Spectral-efficient OOFDM system using compatible SSB modulation with a simple dual-electrode MZM

Zhenbo Xu (1)**, Maurice O'Sullivan** (2) **and Rongqing Hui** (1)*

(1) *Information & Telecommunication Technology Center, University of Kansas, Lawrence, KS 66045, USA*
(2) *Nortel, Ottawa Carling Campus, 3500 Carling Ave., Nepean, ON, K2H 8E9, Canada*
* *rhui@ku.edu*

Abstract: A direct-detection OOFDM transmission is experimentally demonstrated which does not need a guard-band between the carrier and the OFDM sideband. The compatible-SSB modulation is realized through a single dual-electrode MZM.

OCIS codes: (060.2630) Frequency modulation; (060.2330) Fiber optics and optical communications

1. Introduction

Orthogonal frequency division multiplexing (OFDM) for optical transmission has been realized with both direct detection [1] and coherent detection [2]. While coherent detection may provide better receiver sensitivity, direct detection is suitable for short and medium distance transmission because of the relaxed laser linewidth requirement, and receiver simplicity. However, a guard band between the optical carrier and the OFDM sideband is usually required to avoid inter-modulation-induced waveform distortion in the direct detection process [1]. This guard band, which equals to the OFDM bandwidth, reduces the spectral efficiency of the system. One way to eliminate the requirement of this guard-band is to use a compatible single-sideband (SSB) modulation, where the OFDM signal is carried as the exponential envelope [3]. The implementation of compatible SSB requires a complex I/Q modulator in order to independently manipulate the optical amplitude and phase. Although theoretical analysis and numerical simulations have been performed [3], experimental demonstration of this technique has not been reported. In this paper, we demonstrate our OFDM transmission system implementation using compatible SSB modulation. A commercial optical transmitter initially designed for 10Gb/s electrical-domain dispersion compensation (eDCO) [4, 5] is used for this experiment, which includes two 22Gs/s DACs and a single dual-electrode Mach-Zehnder modulator (MZM). Negligible degradation in terms of the required-OSNR was found after transmission over 125km standard single-mode fiber. Although eDCO transmitter card used in the experiment would allow a 20Gb/s transmission for this OFDM implementation, we chose 10Gb/s data rate because the ADC used in the experiment only has 6GHz analog bandwidth.

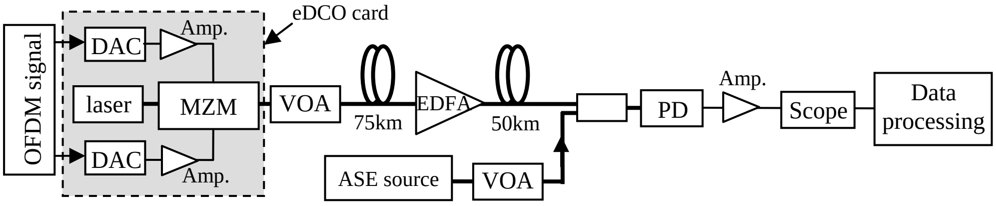


Fig. 1. Transmission system block diagram.

2. Modulation using a dual-electrode MZM

In a previous numerical analysis of OFDM transmission using compatible SSB modulation [3], an I/Q modulator was proposed for the transmitter. Given our implementation, which is based on a simple dual-electrode MZM, equivalent signal waveforms have to be derived for the two electrodes of the MZM. For a real value OFDM signal $\sigma(t)$, $\sigma(t)+jH(\sigma(t))$ is usually used for SSB modulation, where $H[\ ]$ denotes Hilbert transform. In compatible SSB modulation, the signal optical field is [3],

$$n(t)=\exp\{\sigma(t)+jH[\sigma(t)]\}=A(t)\exp[j\Phi(t)] \qquad (1)$$

where $A(t)=\exp[\sigma(t)]$ and $\Phi(t)=H[\sigma(t)]$, and the OFDM signal is carried only by the amplitude of the optical field. In the receiver, the OFDM signal can be recovered through amplitude detection so that $\sigma(t)=\ln[A(t)]$. With a DC bias set to the quadrature point, the modulation-induced phase shifts applied to the two arms of the modulator should be related to the OFDM signal σ(t) by:

$$\varphi_1(t)=H[\sigma(t)]+e^{\sigma(t)} \qquad (2a)$$

$$\varphi_2(t)=H[\sigma(t)]-e^{\sigma(t)} \qquad (2b)$$

A digital representation of the required electrical waveforms is fed to a pair of DACs whose amplified analog outputs drive the two electrodes of a dual drive MZM.

3. Experimental results

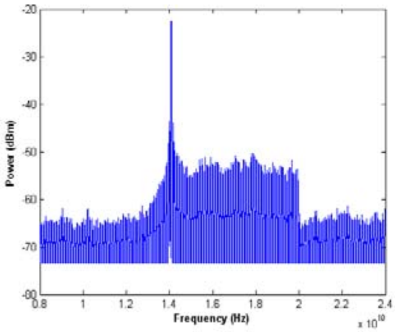
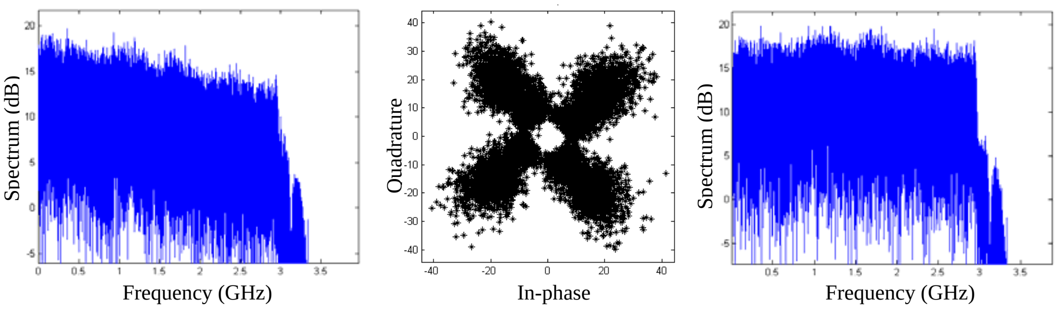


Fig.2, compatible OSSB optical spectrum measured by coherent heterodyne detection

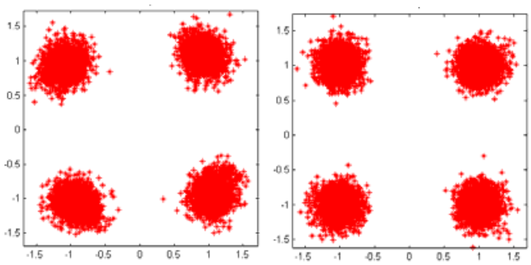
The experimental schematic is illustrated in Fig. 1. A Nortel commercial eDCO card was used in this experiment as the OFDM transmitter, which is equipped with two 22Gs/s DACs with 6-bits resolution and a balanced dual-electrode MZM. A 10Gb/s data stream was partitioned into 64 OFDM subcarriers with QPSK modulation format [5], and the total OFDM signal bandwidth was about 5.8GHz. The length of cyclic prefix was four percent of the FFT size. Hermitian symmetry was adopted in FFT matrix to guarantee the real value of the OFDM signal that fed to the two-channel DAC. Then the converted analog voltage signals were amplified before feeding to the two electrodes of the MZM. Electro-optic signal conversion based on equations (1) and (2) ensured single-sideband optical spectrum at the output of the electro-optic modulator. To minimize the optical carrier component and maximize the modulation index, we had to adjust the DC levels of the driving electrical waveforms $\varphi_1(t)$ and $\varphi_2(t)$ so that the MZM operated in the linear region. The gain of the electrical amplifiers that drive the MZM was controlled to obtain specific modulation index. The typical spectrum of the generated compatible SSB optical signal is shown in Fig.2, where the OFDM signal has a uniform spectral density from 10MHz to 5.8GHz, on one side of the optical carrier. The optical system consists of two spans of standard single-mode fibers with 75 km and 50 km lengths. An EDFA was used between the two fiber spans to amplify the optical signal. A variable optical attenuator (VOA) at the fiber system input adjusts the optical power level that launches into the fiber. In this system, approximately 4dBm average launched optical power appeared to give the best performance. In order to be able to measure the required OSNR to achieve a certain bit-error-rate, ASE noise loading was applied before the optical receiver, which consists of an ASE noise source, a VOA, and an optical coupler that adds the extra ASE noise to the received optical signal. A wideband photodiode performs direct detection of the optical signal. The signal electrical waveform was amplified and then digitized by a 20Gs/s LeCroy digital oscilloscope. The reason that we chose the 5.8GHz OFDM signal bandwidth in the experiment was because the 6GHz maximum analog bandwidth of the oscilloscope. The digital signal waveform is recorded for three times the OFDM pattern length for time synchronization and later OFDM demodulation. The oscilloscope sampling offset is corrected in the digital offline processing [5].



(a) (b) (c)

Fig. 3. (a) SSB OFDM spectrum high frequency rolloff, (b) constellation of (a), and (c) after digital pre-compensation

For back-to-back operation without the fiber, the received OFDM signal experienced a significant spectral roll-off of due to the low-pass characteristics of various RF components used in the system. As the consequence, the constellation diagram became unrecoverable. To illustrate this effect, Fig.3 (a) shows the measured OFDM spectrum with only 2.9GHz bandwidth. The corresponding constellation diagram shown in Fig.3 (b) clearly exhibits a significant amplitude distortion. In order to maintain the same OSNR level at the receiver for all subcarriers, we had to apply a digital pre-compensation (a linear power tilt over frequency) on the OFDM spectrum at the transmitter side. In this way, the received baseband OFDM spectrum became flat as illustrated in Fig.3(c). For our system, this pre-compensation effectively improved approximately 10dB high frequency rolloff with the 5.8GHz OFDM bandwidth, and the constellation diagram is shown in Fig.4 (a). Based on the system block diagram and the signal-processing algorithm described above, we have also developed a simulation model. The simulated constellation diagram shown in Fig.4 (b) exhibits similar characteristics as the measured one, which indicated that the experimental system was optimized. ASE noise loading technique was then applied to evaluate the BER as the function OSNR at the receiver. Fig.5 (a) shows the measured results for back-to-back as well as for the system with 125km standard single-mode fiber. It is clear that the 125km fiber in the system introduces negligible penalty in the transmission performance. In both cases, the required OSNR to achieve the BER of 10^{-3} was approximately 29dB. This system using compatible SSB modulation apparently demands higher OSNR in comparison to OFDM systems previously reported using the same transmitter [5]. The reason is that by putting the OFDM signal into the exponential as indicated by equation (1), the peak-to-average ratio is increased and the effective modulation index is reduced, especially for the part of waveforms with small amplitudes. This is the price paid to improve the bandwidth efficiency by eliminating the spectral guard band between the carrier and the OFDM sideband.



(a) (b)

Fig. 4. Back-to-back constellation for the SSB OFDM signal (a) experimental result, (b) numerical result

As an attempt to investigate the effect of modulation index, we adjusted the gain of the electrical amplifiers that drive the MZM. This allowed us to vary the carrier-to-signal ratio (CSR), which is defined as the ratio between the powers in the optical carrier and in the OFDM sideband. In the MZM transfer function, when the modulation index is higher than 100%, clipping will happen. On the other hand, if the modulation index is too small, CSR will be very high and the system is vulnerable to the ASE noise. The tradeoff between the two effects provided a guideline to find the optimized modulation index. Fig.5 (b) shows the measured BER versus OSNR at the receiver for different CSR values corresponding to specific different modulation indices. When the modulation index is too low (for example for CSR = 15dB), the required OSNR for BER = 10^{-3} is as high as 34dB. On the other extreme if the modulation index is too high (for CSR = 8dB), the BER value cannot reach 10^{-3} even for very high OSNR. In this case, most of the errors were caused by clipping. The best modulation index corresponds to the CSR of 10dB in this experiment.

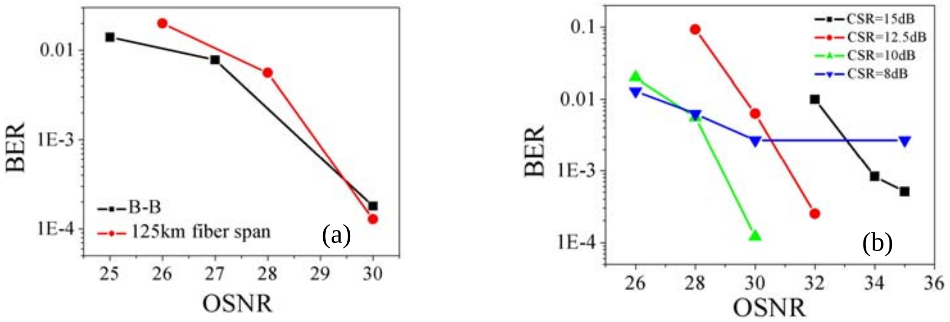


Fig. 5. (a) The required OSNR for B-B and after 125km fiber span with the same OFDM power modulation on MZM. (b) The required OSNR vs. BER after 125km fiber span correspond with different carrier to subcarrier power ratio.

4. Conclusion

We have experimentally demonstrated OFDM transmission using compatible SSB modulation, in which the guard-band between the optical carrier and the OFDM sideband is not required. The implementation uses a commercial Nortel eDCO transmitter card equipped with a simple dual-electrode MZM. Although the bandwidth efficiency is doubled in comparison to intensity-modulated OFDM systems, the major challenge is the increased peak-to-average ratio arising from the exponentiation of Eq.(1) , which increases the required OSNR. Further investigations in nonlinear signal pre-distortion may help improve the system performance.

5. References

[1] A. J. Lowery and J. Armstrong, "Orthogonal-frequency-division multiplexing for dispersion compensation of long-haul optical systems", Optics Express, Vol. 14, No. 6, pp. 2079-2084 (2006)

[2] W. Shieh and C. Athaudage, "Coherent optical orthogonal frequency division multiplexing", *IEE Electronic Letters*, Vol. 42, pp. 587-589 (2006)

[3] M. Schuster, M. Schuster, S. Randel, C. Alexander, et al, "Spectrally efficient compatible single-sideband modulation for OFM transmission with direct detection," *IEEE Photonics technology Letters***, 20,** 670-672 (2008)

[4] J. McNicol, M. O'Sullivan, K. Roberts, A. Comeau, D. McGhan, L. Strawczynski, "Electrical Domain Compensation of Optical Dispersion," Proc. Conf. Optical Fiber Communications, Anaheim, CA, OThJ3 (2005)

[5] Z. Xu, R. Hui, O. Sullivan, "Dual-band OOFDM system based on tandem single-sideband modulation transmitter". Optics Express, **17,** 13479-13486 (2009).