Spectral Efficiency and Receiver Sensitivity in Direct Detection Optical-OFDM

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Abstract: We show by analysis and simulation that by proper biasing of the optical modulator, the intermodulation distortion is minimized. Thus the spectral efficiency can be improved and receiver sensitivity can be exchanged against spectral width.

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

1. Introduction

Optical transmission systems employing orthogonal frequency division multiplexing (OFDM) have gained considerable research interest because OFDM can combat fiber chromatic dispersion [1,2] and has the capability to use higher level modulation formats to increase spectral efficiency [3]. In direct detection optical-OFDM (DD-OFDM), however a spectrally-inefficient frequency gap (W_g) between the optical carrier and the data spectrum, with a bandwidth equal to the signal bandwidth (B_{ofdm}), is typically needed to avoid the second-order intermodulation distortion (IMD) near the optical carrier due to the square low photodetector (PD) [4].
In this contribution, we show the dependency of the OFDM signal distortion and the receiver sensitivity on the Mach-Zehnder modulator (MZM) bias point. In addition we propose a possibility of receiving the data signal with a reduced frequency guard-band. By simulation, we show that transmission of 40Gb/s over 640km of an uncompensated standard single-mode fiber is possible.

2. DD-OOFDM System setup

The general DD-OFDM system setup is shown in fig. 1. The real valued OFDM signal is generated by using a complex conjugate extension for the input to IFFT [5]. The resulting signal has to be biased for driving an external optical MZM in order to achieve sufficient carrier power for direct detection. A Single-Side-Band (SSB) optical filter is used to transmit only one sideband together with the optical carrier. The optical transmission line consists of 8 spans of 80 km of standard single-mode fiber (SSMF) without dispersion compensation. Span loss is compensated for by means of inline optical amplifiers. For the receiver, a variable optical attenuator (VOA) in front of the optical preamplifier, (erbium doped fiber amplifier, EDFA), allows for OSNR tuning. OFDM demodulation is performed including removing of cyclic prefix, serial-to-parallel conversion, FFT, post detection OFDM equalization, symbol de-mapping and parallel-to-serial conversion.

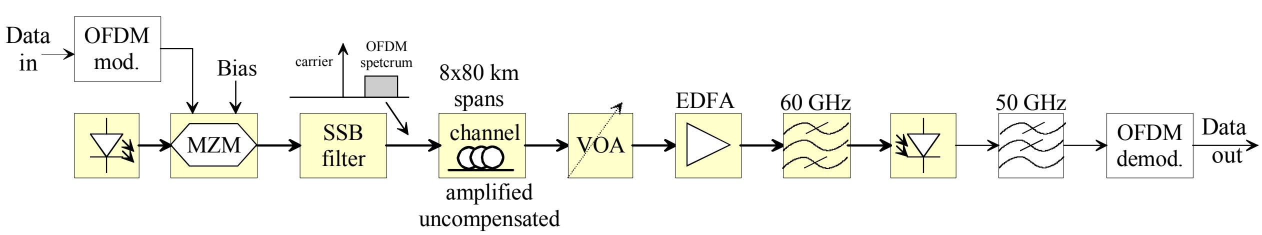

Fig.1. Direct detection-OFDM system setup

For our investigation we change the drive conditions of the MZM (bias and signal variance) and we reduce the frequency gap W_g (see fig.3) between carrier and OFDM spectrum (by using appropriate zero padding in the OFDM modulator) in order to reduce the total bandwidth occupancy and thus increase spectral efficiency. The system parameters used in the simulation are: input data stream of PRBS 2^{16} -1, data rate of 42.8 Gb/s including 7% overhead for FEC, QPSK format, cyclic prefix of 1/8 of the useful OFDM symbol duration, number of subcarriers of N=1024, and fiber input power of 0dBm. The received raw data rate after FEC decoding and removing of cyclic prefix is 40 Gb/s.

3. Optimizing Receiver Sensitivity

For investigation into receiver sensitivity, the fiber channel is neglected. For high linearity, the MZM is biased at its quadrature point (i.e. V_{bias}/V_π=0.5), where V_π is the switching voltage at which the voltage-induced phase difference reaches 180^0. For fixed bias, carrier power is fixed, too. Now, the amplitude of the zero-mean driving signal is varied. Obviously, there is a trade-off: For low amplitude, carrier power is much higher than the power in the sideband yielding low sensitivity. Increasing the signal amplitude improves the sensitivity. For exceedingly high amplitude, however, the signal suffers nonlinear distortions.

To avoid nonlinear distortions the driving amplitude still has to be chosen sufficiently low. The power of the optical carrier wastes a high percentage of the total power. Therefore, in our approach a variable bias is introduced. Choosing the bias voltage such that carrier power is reduced improves sensitivity, but at the cost of worse linearity. As long as the resulting degradation does not overcompensate for the benefit due to reduced carrier power, receiver sensitivity increases [6]. Fig. 2(a) shows simulation results for different values of the bias. Increasing the value for the bias improves the sensitivity. It seems that better performance is achieved the lower the carrier power is. However, this results in high insertion loss of the MZM. Therefore, the bias voltage that is allowed is limited to a certain value (e.g. $0.8V_\pi$). Moreover, it is found by simulation, that the optimum value for the bias, for which optimum sensitivity is achieved, is when the carrier to sideband power ratio (PR) is unity as depicted in fig. 2(b).

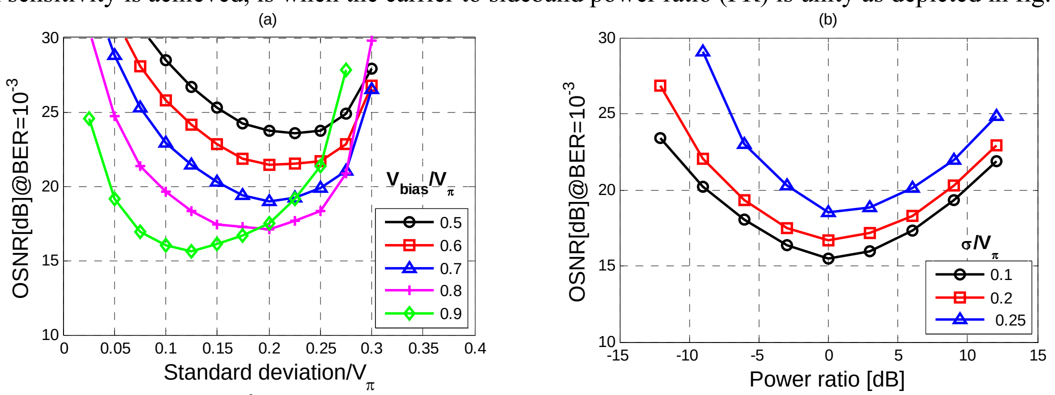

Fig.2. Required OSNR for BER=10^{-3} versus standard deviation of OFDM driving signal for different bias points (a) and versus carrier-to-sideband power ratio for different values of standard deviation of driving signal (b)

4. Optimizing Spectral efficiency

In this section, small-signal analysis of the cascade of MZM and PD, neglecting transmission fiber, is performed in order to estimate the amount of nonlinear distortions. The bandpass output E-field of the MZM is

$$E_{out}(t) \propto \cos(2\pi f_c t)\cos\left[\frac{\pi}{2V_\pi}\left(x(t)-V_{bias}\right)\right], \qquad (1)$$

where f_c denotes the optical carrier frequency. $E_{out}(t)$ first needs to be filtered by the SSB filter before the squaring operation of the PD is applied. According to [7], second-order analysis results in the following expression for the output current:

$$i_{SSB}(t) \approx K\left(1+\cos\left[\pi\frac{V_{bias}}{V_\pi}\right]+\frac{\pi}{2}\frac{x(t)}{V_\pi}\sin\left[\pi\frac{V_{bias}}{V_\pi}\right]-\frac{\pi^2}{16}\frac{x^2(t)}{V_\pi^2}\left(1+3\cos\left[\pi\frac{V_{bias}}{V_\pi}\right]\right)+\frac{\pi^2}{16}\frac{\hat{x}^2(t)}{V_\pi^2}\left(1-\cos\left[\pi\frac{V_{bias}}{V_\pi}\right]\right)\right). \qquad (2)$$

Here, '^' denotes the Hilbert transform and K is proportionality constant. For V_{bias}/V_π=0.5, $i_{SSB}(t)$ simplifies as:

$$i_{SSB}(t) \approx K\left(1+\frac{\pi}{2}\frac{x(t)}{V_\pi}+\underbrace{\frac{\pi^2}{16}\frac{\hat{x}^2(t)-x^2(t)}{V_\pi^2}}_{A}\right). \qquad (3)$$

It is found that term A in (3) does not exhibit spectral components around zero frequency. This is confirmed in fig. 3, where the PSD of $i_{SSB}(t)$ is shown comparing two different settings for the bias. Obviously, setting V_{bias}/V_π=0.5 results in low IMD. Thus we conclude that the frequency gap (W_g) can be reduced significantly resulting in a more spectrally efficient transmission. Thus we investigate by simulation the impact of decreasing the frequency gap (W_g) on the receiver sensitivity in order to increase the spectral efficiency.

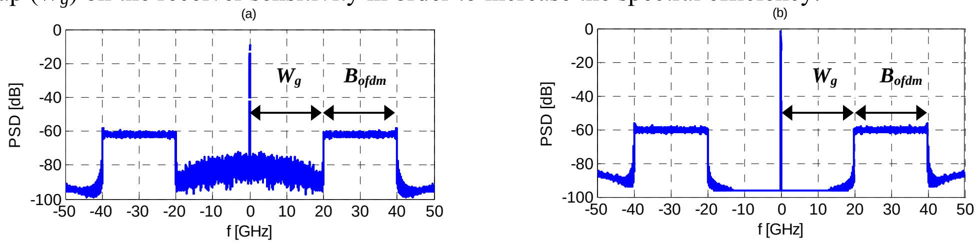

Fig.3. Received PSD after PD for B2B of DD-OFDM for SSB with V_{bias}/V_π=0.7 (a) and V_{bias}/V_π=0.5 (b)

Fig. 4(a) shows the results for B2B-transmission. It can be shown that for V_{bias}/V_π=0.5 (PR=20), the frequency gap can be removed completely resulting in doubling of spectral efficiency. On the other hand, for PR=1 the optimal sensitivity is better by 8 dB. However, 90% of the frequency gap must be maintained due to the effect of IMD. Fig. 4(b) shows the results for an uncompensated link of 8x80km of SSMF. For V_{bias}/V_π=0.5, still up to 50% of the frequency gap can be removed for the same receiver sensitivity. The increase of required W_g compared to the B2B-case is attributed to IMD of second order that is not obtained in the analytical analysis above as the fiber transfer function was neglected. Increasing V_{bias}/V_π from 0.5 towards 0.86 results in decreasing of PR and a graceful trade-off between spectral efficiency and sensitivity.

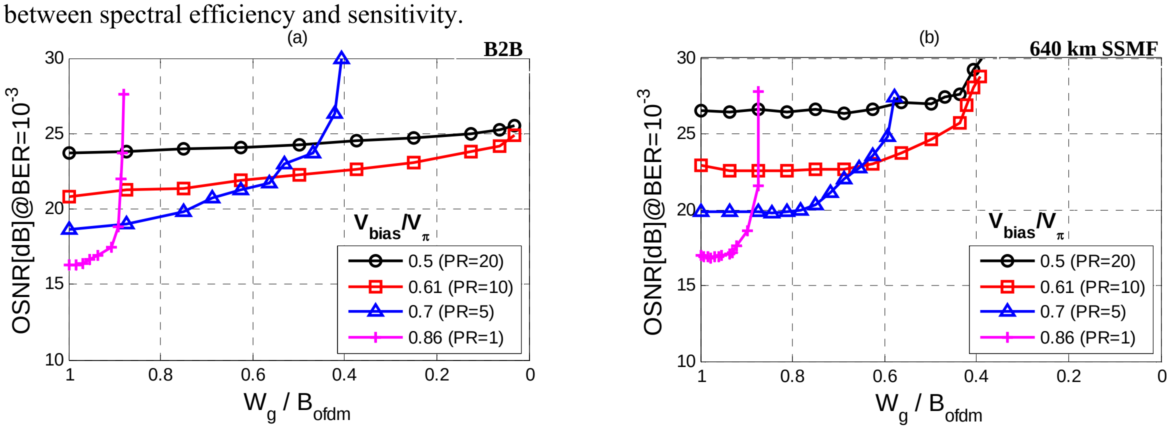

Fig.4. Required OSNR for BER=10^{-3} versus frequency gap for back-to-back (a) and 8x80km uncompensated spans link (b).

5. Conclusion

The dependency of the receiver sensitivity on the MZM operating point is shown. Proper selection of modulator bias improves sensitivity by several dB. Morever, it is shown analytically and by simulation that biasing the MZM at the quadrature point results in a significant reduction of intermodulation distortion which allows for reduction of the frequency gap by at least 50% for a realistic system. This has a big advantage for systems which consider the bandwidth efficiency as a first priority.

6. References

[1] A. J. Lowery and J. Armstrong, “Orthogonal-frequency-division multiplexing for dispersion compensation of long-haul optical system,” OPTICS EXPRESS, Vol. 14, March 2006.

[2] Y. Tang, X. Yi, W. Shieh and R. Evans, “Optimum Design for Coherent Optical OFDM Transmitter,” Optical Fiber Comm. Conf. (OFC 2006), Paper JThA47.

[3] Z. Jia, J. Yu, D. Qian, G. Ellinas, G. K. Chang, “Experimental demonstration for Delivering 1-Gb/s OFDM signals over 80-km SSMF in 40-GHz Radio-over-Fiber Access Systems,” Optical Fiber Comm. Conf. (OFC2008), paper JWA108

[4] W-R. Peng, X. Wu, V. R. Arbab, B. Shamee, J-Y. Yang, L. C. Christen, K-M. Feng, A. E. Willner and S. Chi, “Experimental Demonstrationof 340 km SSMF Transmission Using a Virtual Single Sideband OFDM Signal that Employes Carrier Suppressed and Iterative Detection Technique,” Optical Fiber Comm. Conf. (OFC 2008), Paper OMU1.

[5] A. Ali, J. Leibrich and W. Rosenkranz, “Impact of Nonlinearities on Optical OFDM with Direct Detection” ECOC 2007, Paper P095

[6] J. Leibrich, A. Ali and W. Rosenkranz, “OFDM Transceiver Design for Optimizing Sensitivity and Long-Haul Performance,” LEOS Summer Topic on Next Generation Transceiver Tech. for Long Haul Optical Comm., 2008.

[7] A. Ali, J. Leibrich and W. Rosenkranz, “Spectrally efficient OFDM-transmission over Single-Mode Fiber Using Direct Detection” 13th international OFDM-Workshop (InOWo’08), Hamburg, Germany, 2008, pp 221-225