able to operate error-free. Notice that other FEC schemes based on RS codes [such as RS(255,223)] or concatenated RS codes are not able to operate at all for 16-QAM-OFDM because the error floor of uncoded signal is too high for their error correction capabilities. In Fig. 4 (right), different classes of LDPC codes are compared for QPSK-U-OFDM, and it was found that an irregular LDPC code of rate 0.75 outperforms the other two classes of LDPC codes. In Fig. 4, LDPC-coded B-OFDM, U-OFDM, and C-OFDM are compared in terms of BER, and it was found that B-OFDM and U-OFDM perform comparable, while the C-OFDM is about 0.5 dB worse. Notice, however, that clipped-OFDM is the most efficient in terms of power efficiency, and the B-OFDM is the worst in that sense.

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