Spectrally Efficient OFDM-Transmission over Single-Mode Fiber Using Direct Detection

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Abstract—**For the direct-detection optical orthogonal frequency division multiplexing (DD-OOFDM) system, the influence of the Mach-Zehnder modulator (MZM) operating point on the receiver sensitivity is studied here. Analysis and simulation show that by proper biasing of MZM, the second-order intermodulation distortion (IMD) is significantly decreased. Morever, a trade-off between spectral efficiency and receiver sensitivity is observed and confirmed by simulation. It is shown that transmission of 40Gb/s over 640km of standard single-mode fiber is possible without any optical dispersion compensation.**

Index terms—**optical OFDM, sensitivity, spectral efficiency, optical communications.**

I. INTRODUCTION

Orthogonal-Frequency Division Multiplexing (OFDM) has been widely adopted in RF-wireless systems such as cellular-networks, digital-audio broadcasting and digital-video broadcasting [1-2].

Due to its high spectral efficiency and robustness towards channel impairments, such as inter-symbol-interference (ISI), Orthogonal frequency division multiplexing (OFDM) becomes an intriguing candidate for optical high-speed transmission. Recently, optical transmission systems employing OFDM have gained considerable research interest because OFDM can combat fiber chromatic dispersion [3] and has the capability to use higher level modulation formats to increase spectral efficiency.

Optical OFDM (OOFDM) itself offers different options for implementation. An important issue is optical demodulation that can be realized either by means of direct detection (DD) or coherent detection (CO) using a local oscillator [4-5]. In coherent detection optical OFDM (CO-OOFDM), a very narrow linewidth laser is required at the transmitter and receiver because of the sensitivity of OFDM to frequency offset and phase noise. An alternative approach to overcome this limitation is the direct detection optical OFDM (DD-OOFDM).

In DD-OOFDM, the OFDM signal modulates the intensity of the light using the Mach-Zehnder modulator (MZM). Due to the fact that the electrical OFDM signal is quasi-analog with zero mean, a bias tee (which adds a DC component) is needed to provide the carrier required for direct detection. Due to the high peak-to-average-power ratio of an OFDM signal, the MZM produces a distortion due to its nonlinear characteristic. Biasing the MZM at the quadrature point, the most linear part of the power characteristic, reduces the nonlinear distortions but on the other hand degrades the receiver sensitivity because half of the transmitted power will be allocated for the optical carrier which carries no information. Thus, a trade-off between the MZM nonlinearity and receiver sensitivity should be considered. Furthermore, due to the nonlinear modulator characteristic, an optical link inherently shows nonlinear behavior. Moreover, the optical fiber as transmission medium is a nonlinear element as soon as the launch power exceeds a certain threshold [6].

DD-OOFDM system is combined with a single-sideband format (SSB-DD-OOFDM) to overcome the dispersion induced power fading occuring with a double-sideband transmission [3]. In addition, in DD-OOFDM, a spectrally-inefficient frequency guard-band between the optical carrier and the data signal, with a bandwidth equal to the signal bandwidth, is typically needed to avoid the second-order intermodulation distortion near the optical carrier due to the square low photodetector [7].

In this contribution, we show the dependency of the OFDM signal distortion and the receiver sensitivity on the MZM bias point. It is found that optimum sensitivity is obtained when the carrier to single-sideband power ratio (PR) is unity. 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.

II. DD-OOFDM System Setup

The general DD-OOFDM system setup is shown in fig. 1. The serial input channel at 42.8 Gb/s , including 7% FEC overhead, is parallelized by S/P converter. Each data path is mapped using QPSK format and presented to the input of an IFFT processor. To generate a real output signal, complex conjugate symbols are created appropriately and fed into the IFFT, too. Moreover, half of the input of the IFFT around the DC value is filled with zeros to displace the signal band from the optical carrier by a frequency gap (W_g) which ensures that the second-order intermodulation distortion (IMD), due to photodetection, will mainly fall outside the OFDM band [8]. Alternatively, this signal can be constructed by means of a complex IFFT followed by electrical I-Q up-conversion. Finally, the cyclic prefix is added.
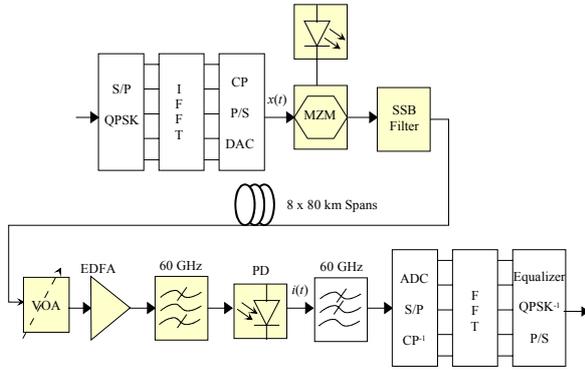

Fig.1. DD-OOFDM system blockdiagram.

The resulting signal has to be biased for driving an external optical Mach-Zehnder-modulator (MZM). A Single-Side-Band (SSB) optical filter is used to transmit only one side of the two-sided OFDM spectrum and the optical carrier. The optical transmission line consists of 8 spans of 80 km of standard single-mode fiber (SSMF) without dispersion compensating fiber (DCF). 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. The optical amplified spontaneuous emission (ASE) noise is reduced by means of an optical filter with bandwidth B_{opt}=60GHz. An electrical 60GHz post-detection filter models the bandwidth of the electrical circuit. OFDM demodulation is performed including removing of Guard interval, serial-to-parallel conversion, FFT, post detection OFDM equalization, symbol de-mapping and parallel-to-serial conversion.

III. Optimizing Receiver Sensitivity

A. Trade-off between Noise Requirements and Nonlinearity

For investigation into receiver sensitivity, the fiber channel is neglected. The MZM characteristic with different bias points is shown fig. 2 [9]. 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 π (or 180^0).
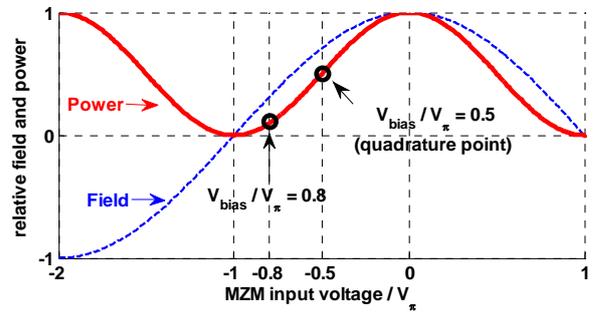

Fig.2. MZM characteristic with different bias points for the input voltage.

Intensity modulation inherently requires a carrier. For fixed bias, carrier power is fixed, too. Now, the amplitude of the zero-mean driving signal is varied.
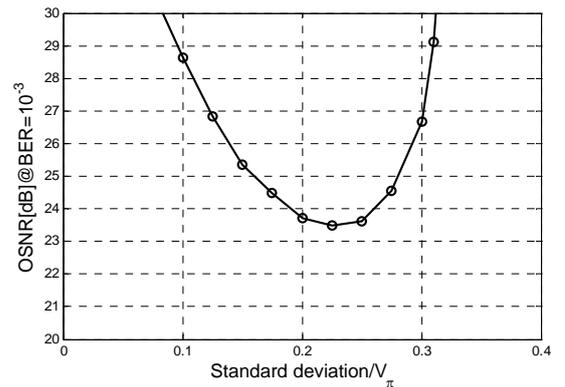

Fig.3. Required OSNR for BER=10^{-3} over standard deviation of driving voltage when biasing the MZM at quadrature point.

Obviously, there is a trade-off: For low amplitude, carrier power is much higher than the power in the sideband yielding low sensitivity (because the carrier carries no information).

Increasing the signal amplitude improves the sensitivity. For high amplitude, however, the signal suffers nonlinear distortion. The optimum driving amplitude, quantified by its standard deviation normalized by V_π, is shown fig. 3.

B. Improving Sensitivity by Means of Proper Biasing

The results in fig. 3 show the basic dilemma when MZM is biased at the point of highest linearity: To avoid nonlinear distortion the driving amplitude still has to be chosen 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 (i.e. on the power characteristic given in fig. 2 we move to the left) 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.
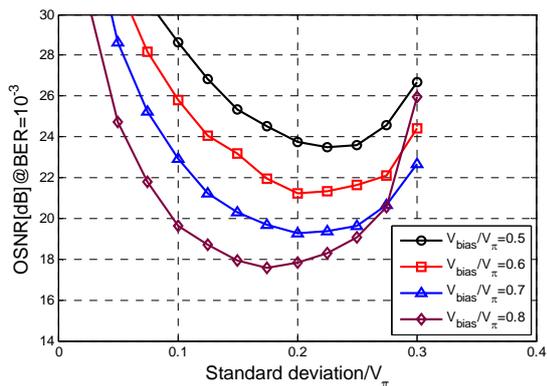

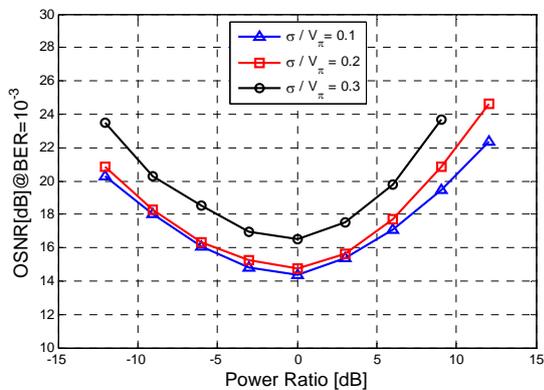Fig.4. Required OSNR for BER=10^{-3} over standard deviation of driving voltage with different MZM bias points.

Fig.5. Required OSNR for BER=10^{-3} over power ratio for different standard deviation of driving voltage.

Fig. 4 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. $0.8V_\pi$) [10]. 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 confirmed in fig.5.

IV. OPTIMIZING SPECTRAL EFFICIENCY

A. Minimization of IMD

In this section, small-signal analysis of the cascade of MZM and PD, neglecting transmission fiber, is performed. First, analysis is carried out for DSB transmission. Afterwards, analysis is extended to SSB. For DSB, the following expression for the output current $i(t)$ of PD as function of the zero-mean real driving OFDM signal $x(t)$ of MZM is found:

$$i_{DSB}(t) = K\left(1 + \cos\left[\frac{\pi}{V_\pi}\left(x(t) - V_{bias}\right)\right]\right), \quad (1)$$

where K denotes some constant depending e.g. on transmission power. After expansion up to second order in $x(t)$,

$$i_{DSB}(t) \approx K\left(1 + \cos\left[\pi\frac{V_{bias}}{V_\pi}\right] + \pi\frac{x(t)}{V_\pi}\sin\left[\pi\frac{V_{bias}}{V_\pi}\right] - \underbrace{\frac{\pi^2}{2}\frac{x^2(t)}{V_\pi^2}\cos\left[\pi\frac{V_{bias}}{V_\pi}\right]}_{IMD}\right).$$

$$(2)$$

For $V_{bias}/V_\pi=0.5$, second order IMD is completely eliminated as illustrated in fig.6, where the PSD of $i_{DSB}(t)$ is shown comparing two different settings for the bias.
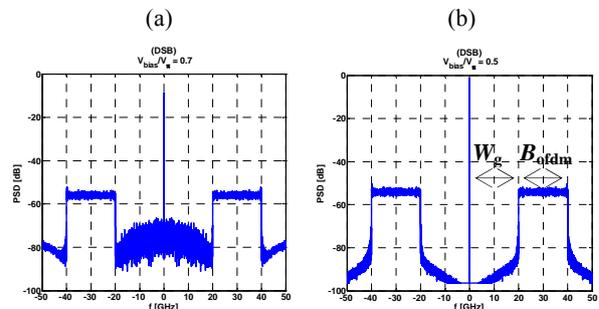

Fig.6. Received PSD after PD of DD-OOFDM for DSB with (a) $V_{bias}/V_\pi=0.7$ and (b) $V_{bias}/V_\pi=0.5$

As mentioned above, in DSB transmission a power fading occurs, due to the chromatic dispersion, resulting in complete suppression of specific OFDM subcarriers. This can be avoided by suppressing the lower sideband of the symmetric spectrum.

In case of SSB, the bandpass output E-field of the MZM is

$$E_{out}(t) \propto \cos(2\pi f_c t)\cos\left[\frac{\pi}{2V_\pi}(x(t)-V_{bias})\right], \qquad (3)$$

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. Without going into algebraic details, second-order analysis results in the following expression for the output current:

$$i_{SSB}(t) \approx K\left(1+\cos\left[\pi\frac{V_{bias}}{V_\pi}\right]+\frac{\pi}{2}\frac{x(t)}{V_\pi}\sin\left[\pi\frac{V_{bias}}{V_\pi}\right]\right.$$
$$\left.-\frac{\pi^2}{16}\frac{x^2(t)}{V_\pi^2}\left(1+3\cos\left[\pi\frac{V_{bias}}{V_\pi}\right]\right)+\frac{\pi^2}{16}\frac{\hat{x}^2(t)}{V_\pi^2}\left(1-\cos\left[\pi\frac{V_{bias}}{V_\pi}\right]\right)\right). \qquad (4)$$

Here, '^' denotes the Hilbert transform. For V_{bias}/V_π=0.5, $i_{SSB}(t)$ can be written as:

$$i_{SSB}(t) \approx K\left(1+\frac{\pi}{2}\frac{x(t)}{V_\pi}+\underbrace{\frac{\pi^2}{16}\frac{\hat{x}^2(t)-x^2(t)}{V_\pi^2}}_{A}\right). \qquad (5)$$

From our simulation, we found that term A in (5) does not exhibit spectral components around zero frequency. This is confirmed in fig. 7, 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.
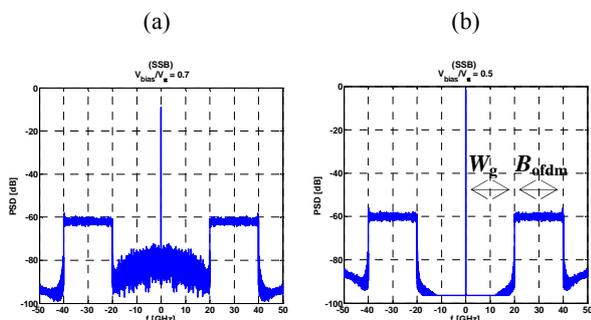
Thus we conclud that we can reduce the frequency gap (W_g) in order to improve the spectral efficiency of the transmission.

B. Simulation Results

Simulation is employed to investigate the impact of decreasing the frequency gap (W_g) on the receiver sensitivity in order to increase the spectral efficiency. This is carried out for two setups: In the first one, which targets at high receiver sensitivity, the MZM is biased just above its intensity null ($V_{bias}/V_\pi \approx< 1$), i.e. the modulator is operating near the linear field region, providing a unity carrier to sideband power ratio (PR=1) to achieve optimal receiver sensitivity. In the second system, the MZM is biased at quadrature point V_{bias}/V_π=0.5 to reduce the IMD effect and achieve high spectral efficiency. The DD-OOFDM 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, cyclic prefix of 1/8 of the useful OFDM symbol duration, number of subcarriers of N=1024, normalized standard deviation of the driving signal of σ/V_π=0.2, and fiber input power of 0dBm. The received raw data rate after FEC decoding and removing of cyclic prefix is 40 Gb/s.

B.1 Back-to-Back Transmission

Fig. 8 shows the results for B2B-transmission, to investigate the receiver sensitivity after decreasing the frequency gap. It can be shown that for V_{bias}/V_π=0.5, the frequency gap can be removed 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.
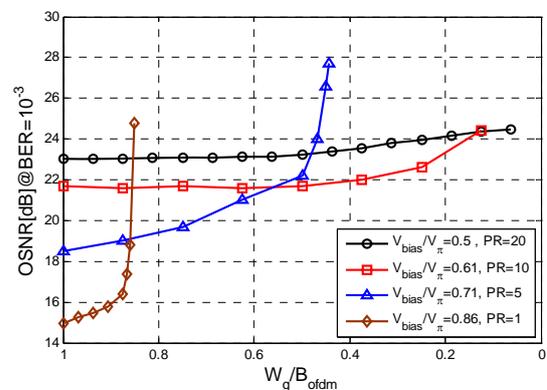

Fig.8. Required OSNR for BER=10^{-3} versus gap width with different values for the bias for B2B transmission.

Fig.7. Received PSD after PD of DD-OOFDM for SSB with (a) V_{bias}/V_π=0.7 and (b) V_{bias}/V_π=0.5

B.2 640km Transmission

Fig. 9 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.
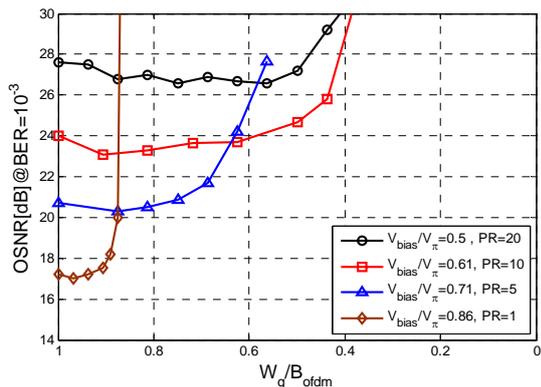

Fig.9. Required OSNR for BER=10^{-3} versus gap width with different values for the bias for 8x80km spans link.

V. 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.

VI. References

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