

Coded-subcarrier-aided chromatic dispersion monitoring scheme for flexible optical OFDM networks

Kam-Hon Tse and Chun-Kit Chan*

Department of Information Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
*ckchan@ie.cuhk.edu.hk

Abstract: A simple coded-subcarrier aided scheme is proposed to perform chromatic dispersion monitoring in flexible optical OFDM networks. A pair of coded label subcarriers is added to both edges of the optical OFDM signal spectrum at the edge transmitter node. Upon reception at any intermediate or the receiver node, chromatic dispersion estimation is performed, via simple direct detection, followed by electronic correlation procedures with the designated code sequences. The feasibility and the performance of the proposed scheme have been experimentally characterized. It provides a cost-effective monitoring solution for the optical OFDM signals across intermediate nodes in flexible OFDM networks.

©2014 Optical Society of America

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation.

References and links

1. M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies," *IEEE Commun. Mag.* **47**(11), 66–73 (2009).
2. W. Shieh, "OFDM for flexible high-speed optical networks," *J. Lightwave Technol.* **29**(10), 1560–1577 (2011).
3. W. Shieh, R. S. Tucker, W. Chen, X. Yi, and G. Pendock, "Optical performance monitoring in coherent optical OFDM systems," *Opt. Express* **15**(2), 350–356 (2007).
4. M. Mayrock and H. Haunstein, "Performance monitoring in optical OFDM systems," in *Optical Fiber Communication Conference*, San Diego, CA USA (2009), Paper OWM3.
5. X. R. Cai, D. J. Geisler, R. Proietti, Y. Yin, R. P. Scott, and S. J. B. Yoo, "Spread-spectrum chromatic dispersion monitoring technique for flexible bandwidth channels," in *Conference on Lasers and Electro-Optics*, San Jose, CA (2012), Paper CF2I.1.
6. S. Shimizu, G. Cincotti, and N. Wada, "Chromatic dispersion monitoring and adaptive compensation in an 8 x 12.5 Gb/s all-optical OFDM system," in *European Conference on Optical Communications*, London, UK (2013), Paper P.3.2.
7. C. K. Chan, "Chromatic dispersion monitoring of optical OFDM signals in flexible optical networks," in *Proc. Asia Communications and Photonics Conference & International Conference on Information Photonics and Optical Communications (ACP/IPOC)*, Beijing, PRC (2013), Paper AF1H.2.
8. W. Shieh, H. Bao, and Y. Tang, "Coherent optical OFDM: theory and design," *Opt. Express* **16**(2), 841–859 (2008).
9. J. Armstrong, "OFDM for optical communications," *J. Lightwave Technol.* **27**(3), 189–204 (2009).

1. Introduction

In future flexible optical networks, flexible transceivers and bandwidth flexible optical cross-connects will be equipped to provision data traffic on flexible grid, so as to achieve high bandwidth flexibility and high spectral efficiency [1]. To date, optical orthogonal frequency division multiplexing (OFDM) format [2] is one of the feasible and promising signal formats to support such flexible optical networks. It has shown superior tolerance to transmission impairments [2], as well as its signal bandwidth can be adjusted by accommodating different number of optical subcarriers to cope with different traffic needs. To assure the quality of the service provisioning, optical performance monitoring (OPM) is an indispensable element in network management. The signal quality and the working status of various network elements can be continuously monitored so as to facilitate the network control and assure good signal

quality in data delivery. Moreover, when the lightpaths are dynamically reconfigured according to different demand requests, the accumulated chromatic dispersion (CD) on each lightpath would vary and have to be carefully monitored at intermediate nodes and the receiving node, so as to facilitate impairment-aware routing, as well as impairment compensation.

Recently, there have been some interesting schemes proposed for optical performance monitoring of optical OFDM signals. In [3, 4], sophisticated coherent receiver was needed for channel estimation. The accumulated signal impairments were estimated, via statistical sampling at the destination node of the lightpath. In [5], a low-index intensity modulation was applied over the signal bandwidth, and two separate portions of the signal spectrum were optically filtered to measure the relative delay difference of the two detected low-speed over-modulation signals. In [6], a pilot symbol was added to each of the both ends of the all-optical OFDM signal spectrum and the relative delay of these two pilot symbols was estimated by optical gating, via an optical electro-absorption modulator. In [7], we have recently proposed a novel scheme to monitor the accumulated chromatic dispersion of optical OFDM signals at the intermediate/receiving nodes by employing a pair of coded optical label subcarriers, without the need of expensive coherent receiver. At the signal transmitter, a pair of coded optical label subcarriers, each carries a unique code sequence, are inserted into the leading and the trailing edges of the signal spectra of the optical OFDM signal. At each intermediate node or the receiver node, part of the signal power is tapped off and directly detected, via a photo-detector. By performing electronic signal correlation to the detected signal with those two designated code sequences, two correlation peaks will be obtained. The relative temporal delay between these two correlation peaks can be used to deduce the group delay information of the optical OFDM, thus CD monitoring is achieved. The retrieved CD information is useful to monitor the signal quality as well as to facilitate the impairment-aware routing of the signals. The work in [7] presented the preliminary numerical simulation study of the proposed scheme. In this paper, we have performed further experimental demonstration and characterization to show the feasibility of the proposed CD monitoring scheme.

The rest of the paper is organized as follows. Section 2 illustrates the principle of proposed CD monitoring scheme by means of inserting a pair of coded optical label subcarriers to the optical OFDM signal. Section 3 presents the experimental demonstration and characterization of the proposed CD monitoring scheme. Finally, section 4 summarizes the paper.

2. Chromatic dispersion monitoring of optical OFDM signals

Optical OFDM systems can be classified into coherent optical OFDM (CO-OFDM) [8] and direct-detection OFDM (DD-OFDM) [9]. CO-OFDM provides better receiver sensitivity, high spectral efficiency and tolerance to polarization mode dispersion, compared with DD-OFDM, at the expense of complex structure of the transmitters and receivers. In this paper, we propose a CD monitoring scheme, using simple direct detection of the coded optical subcarriers, for CO-OFDM systems at the intermediate nodes. Figure 1 shows the structure of the proposed transmitter. It follows the conventional coherent OFDM transmitter's structure, but a pair of designated codes, c_1 and c_2 , are inserted during the inverse-Fast-Fourier-Transform (IFFT) stage, as the label signals. Thus, two more coded optical label subcarriers are generated. Each of them is located at either edge of the signal spectrum, and carries the respective designated code, as shown in Fig. 1.

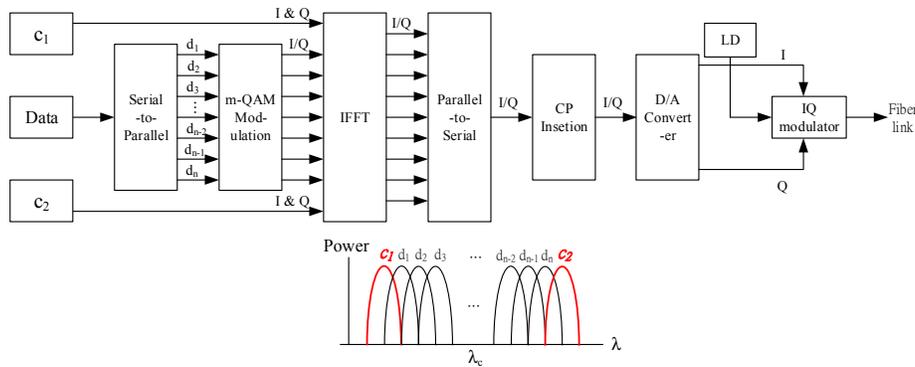


Fig. 1. The block diagram of the proposed CO-OFDM transmitter. The output spectrum of the generated optical OFDM signal, two inserted optical coded label subcarriers, c_1 and c_2 (in red), is also shown. (I&Q: inphase and quadrature phase components, IFFT: inverse fast Fourier transform, m-QAM: multilevel quadrature amplitude modulation, CP: cyclic prefix, D/A digital-to-analog, LD: laser diode)

The two distinct designated codes, c_1 and c_2 , for each optical OFDM signal are generated according to the following procedure. First, a 2^k -length orthogonal Gold sequence c_1 is generated. Each bit of c_1 is then encoded into a p -bit sequence in such a way that a bit 1 is encoded with “101010...” pattern while a bit 0 is encoded with “010101...” pattern, thus C_1 is formed. Such alternating polarity nature of the bits provides stronger orthogonality of the codes. Each bit in the sequence C_1 is set to have a time period of m times of the bit period of the optical OFDM payload symbol. In the duration of the whole length of OFDM data stream with n symbols, one cycle of orthogonal Gold code sequence is transmitted for the label. Assume the bit period of the optical OFDM payload symbol has a duration of T_s seconds, each bit in C_1 thus has a duration of mT_s seconds, and each chip of the code sequence c_1 has a duration of mpT_s . The label rate is m times slower than the payload rate. Figure 2 illustrates an example of the code generation procedure with $k = 7$, $p = 4$ and $m = 4$. The encoding of the payload is also shown for comparison.

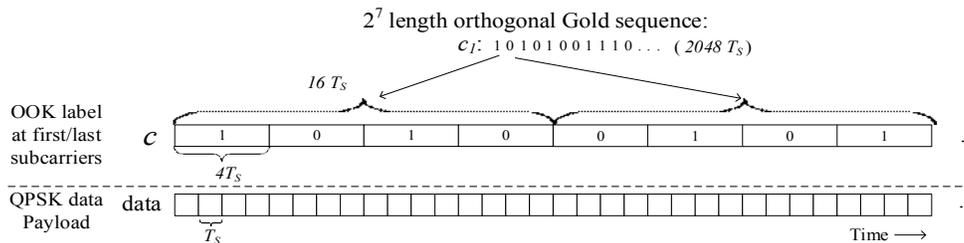


Fig. 2. A CDMA label code generation and expansion example with $k = 7$, $p = 4$ and $m = 4$. T_s is the bit period of the optical OFDM payload.

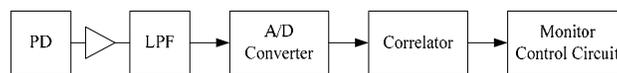


Fig. 3. The structure of the monitoring unit. (PD: photo-detector, LPF: electrical low pass filter).

Each intermediate node is incorporated with a monitoring unit, as shown in Fig. 3. A photo-detector, followed by an electrical low-pass filter, is used to detect the composite signals, comprising the incoming wavelength channel, through direct detection. As the designated labels are at relatively much lower data rates than the respective payload data, the low-pass frequency response of the photo-detector and the electrical filter will extract low-

pass signal components including the designated coded label spectra, as well as the residual low-frequency components of the signal payload. Such composite signal is further sampled, quantized and undergone the procedure of signal correlation so as to extract the individual designated coded label and suppress the unwanted residual payload data. The code sequences of the first and the last coded label subcarriers (denoted as c_1 and c_2) are different. By correlating with the code sequences c_1 and c_2 , individually, we obtain two sets of correlation results, one for each code sequence. As the first and the last coded subcarriers suffer from different amount of walk-off, due to the fiber chromatic dispersion, the code sequences, modulated on those two edge label subcarriers, will experience different amount of temporal spread, accordingly. Such phenomena will lead to larger difference between the temporal positions of the two obtained correlation peaks, when the optical OFDM signal is suffered from a higher value of accumulated chromatic dispersion. Hence, by examining the temporal positions of the correlation peaks of the two edge optical label subcarriers, the accumulated chromatic dispersion value as well as the dispersion sign of the optical OFDM signal can be derived and monitored.

3. Experimental demonstration and characterization

We have experimentally demonstrated the proposed CD monitoring scheme for optical OFDM signals to prove the concept. The optical OFDM system was generated with 40 quadrature phase-shift keying (QPSK) payload subcarriers. On each subcarrier, 2048 symbols were transmitted. The baud rate of each subcarrier was 93.75 MHz, thus gave a payload data rate of 7.5 Gbps. 10% of symbol time of the cyclic prefix was inserted into the optical OFDM signal. The code generation procedure, as illustrated in Fig. 2, was employed in the experiment with $k = 7$, $p = 4$ and $m = 4$. The code sequences were first generated into 2^7 -length orthogonal Gold code sequence. Each bit in the sequence was then encoded into “1010” for bit 1 or “0101” for bit 0. Finally, the generated code sequence was then equally amplitude modulated onto the I and Q components of the subcarriers at a symbol rate which is one quarter of that of payload subcarriers. As a result, a time frame of 2048 payload symbols was used to transmit one period of the code sequence without any repetition.

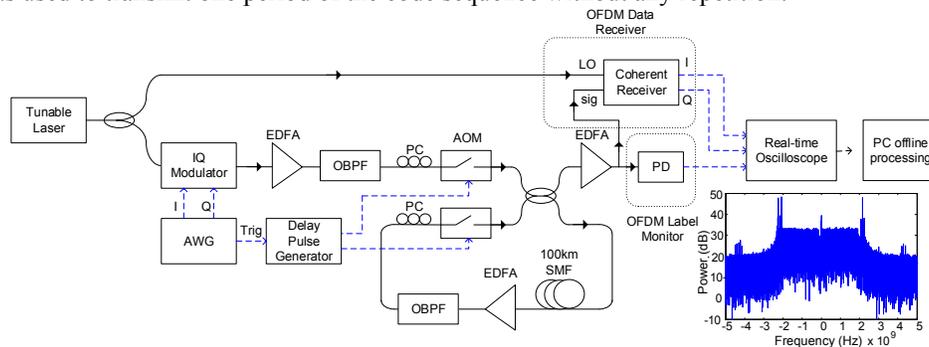


Fig. 4. Experimental Setup (OBPF: optical band pass filter, AOM: acoustic optical modulator, PD: Photo detector, PC: polarization controller). Inset shows the electrical spectra of the generated OFDM signal.

Figure 4 shows the experimental setup. The I and Q components of the OFDM signal were generated by an arbitrary waveform generator. The electrical OFDM signals were then modulated onto an optical carrier at 1547 nm by using an optical IQ modulator. After optical amplification and out-of-band optical noise filtering, the optical OFDM signal was then fed to the optical re-circulating loop gated by a pair of acousto-optical modulators, to simulate long distance fiber transmission. Inside the optical re-circulating loop, there was a spool of 100-km standard single mode fiber (SSMF), an Erbium-doped fiber amplifier (EDFA) and an optical filter. At the output of the optical re-circulating loop, the optical OFDM signal was detected with a single photo-detector for the optical OFDM label subcarrier detection and a coherent optical receiver for reception of the OFDM data payload. The output from the

tunable laser acted as the local oscillator signal of the optical coherent receiver. The electrical signals were captured by a real-time oscilloscope and were uploaded into a computer for offline processing. The inset of Fig. 4 shows the measured electrical amplitude spectra of the generated OFDM signal with coded label subcarriers at the two edges of the signal spectra, and its spectral width was measured to be about 0.035 nm.

Figures 5 (a) and (b) show the measured correlation results of the optical OFDM signal with a matched code and an unmatched code, respectively. Their peaks had the amplitudes of 1.82×10^5 and 4.90×10^4 , respectively. Thus, the correlation peak ratio of the coded label was 3.7. In addition, with the matched code sequence, the correlation peak was located in the middle of the correlation trace with nearly zero correlation time offset. Figure 5(c) illustrates temporal differences between the correlation peaks of the two coded labels, after transmission of 800 km (top), and 1600 km (bottom). Such temporal differences will be translated into their respective accumulated chromatic dispersion values.

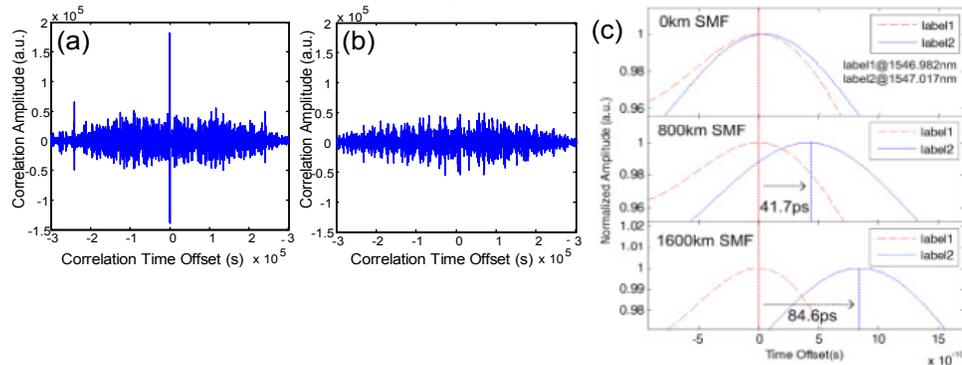


Fig. 5. Measured correlation results with (a) matched code sequence, (b) unmatched code sequence, and (c) temporal differences between the correlation peaks of the two coded labels, after 800-km and 1600-km transmissions.

Figure 6(a) shows the experimental measurement of the accumulated chromatic dispersion when the optical OFDM signal at 1547 nm passed through the fiber re-circulating loop ranged from 0 km to 1800 km. The SSMF had a dispersion specification of ~ 16.3 ps/nm/km, at signal wavelength of 1550 nm (that is, ~ 16 ps/nm/km at 1547 nm), and zero dispersion wavelength of 1312 nm. Each accumulated chromatic dispersion values was calculated by computing the measured temporal difference of the correlation peaks between the two coded optical label subcarriers and divided it by the spectral width of the optical OFDM signal (i.e. 0.035 nm in the experiment). When the fiber transmission distance increased, the obtained accumulated chromatic dispersion values increases linearly with positive slope value of about 15.8 ps/nm/km, which agreed well with dispersion specification of the SSMF. In order to show the proposed CD monitoring scheme was capable of measuring the dispersion sign, in addition to absolute value of the accumulated chromatic dispersion, the single mode fiber was replaced by a span of dispersion compensation fiber (DCF) with a dispersion specification of -810 ps/nm at 1545 nm, in the re-circulating loop. Similar measurements were repeated and the results were depicted in Fig. 6(b). The measured averaged dispersion value was about -824 ps/nm per loop at 1547 nm, which also agreed well with the dispersion specification of the DCF. It was shown that the obtained accumulated dispersion values exhibited a negative slope when the fiber transmission distance increased. Therefore, the proposed scheme was shown to monitor both the chromatic dispersion values and the dispersion sign, at the same time.

On the other hand, when the optical OFDM signal was transmitted along the fiber span with in-line EDFAs for optical amplification, the OSNR of the OFDM signal would degrade gradually. Figure 7(a) shows the correlation peak ratios of the two coded label subcarriers when the OSNR of the optical OFDM signal before the label detector was varied between 6 to 24 dB. The results showed that the label detection was quite insensitive to the OSNR values

within this OSNR range, as the integrated noise at the photodiode was largely alleviated by dc filtering before the code correlation procedures. Finally, the impact of the insertion of two coded label subcarriers on the performance of the optical OFDM signal was investigated, and the respective error-vector magnitude (EVM) performances over different OSNR values were measured under the cases of back-to-back as well as after 200-km transmission. At the same EVM level, only about 0.8-dB OSNR penalty in the optical OFDM signal was observed after the insertion of the coded label subcarriers.

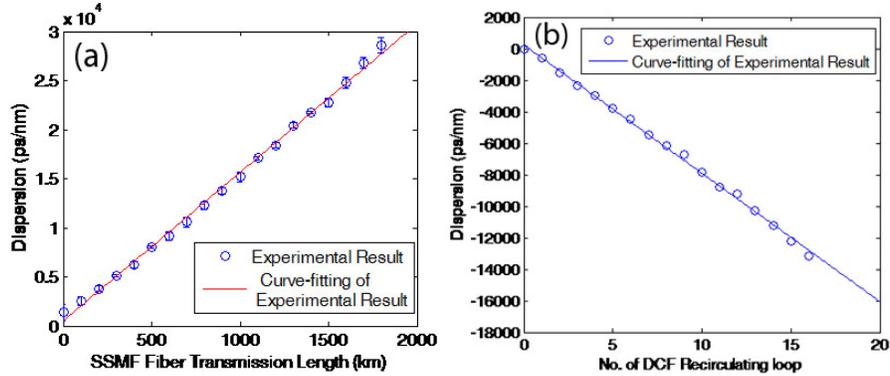


Fig. 6. Accumulated chromatic dispersion of the optical OFDM signal, (a) with different lengths of SSMF fiber transmission (with error bars), (b) with different number of recirculating loop containing DCF inside each loop.

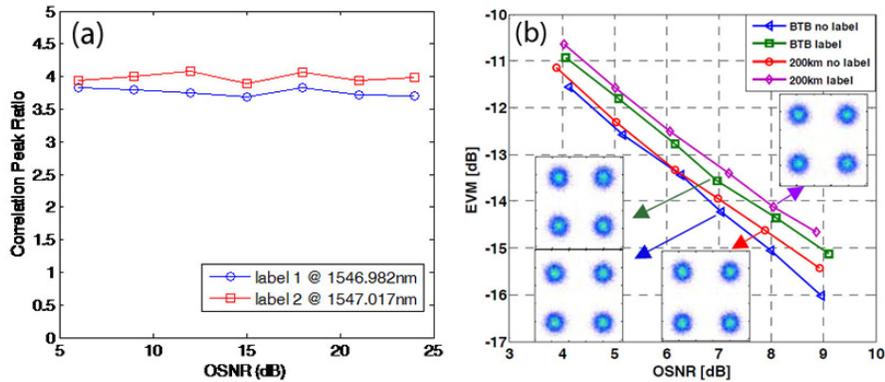


Fig. 7. (a) Measured correlation peaks ratios of the two coded label subcarriers at different values of OSNR. (b) Measured BER performance of the optical OFDM signal measured under different OSNR values, with and without the insertion of the two coded label subcarriers, for back to back and after 200-km transmission. Insets show the signal constellation diagrams.

4. Summary

We have proposed to employ to a pair of coded label subcarriers to realize chromatic dispersion monitoring in flexible optical OFDM networks. The signal monitoring is performed, via simple direct detection, followed by electronic correlation procedures with the designated code sequences. The accumulated chromatic dispersion, as well as the dispersion sign, of the signal can be monitored by measuring the relative temporal difference of the two correlation peaks. The proposed scheme provides a cost-effective monitoring solution for the optical OFDM signals across intermediate nodes in flexible OFDM networks.

Acknowledgments

This work was partially supported by a research grant from Hong Kong Research Grants Council (General Research Fund: CUHK410512).