Long-haul Coherent Optical OFDM Point-to-Point Transmission using Optical Phase Conjugation

Thosaphon Jaemkarnjanaloha, Rachata Maneekut and Pasu Kaewplung
Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University, Pathumwan, Bangkok, Thailand

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Abstract: In this paper, we demonstrate the superchannel polarization division multiplexed coherent optical orthogonal frequency-division Multiplexing (PDM-CO-OFDM) system employing midway optical phase conjugation (OPC). The system is designed to show the optimum number of sub-carriers, amplifier spacing and the maximum achievement reach at data rate 1Tb/s (10x100 Gb/s). The system is simulated with 10-WDM superchannel at 50 GHz channel spacing. From the simulation results, PDM-CO-OFDM, with midway OPC and the optimum system parameters, we can achieve the maximum reachable distance of 24,000 km at BER $4x10^{-3}$.

1 INTRODUCTION

Long-haul optical fiber transmissions with data rates beyond Tb/s are next generation transmission systems to support consumer applications such as video-on-demand, cloud storage and social networking which demand huge data load (Chandrasekhar and Liu, 2012). The performance of the optical transmission system is limited by the waveform distortion induced from signal attenuation, the fiber dispersion and the nonlinear Kerr effect of optical fiber (Lowery et al., 2006). The signal attenuation due to the fiber loss is periodically compensated by using erbium-doped fiber amplifiers (EDFA's) as the optical amplifier gains. Moreover, we can mitigate the effect of the dispersion and the nonlinear waveform by using midway optical phase conjugation (OPC), since the enhancement of phase noise through the interaction between the fiber dispersion and nonlinear waveform can be sufficiently compensated by the OPC. Conventional digital signal processing (DSP) in coherent optical fiber communication scheme can compensate fiber dispersion. The OPC conjugates the signal phase after transmission in the first section of fiber link in order to achieve a net cancellation of the nonlinear waveform by using the nonlinearity generated in the second section of the fiber link (Le et al., 2015). We can also use the advance modulation formats to increase the bandwidth efficiency. One of the modulation methods that can yield the highest bandwidth efficiency in optical fiber transmission is the orthogonal frequency division multiplexing (OFDM). OFDM is a special form of multicarrier modulation where a single data stream is transmitted over a large number of lower rate orthogonal subcarriers (Shieh et al., 2008). Comparing single-carrier transmission with the coherent multiple-carriers transmission, coherent optical orthogonal frequency division multiplexing (CO-OFDM) has the advantage of a well-defined power spectrum that enables superchannel transmission achieving an ultra-high spectral efficiency (Wei-Ren et al., 2011). This modulation scheme provides the orthogonal relation among subcarrier channels with the sufficient tolerance to fiber dispersion comparing with the on-off keying (OOK) modulation format. In addition, CO-OFDM utilises available fiber bandwidth very efficiency since each subcarrier can be placed with channel spacing equivalent to the Nyquist frequency. These closely packed carriers that travel from the same origin to the same destination in a WDM system collectively form a superchannel. Thus, Polarization Division Multiplexed (PDM) CO-OFDM superchannel is an efficiency system for long-haul high-capacity optical transmission system.

In this paper, we propose the use of midway OPC to improve the performance of long-distance CO-

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OFDM transmission system by employing midway OPC at data rates of 10x100 Gb/s. Then, we analyse the system parameters. For example, we use computer simulation to analyse the number of subcarriers, the amplifier spacing that affects the transmission performance over c-band.

2 COHERENT OPTICAL OFDM TRANSMISSION SYSTEM EMPLOYING OPC

WDM systems classification based on the channel spacing or bandwidth allocation. Figure 1 shows the proposed high spectral efficiency systems using advanced modulation formats with coherent detection as CO-OFDM.

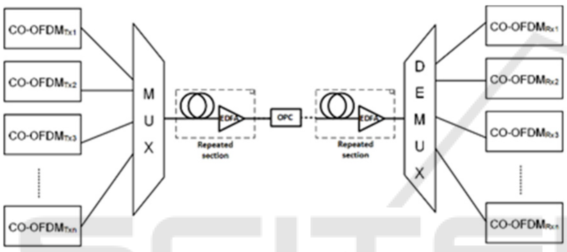

Figure 1: Configuration of Long-distance CO-OFDM transmission system employing midway OPC.

We simulate at 1-Tb (10x100-Gb/s PDM-CO-OFDM). The CO-OFDM condition for forming a superchannel can be shown as follow, each subcarrier must be placed with channel spacing equivalent to the Nyquist frequency to form a superchannel. For WDM superchannel systems detection, wavelength channels are first de-multiplexed before being received. The modulated carriers inside each superchannel are closely packed to be separated by WDM filters as coherent detection enables banded-detection of a superchannel.

Figure 2 shows the spectrum of wavelength-division-multiplexed (WDM) N-channels with CO-OFDM modulation in optical fiber transmission and Figure 3 shows the zoomed-in optical spectrum for each wavelength channel. We use the bandwidth of the first one WDM channel to set channel spacing of each wavelength channel (Shieh, 2011).

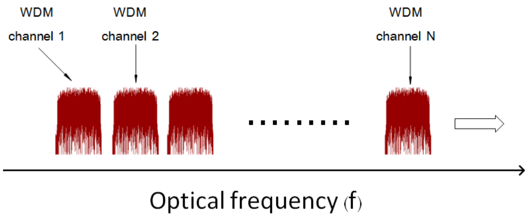

Figure 2: The optical spectrum for N wavelength-division-multiplexed CO-OFDM channels.

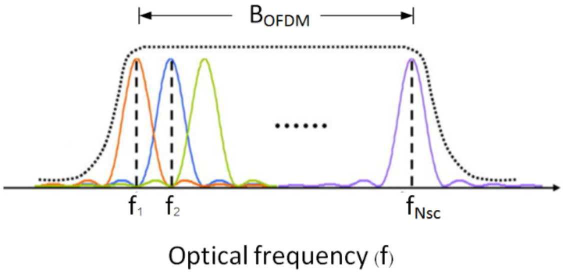

Figure 3: The zoomed-in optical spectrum for one WDM channel.

Midway optical phase conjugation was used to mitigate the nonlinear phase noise (Lorattanasane and Kikuchi, 1997). As shown in Figure 4, a long-distance transmission system employing midway optical phase conjugation (OPC) where the two repeated section fiber spans are sandwiched with OPC. OPC uses to compensate for fiber nonlinearity. By conjugating the signal in the first half of the system near the midway of the link, the fiber nonlinearity that generated in the second half of the system mitigate the fiber nonlinearity generated in the first half. It shows that by using midway optical phase conjugation, the self-phase modulation (SPM) is totally removed and phase noise can be significantly reduced (Watanabe and Shirasaki, 1996); (Jansen et al., 2005).

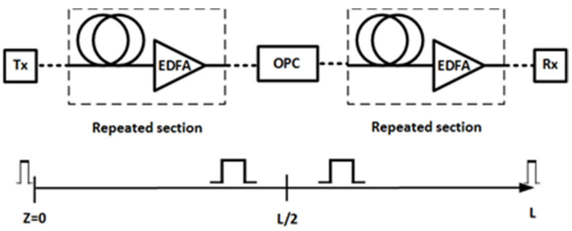

Figure 4: Long-distance transmission system employing midway optical phase conjugation (OPC).

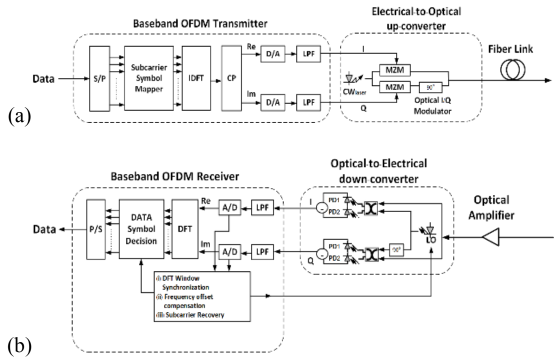

Figure 5: Conceptual diagram for complete CO-OFDM system (a) T_x , and (b) R_x .
S/P: serial-to-parallel; (I)DFT: (inverse) discrete Fourier transform; CP: cyclic prefix; D/A: digital-to-analog; LPF: lowpass filter; MZM: Mach-Zehnder modulator; A/D: analog-to-digital; PD: photodiode; LD: laser diode.

A conceptual diagram of an OFDM transmitter is shown in Figure 5. The function of the OFDM transmitter is mapping the data bits into each OFDM symbol by subcarriers symbol mapper. Next, generate the time series by inverse discrete Fourier transform (IDFT) that used in OFDM modulation. It can be represented like a digital filter that naturally produces a well-confined square-like signal spectrum. Afterwards including cyclic prefix then converted back to serial signal at digital to analog conversion (D/A). Next, upconvert to an appropriate RF frequency to be fed into an optical upconverter. The function of the optical upconverter is to linearly shift the OFDM spectrum from the RF domain to the optical domain. After that used I/Q modulator to form CO-OFDM signal shows an approach using two optical Mach-Zehnder modulator and subsequently signals transmit through the single-mode fiber (SMF) ITU-T G.655.D.

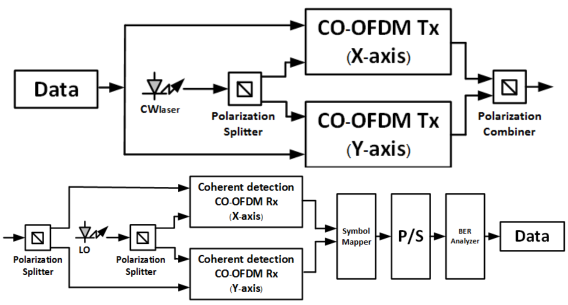

Figure 6: Conceptual diagram for PDM-CO-OFDM system.

To generate a PDM-CO-OFDM signal, we use CWlaser connect to polarization Splitter to split laser into both axis of CO-OFDM signal transmission then transmit to CO-OFDM Tx (X-axis) and CO-OFDM Tx (Y-axis) afterward use polarization combiner to combine the signal from both axis together.

According to Figure 6, we use computer simulation for the PDM-CO-OFDM transmission system by Optical simulation software. The PDM-CO-OFDM signal is generated by continuous-wave (CW) laser then transmit into both axis of CO-OFDM Tx then split by polarization splitter. After that the signals after CO-OFDM Tx are combined again by polarization combiner .The data rate is 100 Gb/s per channel x 10 channels that mean data rate is 50 Gb/s for one polarization axis, sequence length is 8192 bits. The channel spacing is 50 GHz. The optical spectrum for 10 WDM CO-OFDM channels is showed in Figure 7 which is the optical spectrum of signal system after WDM superchannel multiplexing.

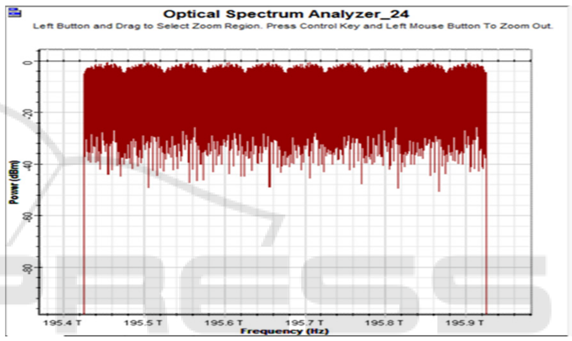

Figure 7: The optical spectrum for 10 WDM CO-OFDM channels.

For optical fiber link, we use ITU-T G.655.D single mode optical fiber ITU-T standard. The fiber is connected to EDFA to compensate signal attenuation from fiber loss. We use midway OPC between the fiber repeated sections. At the receiver, the optical coherent detection converts CO-OFDM signal to electrical signal followed by four balance photodetector with thermal noise at 18.14 pA/$\sqrt{Hz}$ and dark current at 5 nA. Then down-conversion modulates RF at 50 GHz.

3 SIMULATION RESULT

We can mitigate the effect of the dispersion and the nonlinear waveform by using midway OPC, since the enhancement of phase noise through the interaction between the fiber dispersion and nonlinear waveform distortion can be sufficiently compensated by the OPC as shown in Figure 8. The constellation of PDM-CO-OFDM transmission system employing OPC (b) after 350 km transmission is recovered with four distinct clusters compare to the residual noises spreading constellation of PDM-CO-OFDM transmission system (a) point are from nonlinearity of optical fiber. In conclusion, the distorted waveform due to dispersion in the first fiber section is compensated by the OPC and the following propagation through the second fiber section has the same dispersive characteristics.

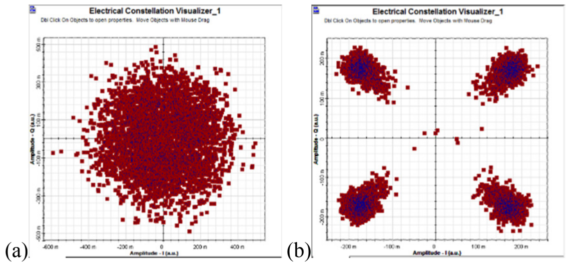

Figure 8: Received constellation diagram after 350 km transmission. The PDM-CO-OFDM transmission system (a) without OPC and (b) with OPC.

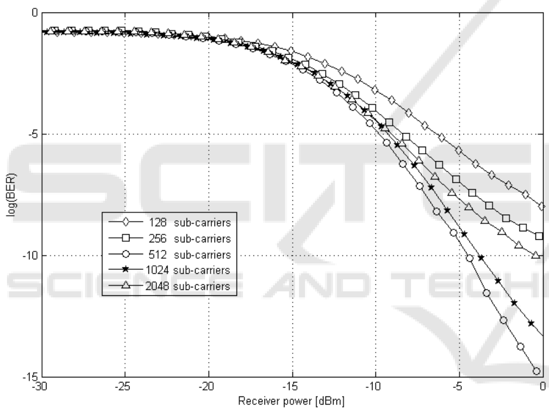

Figure 9: Relation between log(BER) and receiver power [dBm] for various number of sub-carriers at 128, 256, 512, 1024 and 2048 respectively.

Figure 9 shows the relation between log(BER) and receiver power for all 10 wavelength-division-multiplexed PDM-CO-OFDM channels. The simulation results indicate that the BER of the signals from 512 sub-carriers has the lowest BER. The number of sub-carriers affects the system performance. This is due to the phase noise effects. The other is loss of orthogonality or inter-symbol interference (ISI) that are error terms which affect the demultiplexed signal and a common phase rotation while a greater number of sub-carriers can cause a better protection in preparation for multipath delay spread. In contrast phase noise effects are worsened in this situation.

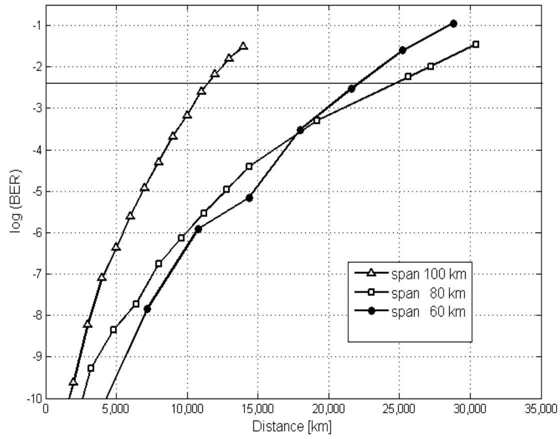

Figure 10: Maximum reach of 10-WDM channels PDM-CO-OFDM 4-QAM systems at 100 Gb/s per channel for each amplifier spacing.

We demonstrate maximum reach of the system for various values of the amplifier spacing. At BER $4x10^{-3}$, the transmission system at amplifier spacing 80 km was chosen to match the PDM-CO-OFDM 4-QAM system. To characterize the linear and nonlinear transmission performance of 10-WDM channels PDM-CO-OFDM 4-QAM system, the maximum reach is displayed in Figure 10. The results show that the maximum reachable distance is 24,000 km at BER $4x10^{-3}$.

4 CONCLUSION

We demonstrated the superchannel PDM-CO-OFDM system employing midway OPC by using computer simulations in long-distance transmission systems using EDFA's at data rate 1Tb/s (10x100 Gb/s). From the simulation results, the following points can be concluded. For the PDM-CO-OFDM system operating with 4-QAM at 1 Tb/s, the bandwidth of the optical signal is 50GHz. The PDM-CO-OFDM 4-QAM signal also has a high tolerance to nonlinearity. The advantage is increased spectral efficiency. The results have also confirmed that midway OPC can compensate for the nonlinearity and dispersive waveform distortion. The simulation results indicate that the BER of the PDM-CO-OFDM signals from 512 sub-carriers have the lowest BER. The optimum input power corresponds to the maximum reach of 24,000 km for PDM-CO-OFDM.

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REFERENCES

Chandrasekhar, S. & Liu, X. 2012. OFDM Based Superchannel Transmission Technology. *Journal of Lightwave Technology*, 30, 3816-3823.

Lowery, A. J., Liang, D. & Armstrong, J. Orthogonal Frequency Division Multiplexing for Adaptive Dispersion Compensation in Long Haul WDM Systems. *2006 Optical Fiber Communication Conference and the National Fiber Optic Engineers Conference*, 5-10 March 2006 2006. 1-3.

Le, S. T., Mccarthy, M. E., Turitsyn, S. K., Phillips, I., Lavery, D., Xu, T., Bayvel, P. & Ellis, A. D. Optical and Digital Phase Conjugation Techniques for Fiber Nonlinearity Compensation. *Opto-Electronics and Communications Conference (OECC)*, 2015, June 28 2015-July 2 2015 2015. 1-3.

Shieh, W., Bao, H. & Tang, Y. 2008. Coherent optical OFDM: theory and design. *Optics Express*, 16, 841-859.

Wei-Ren, P., Takeshima, K., Morita, I., Takahashi, H. & Tanaka, H. Scattered pilot channel tracking method for PDM-COOFDM transmissions using polar-based intra-symbol frequency-domain average. *Optical Fiber Communication Conference and Exposition (OFC/NFOEC)*, 2011 and the National Fiber Optic Engineers Conference, 6-10 March 2011 2011. 1-3.

Shieh, W. 2011. OFDM for Flexible High-Speed Optical Networks. *Journal of Lightwave Technology*, 29, 1560-1577.

Lorattanasane, C. & Kikuchi, K. 1997. Design theory of long-distance optical transmission systems using midway optical phase conjugation. *Journal of Lightwave Technology*, 15, 948-955.

Watanabe, S. & Shirasaki, M. 1996. Exact compensation for both chromatic dispersion and Kerr effect in a transmission fiber using optical phase conjugation. *Journal of Lightwave Technology*, 14, 243-248.

Jansen, S. L., Borne, D. V. D., Monsalve, C. C., Spalter, S., Krummrich, P. M., Khoe, G. D. & Waardt, H. D. 2005. Reduction of Gordon-Mollenauer phase noise by midlink spectral inversion. *IEEE Photonics Technology Letters*, 17, 923-925.