Recent progress on coherent optical OFDM

Qi Yang*[a], Zhixue He[a], Ming Luo[a], Xiaoying Zhang[a], Zhu Yang[a], Shaohua Yu[a], Shanhong You[b], Gangxiang Shen[b], Xingwen Yi[c], and William Shieh[d]

[a]State Key Lab. of Optical Comm. Tech. and Networks, Wuhan, Hubei 430074, China;
[b]School of Electronic and Information Engineering, Soochow University, Suzhou 215006, China;
[c]School of Comm. and Info. Engin., Univ. of Elec. Sci. and Tech. of China, Chengdu, 611731, China;
[d]Centre for Ultra-Broadband Information Networks, University of Melbourne, VIC 3010, Australia

ABSTRACT

Coherent optical OFDM (CO-OFDM) has recently received much attention as a candidate for long haul transmissions. In this paper, we review historical progress on CO-OFDM. Following that, we show some recent experimental demonstrations on both transmission and networks.

Keywords: coherent detection, OFDM

1. INTRODUCTION

We have witnessed a dramatic increase of interest in orthogonal frequency-division multiplexing (OFDM) from optical communication community in recent years. The number of publications on optical OFDM has grown dramatically since it was proposed as an attractive modulation format for long-haul transmission either in coherent detection [1] or direct-detection [2, 3]. Over the last few years, net transmission data rates grew at a factor of 10 per year at the experimental level. To date, experimental demonstration of up to 10 Tb/s transmission in a single channel [4] whereas demonstration of real-time optical OFDM with digital signal processing has surpassed 40 Gb/s [5]. These progresses may eventually lead to realization of commercial transmission products based on optical OFDM in the future, with the potential benefits of high spectral efficiency and flexible network design. In this paper, we first review the historical development of CO-OFDM. Then we show some of our recent demonstrations on several issues, such as nonlinearity improvement, sensitivity improvement, and applications on next generation networks.

2. HISTORICAL PERSPECTIVE OF OFDM

OFDM plays a significant role in the modem telecommunications for both wireless and wired communications. The history of frequency division multiplexing (FDM) began in 1870s when the telegraph was used to carry information through multiple channels [6]. The fundamental principle of orthogonal frequency division multiplexing was proposed by Chang [7] as a way to overlap multiple channel spectra within limited bandwidth without interference, considering the effects of both filter and channel characteristic. Since then, many researchers have investigated and refined the technique over the years and it has been successfully adopted in many standards.

Although OFDM has been studied in RF domain for over four decades, the research of OFDM in optical communication began only in the late 1990s [8]. The fundamental advantages of OFDM in an optical channel were first disclosed in [9]. In the late 2000s, long-haul transmission by optical OFDM has been investigated by a few groups. Two major research directions appeared, direct-detection optical OFDM (DDO-OFDM) [10,11] looking into a simple realization based on low-cost optical components and coherent optical OFDM (CO-OFDM) [12] aiming to achieve high spectral efficiency and receiver sensitivity. Since then, the interest in optical OFDM increases dramatically. In 2007, the world's first coherent optical OFDM experiment with line rate of 8 Gb/s was reported [13]. In the last few years, the transmission capacity continued to grow about 10 times per year. In 2009, up to 10 Tb/s optical OFDM was successfully experimentally demonstrated [4]. Table 1 shows the development of optical OFDM in the last two decades.

Photonics and Optoelectronics Meetings (POEM) 2011: Optical Communication Systems and Networking, edited by Zisen Zhao, Richard Penty, Chester Shu, Tao Jiang, Proc. of SPIE Vol. 8331, 83310D · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.919993

Table 1 Progress of optical OFDM

year	Offline OFDM Time-line paper relevant information
1996	Pan and Green, OFDM for CATV[8]
2001	You and Kahn, OFDM in direct modulation (DD) systems[14]
2005	Jolley, et al., experiment of 10 Gb/s optical OFDM over multimode fiber (MMF)[15]
	Lowery and Armstrong, power efficient optical OFDM in DD systems[16]
2006	Lowery and Armstrong (Monash University) [2], and Djordjevic and Vasic (University of Arizona) [3], long-haul direct-detection optical OFDM (DDO-OFDM)
May/2006	Coherent Optical OFDM was firstly proposed [1]
Feb/2007	8 Gb/s CO-OFDM transmission was published [17]
Aug/2007	polarization-division-multiplexing (PDM)-OFDM concept was proposed [18]
Feb/2008	>100Gb/s PDM-OFDM transmission-over 1000km SSMF[19,20,21]
Mar/2009	Offline Processing per single channel >1Tbit/s [22,23,24]
Mar/2011	Offline Processing per single channel has achieved >10Tb/s [4]

3. RECENT EXPERIMENTAL DEMONSTRATIONS ON SUPERCHANNEL CO-OFDM

3.1 WDM Transmission of terabit CO-OFDM superchannels

The WDM transmission of Tb/s CO-OFDM superchannel is first reported in [25], in which a 1.4Tb/s per superchannel in C/L band is first established using OBM technique. Then 24 channels are employed to carry 24Tb/s PDM-CO-OFDM signal. After 2400km EDFA-only link, the detected BER is under the 3rd generation FEC threshold of 2×10^{-2}. The achieved spectrum efficiency (SE) is 2.92bit/s/Hz. In a similar fashion, we doubled the transmission SE in C band using 16-QAM instead of QPSK in [25]. 16 lasers are used to carry 30.7Tb/s (22Tb/s after FEC) PDM-CO-OFDM signal. The experimental setup is shown in Fig.1(a). The left inserted figures (b) are the spectrum of generated optical carrier sources for superchannels. (c) is the transmitted spectrum after 80km standard single mode fiber (SSMF). After transmission, the BER for all the tested subcarriers are under 2×10^{-2}.Since the modulation format is 16-QAM, the SE within each band is as high as 5.75 bit/s/Hz.

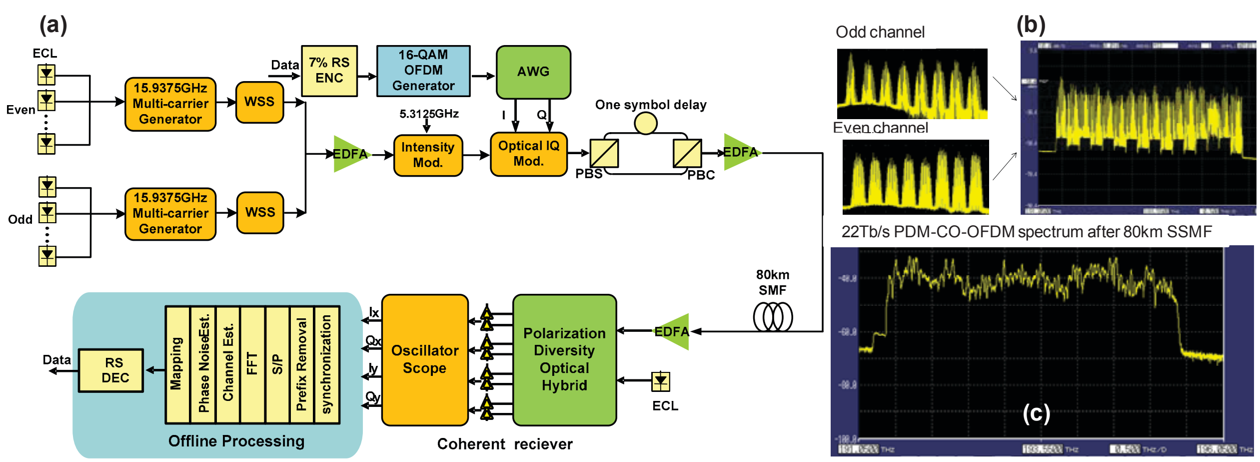

Fig.1(a) System Configuration for Superchannel WDM transmission of 22Tb/s CO-OFDM over 80 km fiber; (b) is the optical carrier source in odd/even and combined channel; (c) transmitted spectrum after 80km SSMF.

3.2 Nonlinearity mitigation for CO-OFDM

Besides the digital-to-analog converter requirement, one the main drawback of optical OFDM is low nonlinear tolerance caused by large peak-to-average power ratio (PAPR). [26] first employ the wireless widely used technique, so called discrete Fourier transform spread (DFT-S) OFDM, into optical research, which effectively much reduce the PAPR for CO-OFDM signal. Based on that concept, we demonstrated a 1.45Tb/s superchannel transmission over 480km fiber link

[27]. The system configuration is shown in Fig.2(a). Fig.2(b) shows the BER as a function of OSNR curve at back-to-back. Transmission results after 480 km fiber link is shown in Fig.2(c).

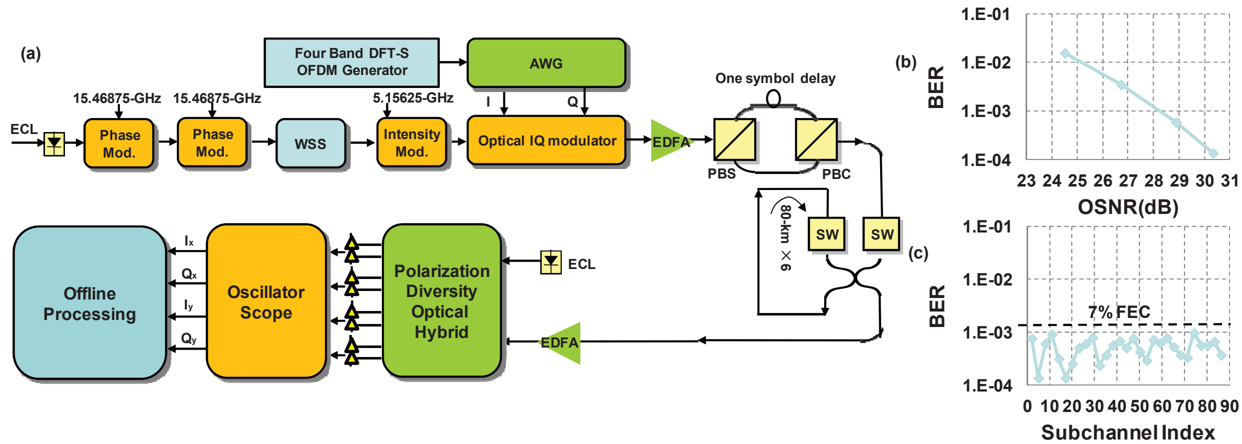

Fig.2(a) The system configuration for 1.45Tb/s DFT-S OFDM transmission; (b) the BER as a function of OSNR curve at back-to-back; (c) BER results after 480 km fiber link.

3.3 Receiver sensitivity improvement using advanced coding

Traditional FEC requires additional bandwidth to accommodate the increased overhead, which will sacrifice the system SE. To maintain high transmission SE while achieve additional coding gain, expanding the modulated constellation instead of extending the signal bandwidth is often employed [28-32]. In the last a few years, TCM has been used for optical communication [28-30]. In [29] transmission of trellis-coded 32-QAM with rate 0.8 for subcarrier modulation is demonstrated in a 44 Gb/s polarization-division multiplexed (PDM) CO-OFDM signal over 990 km SSMF. However, using TCM to achieve good performance, it requires large number of convolution states, which introduces much high computational complexity. In a similar fashion, in [31,32] QPSK CO-OFDM transmission system performance was improved by 4 dB using both of higher order modulation (16-QAM) and another advanced coding, low-density parity-check (LDPC) at 0.5 coding rate, which is shown in fig.3.

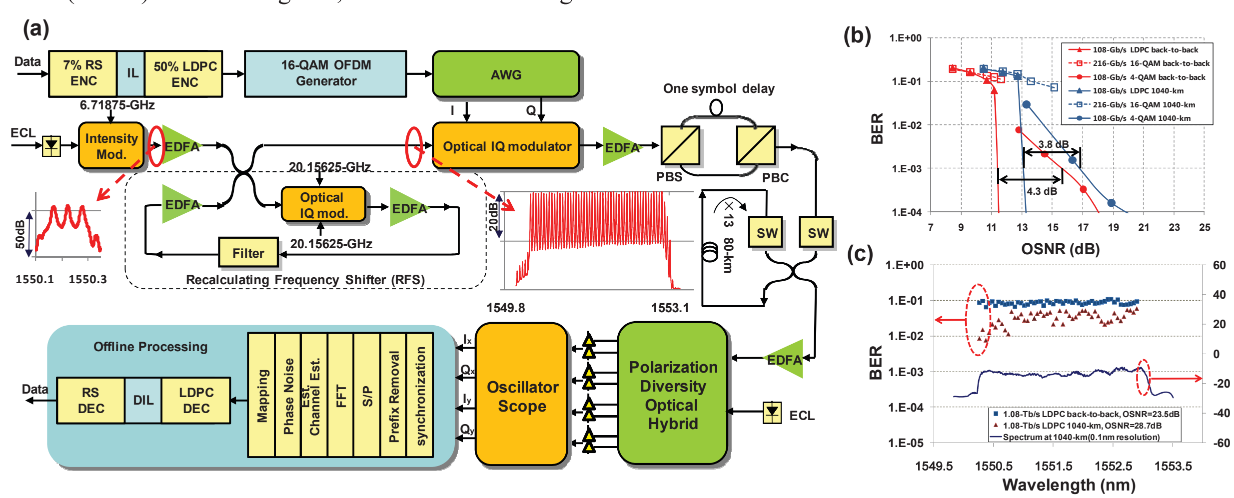

Fig.3 (a) The system configuration for 1Tb/s LDPC-coded OFDM transmission; (b) the BER as a function of OSNR curve for 100Gb/s CO-OFDM system; (c) BER results at back-to-back and after 1000km transmission.

3.4 CO-OFDM Optical Network with Heterogeneous ROADM Nodes

In this study, we experimentally demonstrate the concept of coherent-detection-based OFDM (CO-OFDM) optical transport network. We verify several important subsystems and conceptual operations, including (i) CO-OFDM optical channel switching, (ii) CO-OFDM optical channel bandwidth elasticity, and (iii) CO-OFDM optical channel wavelength tunability. The system setup and main results are shown in fig.4 and 5.

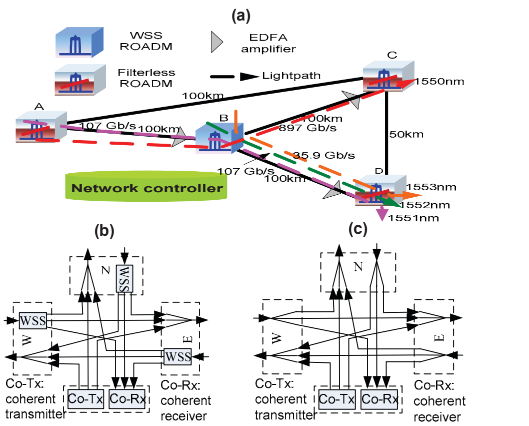

Fig.4(a) CO-OFDM-based optical transport network configuration, (b) WSS ROADM node; (c) Filterless ROADM node.

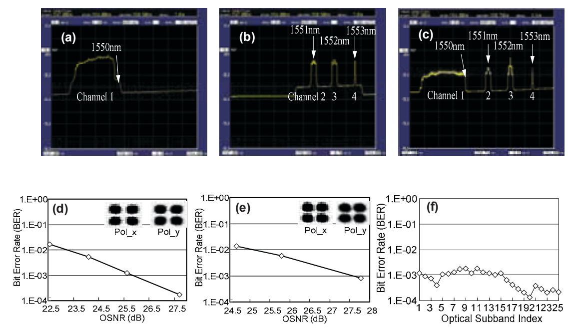

Fig.5 Channel spectra (a) at node C before switching; (b) at node D before switching; (c) at node D after switching; (d) Bit error rate versus OSNR of the 897-Gb/s channel (before switching); (e) Bit error rates of optical subbands of the 897-Gb/s channel (after switching); (f) Bit error rates of optical subbands of the 897-Gb/s channel (before switching).

4. CONCLUSION

The historical progress of CO-OFDM has been reviewed in this paper. We have shown several experimental demonstrations of superchannels CO-OFDM in both transmission and networks. With the high demands for internet traffic, CO-OFDM may potentially become an attractive choice of modulation format for future.

REFERENCES

[1] W. Shieh and C. Athaudage, “Coherent optical orthogonal frequency division multiplexing,” Electron. Lett., vol. **42**, pp. 587-589, 2006

[2] A. J. Lowery, L. Du, and J. Armstrong, “Orthogonal frequency division multiplexing for adaptive dispersion compensation in long haul WDM systems,” in OFC’2006, paper PDP 39, 2006.

[3] I. B. Djordjevic and B. Vasic, “Orthogonal frequency division multiplexing for high-speed optical transmission,” Opt. Express, vol. **14**, pp. 3767–3775, 2006.

[4] J. Yu, Z. Dong, N. Chi, “Transmission and Coherent Detection of 11.2 Tb/s (112x100Gb/s) Single Source Optical OFDM Superchannel” in OFC’2011, paper PDPA6

[5] D. Qian, T. T. Kwok, N. Cvijetic, J. Hu, and T. Wang, "41.25 Gb/s Real-Time OFDM Receiver for Variable Rate WDM-OFDMA-PON Transmission," in OFC’ 2010, paper PDPD9.

[6] U.S. patent 174,465, “Improvement in Telegraphy,” Alexander Graham Bell, Mar. 7, 1876.

[7] R. W. Chang, “Synthesis of band-limited orthogonal signals for multichannel data transmission,” Bell Sys. Tech. J., vol. **45**, pp. 1775-1796, 1966.

[8] Q. Pan and R. J. Green, “Bit-error-rate performance of lightwave hybrid AM/OFDM systems with comparison with AM/QAM systems in the presence of clipping impulse noise,” IEEE Photon. Technol. Lett., vol. **8**, pp. 278–280, 1996.

[9] B. J. Dixon, R. D. Pollard, and S. Iezekiel, “Orthogonal frequency-division multiplexing in wireless communication systems with multimode fiber feeds,” IEEE Trans. Microwave Theory Tech. **49**, 1404-1409 (2001).

[10] A.J. Lowery, L. Du, and J. Armstrong, “Orthogonal frequency division multiplexing for adaptive dispersion compensation in long haul WDM systems,” in Proc. Opt. Fiber Commun. Conf. 2006, Anaheim, paper PDP39
[11] I. B. Djordjevic and B. Vasic, “Orthogonal frequency-division multiplexing for high-speed optical transmission,” Opt. Express, vol. **14**, pp.3767–3775, May 1, 2006.
[12] W. Shieh and C. Athaudage, “Coherent optical orthogonal frequency division multiplexing” Electronic Letters, vol. 42, pp. 587-589, May 11, 2006.
[13] W. Shieh, X. Yi and Y. Tang, “Transmission experiment of multi-gigabit coherent optical OFDM systems over 1000km SSMF fibre,” IEE Electron. Lett., vol. **43**, pp. 183-185, Feb., 2007.
[14] R. You, J. M. Kahn, “Average power reduction techniques for multiple-subcarrier intensity-modulated optical signals”, IEEE Transaction on Communications, vol. **49**, pp. 2164-2171, 2001.
[15] N. E. Jolley, H. Kee, R. Rickard, J. Tang, "Generation and propagation of a 1550 nm 10 Gbit/s optical orthogonal frequency division multiplexed signal over 1000 m of multimode fibre using a directly modulated DFB," OFC AnaheimCA (2005) Paper OFP3.
[16] A. J. Lowery and J. Armstrong, “10 Gbit/s multimode fiber link using power-efficient orthogonal-frequency-division multiplexing,” Optics Expr., vol. **13**, pp. 10003–10009, 2005.
[17] W. Shieh, X. Yi and Y. Tang, “Transmission experiment of multi-gigabit coherent optical OFDM systems over 1000km SSMF fibre,” IEE Electron. Lett., vol. **43**, pp. 183-185, Feb., 2007.
[18] W. Shieh, X. Yi, Y. Ma, and Y. Tang, “Theoretical and experimental study on PMD-supported transmission using polarization diversity in coherent optical OFDM systems,” Opt. Express **15**, 9936-9947 (2007).
[19] W. Shieh, Q. Yang, and Y. Ma, “107 Gb/s coherent optical OFDM transmission over 1000-km SSMF fiber using orthogonal band multiplexing,” Opt. Express **16**, pp.6378-6386, 2008.
[20] S. L. Jansen, I. Morita, and H. Tanaka, "10x121.9-Gb/s PDM-OFDM Transmission with 2-b/s/Hz Spectral Efficiency over 1,000 km of SSMF," in OFC’2008, paper PDP2.
[21] E. Yamada, A. Sano, H. Masuda, E. Yamazaki, T. Kobayashi, E. Yoshida, K. Yonenaga, Y. Miyamoto, K.Ishihara, Y. Takatori, T. Yamada, and H.Yamazaki, “1Tb/s (111Gb/s/ch × 10ch) no-guard-interval COOFDM transmission over 2100 km DSF,” in OECC/ACOFT Conf. , paper PDP6 (2008).
[22] Y. Ma, Q. Yang, Y. Tang, S. Chen, and W. Shieh, "1-Tb/s single-channel coherent optical OFDM transmission over 600-km SSMF fiber with subwavelength bandwidth access," Opt. Express **17**, 9421-9427
[23] R. Dischler and F. Buchali, "Transmission of 1.2 Tb/s Continuous Waveband PDM-OFDM-FDM Signal with Spectral Efficiency of 3.3 bit/s/Hz over 400 km of SSMF," in OFC’2009, paper PDPC2.
[24] S. Chandrasekhar, X. Liu, B. Zhu, and D. W. Peckham, “Transmission of a 1.2-Tb/s 24-carrier no-guard-interval coherent OFDM superchannel over 7200-km of ultra-large-area fiber,”in ECOC’09, post-deadline paper PD2.6.
[25] Z. Dong, J. Yu, X. Xiao, H. Chien, S. Shi, Y. Xia, C. Ge; , "24Tb/s (24×1.3Tb/s) WDM transmission of terabit PDM-CO-OFDM superchannels over 2400km SMF-28," OptoeElectronics and Communications Conference (OECC), 2011 16th , vol., no., pp.756-757, 4-8 July 2011
[26] Y. Tang, W. Shieh, and B. S. Krongold, "Fiber Nonlinearity Mitigation in 428-Gb/s Multiband Coherent Optical OFDM Systems," in OFC’2010, paper JThA6.
[27] Z. He, M. Luo, Z. Yang, S. Yu, and Q. Yang, “Experimental demonstration of 1.45-Tb/s single channel Coherent Optical DFT-Spread OFDM Transmissions”, accepted in ACP’2011.
[28] H. Buelow, G. Thielecke, and F. Buchali, “Optical trellis coded modulation (oTCM),” in OFC’2004, paper WM5.
[29] X. Liu, Q. Yang, S. Chandrasekhar, and W. Shieh, "Transmission of 44-Gb/s Coherent Optical OFDM Signal with Trellis-Coded 32-QAM Subcarrier Modulation," in OFC’2010, paper OMR3.
[30] Q. Yang, Y. Ma, and W. Shieh, “1-Tb/s single-channel coherent optical OFDM transmission with trellis-coded modulation,” Electron. Lett. **45**, 1045-1047 (2009)
[31] Q. Yang, A. Al Amin, X. Chen, Y. Ma, S. Chen, and W. Shieh, "428-Gb/s single-channel coherent optical OFDM transmission over 960-km SSMF with constellation expansion and LDPC coding," Opt. Express **18**, 16883-16889 (2010)
[32] Q. Yang, W. Shieh, and I. B. Djordjevic, "1-Tb/s Large Girth LDPC-Coded Coherent Optical OFDM Transmission over 1040-km Standard Single-Mode Fiber," in OFC’2011, paper JThA035.