Title	Bit-interleaved coded OCDM with nonlinear equalization
Author(s)	Ouyang, Xing; Talli, Giuseppe; Power, Mark; Yang, Mingwei; Djordjevic, Ivan; Townsend, Paul
Publication date	2019-11
Original citation	Ouyang, X., Talli, G., Power, M., Yang, M., Djordjevic, I. and Townsend, P. (2019) 'Bit-interleaved coded OCDM with nonlinear equalization', Asia Communications and Photonics Conference (ACPC) 2019, Chengdu China, 2–5 November, T4B.5 (3pp).
Type of publication	Conference item
Link to publisher's version	http://www.osapublishing.org/abstract.cfm?URI=ACPC-2019-T4B.5 http://www.acpconf.org/ Access to the full text of the published version may require a subscription.
Rights	**© 2019, the Authors. Published by the Optical Society of America. Asia Communications and Photonics Conference 2019: © Optical Society of America.**
Item downloaded from	http://hdl.handle.net/10468/10206

Bit-Interleaved Coded OCDM with Nonlinear Equalization

Xing Ouyang[1,†], Giuseppe Talli[1], Mark Power[1], Mingwei Yang[2], Ivan Djordjevic[2] and Paul Townsend[1]
[1] Photonic Systems Group, Tyndall National Institute, Cork City Centre, Ireland, T12 R5CP
[2] Department of Electrical and Computer Engineering, The University of Arizona, Tucson, AZ85721, USA
[†] Author e-mail address: xing.ouyang@tyndall.ie

Abstract: We propose a bit-interleaved coded OCDM with nonlinear IB-DFE for IM/DD systems, and for the first time experimentally demonstrate a 31-Gbit/s KP4-coded OCDM signal over 50-km S-SMF achieving additional 5-dB coding gain with IB-DFE. © 2019 The Author(s)

OCIS codes: (060.0060) Fiber optics and optical communications, (060.4080) Modulation.

1. Introduction

Recent advances in optical devices and high-speed digital signal processing technology have substantially boosted the capacity of optical networks to enable continuing support of the ever-increasing demand for high-speed Internet and data services [1]. Recently, orthogonal chirp-division multiplexing (OCDM) has been proposed as a promising advanced digital modulation technique for optical communications [2]. By synthesizing a large group of orthogonal chirps, OCDM signals attain the maximum spectral efficiency (SE) in the sense of the Nyquist signalling rate, overcoming the disadvantage of traditional chirp spread-spectrum (CSS) signal of low SE, while inheriting the advantage of the spread-spectrum feature of CSS in combating impairments in communication systems [3]. Hence, OCDM has been proposed for various high-speed systems and exhibited superior performance in comparison with other digital modulation techniques, such as orthogonal frequency-division multiplexing (OFDM) [4]. For example, it was shown in [5-7] that OCDM is effectively resilient to chromatic dispersion (CD)-induced power fading, a severe distortion in intensity-modulation and direct-detection (IM/DD) systems. This is highly advantageous for cost-sensitive applications, such as, passive optical networks (PON) and datacentre interconnects [8, 9].

In this work, we propose and experimentally demonstrate a bit-interleaved coded (BIC) OCDM combining with nonlinear equalization to further improve the capacity of IM/DD based systems. In the proposed system, a nonlinear iterative block decision feedback equalizer (IB-DFE) is proposed to compensate the CD-induced fading, and by so doing, the capacity of BIC-OCDM is significantly improved by recovering the information corrupted by the fading effect. A 31-Gbit/s KP-4 coded BIC-OCDM signal has been experimentally demonstrated over 50-km standard single-mode fiber (S-SMF). It is shown that the required optical SNR (OSNR) is improved by 7 dB with the IB-DFE at a Pre-FEC bit-error rate (BER) of 2×10^{-4}. The coding gain of the BIC-OCDM is improved by 5-dB OSNR with IB-DFE compared to that without IB-DFE at a Post-FEC BER = 10^{-9}. For comparison, BIC-OFDM is studied. Almost no coding gain is seen under the same conditions, as the OFDM signal is severely degraded above the FEC limit.

2. System Model of the Proposed BIC-OCDM System with IB-DFE

Fig. 1 shows the block diagram of the proposed BIC-OCDM system with nonlinear IB-DFE. The bit from the source is coded based on a codebook, $\mathcal{C}$, and each encoded bit frame is interleaved by a random block interleaver, $\mathcal{P}$, as shown in the inset in Fig. 1 [10]. The coded bits are serial-to-parallel (P/S) converted in blocks, and mapped into symbols. In OCDM, the symbols are modulated onto the chirps digitally by discrete Frensel transform (DFnT) [11],

$$s(n) = \mathcal{F}_{\Psi}^{-1}\left\{x(k)\right\}(n), \quad n = 0,1,\dots,M-1 \tag{1}$$

where $\mathcal{F}_{\Psi}$ denotes the DFnT and $\mathcal{F}_{\Psi}^{-1}$ the inverse DFnT (IDFnT), $x(k)$ is the symbol on the k-th chirp. To generate one-dimensional signals for optical intensity modulation, digital up-conversion (DUC) technique is employed [6]. In the DUC, the signal is up-sampled and then up converted to a passband; the real-part of the passband signal, which is in fact the double-sideband modulated (DSB) signal, is preserved for modulation.

The optical signal is fed into fiber for transmission, and received by the receiver. In IM/DD systems, signals will be distorted by the CD-induced power fading, which arises due to the beating of dispersive optical frequencies at the photodiode (PD). The detected signal at the output of PD is given in the frequency domain, as

$$R(f) = H(f)\cdot S(f) + v_{\Omega}(f) \tag{2}$$

where $H(f)$ is the channel frequency response (CFR) function and $v_{\Omega}(f)$ is the additive noise in the frequency domain. The CFR $H(f)$, can capture linear effects in the system, and one major detrimental effect in the IM/DD system is the CD-induced fading. For example, as shown in Fig. 1(b), after 50 km, the received spectrum is distorted by fading, and the first frequency null occurs at 9 GHz. In a practical system, the signal bandwidth should be limited far away from the notches in order to prevent severe degradation, which largely limits the system capacity.

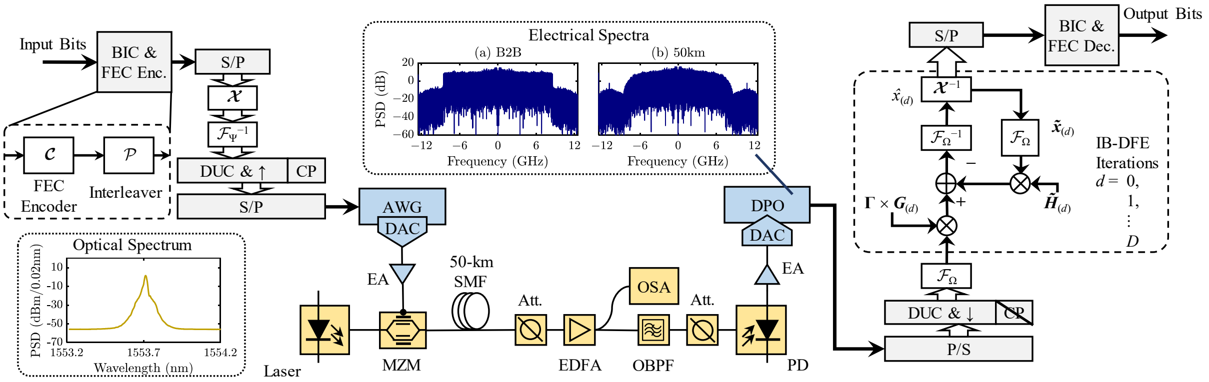

Fig. 1 System setup of the proposed BIC-OCDM system based on IM/DD.

To avoid such limitations, nonlinear equalization based on IB-DFE is adopted [7]. In contrast to a linear equalizer, IB-DFE can compensate the fading and recover the corrupted information due to the frequency notches. It can thus be expected that the information can be further recovered by channel coding. Thus, the system capacity can be further improved by operating the system near the frequency notches. For example, at the receiver as shown in Fig. 1, the OCDM signal after discrete Fourier transform (DFT), $\mathcal{F}_\Omega$, is

$$\begin{aligned} y(m) &= \mathcal{F}_\Omega\{r(n)\} = H(m)\times\mathcal{F}_\Omega\{s(n)\}(m)+v_\Omega(m) \\ &= H(m)\Gamma^*(m)\times\mathcal{F}_\Omega\{x(k)\}(m)+v_\Omega(m), \end{aligned} \tag{3}$$

where $\Gamma(m)$ is the eigen-value of DFnT w.r.t DFT. Considering an ideal case with perfect decisions, the coefficients of the feedforward equalizer (FFE) and DFE are $G_{(d)} = H^*(m)$ and $\tilde{H}_{(d)}(m) = \langle H(m)\rangle - |H(m)|^2$, respectively. The corresponding signal at the output of the IB-DFE is thus

$$\bar{y}_{(d)}(m) = \langle H(m)\rangle \times \mathcal{F}_\Omega\{x(k)\}(m). \tag{4}$$

In the above equation, the IB-DFE output in the d-th iteration is actually the transmitted signal without any fading. If one applies another inverse DFT (IDFT), the transmitted signal can be recovered with only the addition of noise.

3. Experimental Setup

The experimental setup of the proposed BIC-OCDM with IB-DFE is shown in Fig. 1, and the results are provided in the following section. The IM/DD-OCDM signal was generated offline, and downloaded to an arbitrary waveform generator (AWG) operating at 25 GSa/s. The laser had a wavelength of 1553.75 nm and the Mach-Zehnder modulator (MZM) had a V_π of ~5 V. The electrical signal was amplified to a V_{pp} of ~3.5V to drive the MZM at its quadrature point. A spool of 50-km S-SMF was used for transmission. At the receiver, a variable optical attenuator (VOA) was used to control the optical power to the erbium-doped fiber amplifier (EDFA). Following the EDFA, there was a 90:10 splitter. The 10%-port was connected to an optical spectral analyser (OSA) to measure the received OSNR with 0.1-nm resolution. The 90%-port was connected to a 0.6-nm optical bandpass filter (OBPF) to reject the out-of-band amplified spontaneous emission (ASE) noise. An optical power controller was placed at the output of the filter with a fixed output power at 9 dBm to the PD. An electrical amplifier (EA) amplified the signal and a 100-GSa/s digital real-time oscilloscope (RTO) captured the signal for offline processing.

In the proposed BIC-OCDM, the KP4 code, i.e., RS(544, 514) was adopted and a random interleaver permutated the coded bits [12]. The OCDM signal consisted of 688 chirps, each of which was modulated in 16-QAM. The complex-baseband signal was up-sampled to 2048 samples per symbol (oversampling ratio of 2.98) and up-converted by a frequency of 4.35GHz. The guard interval (GI) was 48 samples. As a result, the signal bandwidth was 8.54 GHz, and a net data rate (including FEC) of 31 Gbit/s was attained. For a fair comparison, OFDM was implemented based on discrete multi-tone (DMT) modulation, and the BIC-OFDM employed the same FEC code. In the OFDM system, there were 2048 subcarriers. The first 12 positive subcarriers were set to nulls to avoid AC-coupling, and the following 688 subcarriers were modulated using in 16-QAM. The negative subcarriers were the complex conjugate of the positive symmetries. The GI was also 48 points. Thus, both systems had the same bandwidth and data rate.

4. Results and Discussions

The measured BER versus OSNR performance are provided in Fig. 2. In the back-to-back (B2B) case, the BIC-OCDM has a coding gain ~8-dB at a post-FEC BER = 1×10^{-9} with a pre-FEC BER of 6×10^{-4}. BIC has only mi-

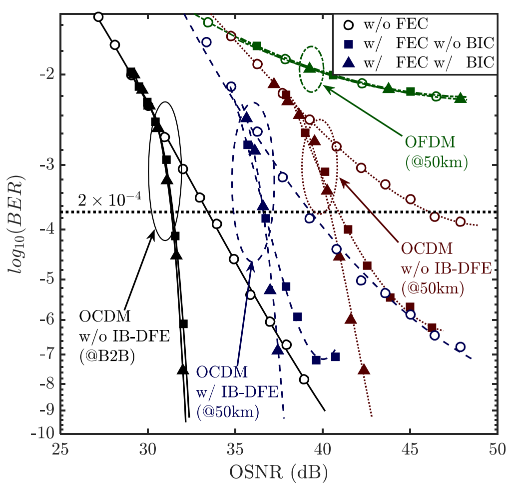

Fig. 2 Measured BER performance versus OSNR of the proposed BIC-IM/DD-OCDM with IB-DFE and OFDM system.

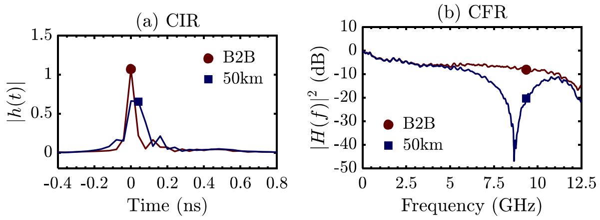

Fig. 3 Measured channel state information, (a) channel impulse response and (b) channel frequency response.

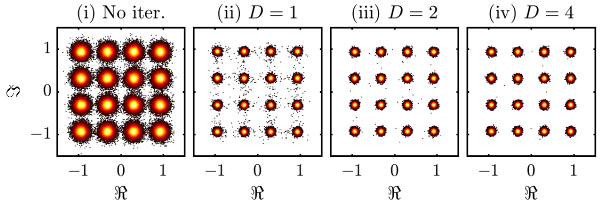

Fig. 4 Received constellation diagram of OCDM signal 16-QAM (at 50-km, OSNR = 43 dB) recovered by IB-DFE with 0, 1, 2, and 4 iterations.

nor improvement since there is almost no fading in the B2B case, as shown in Fig. 3. After 50-km transmission, severe fading occurs at 8.6 GHz. As the signal bandwidth approaches the frequency notch, the system is significantly degraded. It can be seen that if there is no FEC nor IB-DFE, the OCDM system has an error floor at BER = 1×10^{-4} and the OFDM system has a higher error floor at BER = 6×10^{-3}.

In this case, as BER of the OCDM is well below the FEC limit of the KP4 code, the coded OCDM can reach a post-FEC BER at 10^{-9} at an OSNR = 43.5 dB. The BIC contributes a steeper BER curve compared to the coded OCDM without BIC. In contrast, no coding gain can be observed in the BIC-OFDM system, as the BER is above the FEC limit of KP4 code. If the nonlinear equalizer, IB-DFE, is applied, the performance of OCDM is further improved. For example, 7 dB less OSNR is required compared to the case without IB-DFE at a BER = 2×10^{-4}. If the FEC is applied, the BIC-OCDM with IB-DFE achieves about 5 dB more coding gain at a BER = 1×10^{-9} than the BIC-OCDM without IB-DFE. In addition, the BIC can improve the performance, resulting in a steeper BER curve. The effect of nonlinear IB-DFE can be explained in Fig. 4, in which the signal becomes more and more clustered with up to 4 iterations. This is because the IB-DFE can compensate the fading effect, as shown in Fig. 3 (b), and the corrupted information can be still recovered for FEC decoding.

5. Conclusion

In this work, we for the first time propose a BIC-OCDM system with a nonlinear IB-DFE, and experimentally demonstrate a KP-4 coded OCDM signal at 31 Gbit/s over 50 km S-SMF. The experimental results confirm that the nonlinear IB-DFE can effectively compensate the CD-induced power fading and recover the information in the frequency notches. As a result, the coding gain of the BIC-OCDM with IB-DFE is improved by 5 dB compared to that without IB-DFE at a post-FEC BER = 1×10^{-9}. The proposed system does not require a feedback link, and is computational efficient, it can be easily adapted in medium-reach applications based on IM/DD, such as inter-datacenter connection and potentially PON.

Acknowledgement

This work is supported by Science Foundation Ireland (SFI) under the grants 12/IA/1270 and 12/RC/2276.

References

[1] P. J. Winzer and D. T. Neilson, *J. Lightw. Technol.* **35**(5), 1099 (2017).
[2] X. Ouyang and J. Zhao, *J. Lightw. Technol.* **34**(18), 4376 (2016).
[3] X. Ouyang, O. A. Dobre, Y. L. Guan, and J. Zhao, *IEEE Signal. Process. Lett.* **24**(10), 1488 (2017).
[4] A. J. Lowery and L. B. Du, *Opt. Fiber Technol.* **17**(5), 421 (2011).
[5] X. Ouyang, G. Talli, M. Power, and P. Townsend, in *Proc. ECOC 2018*, Sept. 2018, Rome, Italy, p. Mo4F.3.
[6] X. Ouyang, C. Antony, J. Zhao, G. Talli, and P. D. Townsend, in *Proc. CLEO 2018*, May 2018, San Jose, US, p. SM2C.2.
[7] X. Ouyang, G. Talli, and P. D. Townsend, in *Proc. CLEO*, 2019, San Jose, US, SM3G.5.
[8] R. Urata, H. Liu, X. Zhou, and A. Vahdat, in *Proc. OFC 2017*, Mar. 2017, Los Angeles, US, p. W3G.1.
[9] V. Houtsma, D. van Veen, and E. Harstead, *J. Lightw. Technol.* **35**(6), 1228 (2017).
[10] I. B. Djordjevic, M. Arabaci, and L. L. Minkov, *J. Lightw. Technol.* **27**(16), 3518 (2009).
[11] X. Ouyang and J. Zhao, *IEEE Trans. Commun.* **64**(9), 3946 (2016).
[12] M. Yang, L. Li, X. Liu, and I. B. Djordjevic, in *Proc. OFC 2019*, Mar. 2019, San Diego, US, p. W3H.2.