Impact of Mach-Zehnder non-linearity on the Receiver Sensitivity of Direct-Detection Optical OFDM

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Abstract: We show by simulation the impact variations in both the bias point of a Mach-Zehnder modulator and the amplitude of the driving signal has on the receiver sensitivity of a direct-detection optical OFDM system with 4-QAM modulation.

1. Introduction

In optical communications systems, as the data rates increase, combating fibre chromatic dispersion becomes more of a problem. This is because the resistance of these systems to the Inter-Symbol Interference (ISI) resulting from chromatic dispersion degrades quadratically as the data rate. Consequently, with such increases in the data rate, electronic dispersion compensation using serial modulation formats involves time-consuming computations that render them impractical [1].

Orthogonal Frequency Division Multiplexing (OFDM), a multi-carrier modulation technique, has generated a lot of research interest in optical communications. This is because it has been shown that provided the delay spread caused by chromatic dispersion is less than the cyclic prefix interval, OFDM can easily compensate for chromatic dispersion [2]. OFDM is also capable of increasing spectral efficiency using higher modulation formats [3]. There are two flavours of optical OFDM that have been proposed – Coherent Optical OFDM (CO-OFDM) and Direct-Detection Optical OFDM (DD-OOFDM). Of these two, DD-OOFDM uses a single photodiode at the receiver for direct-detection, offering advantages in terms of simplicity and cost-effectiveness over its CO-OFDM counterpart. However, it requires a spectrally-inefficient guard band between the optical carrier and the OFDM band so that when the optical OFDM signal impinges on the square-law photodiode; the Intermodulation Distortion products that arise due to mixing of pairs of subcarriers with themselves fall within this guard band and do not cause significant in-band distortion [4].

The power transfer characteristic (ratio of output power to input power vs. biasing voltage) of the Mach-Zehnder Modulator (MZM) is of the sin^2 form [5]. Consequently, the point at which the MZM is biased, as well as the amplitude of the drive to the MZM, affects the receiver sensitivity [6].

In this paper, we illustrate by simulation how, for a fixed drive to the MZM, variation of the D.C. bias to the MZM results in a variation in the BER. We show that the non-linearity introduced by the MZM has a significant impact on the magnitude of the Intermodulation Distortion products. In the same vein, it will be shown that with a fixed bias to the MZM, a variation in the amplitude of the driving OFDM signal will result in a variation in the BER.

2. System Setup

Figure 1 shows the system setup used for the simulations. The simulations are carried out in OPTSIM, with the electrical OFDM signal generated using the MATLAB custom component module supplied in OPTSIM (indicated as OFDM Tx. in Figure 1). Since intensity modulation is required, the OFDM signal has to be real-valued. To generate this real-valued signal, the input vector to the IFFT module in the OFDM transmitter is constrained to have Hermitian symmetry [7], whereby the first half of the input to the IFFT module contains the baseband modulated symbols while the second half of the input is made up of the complex conjugates of these symbols.

The electrical OFDM signal is generated using 4-QAM modulation with 64 data-carrying subcarriers. In order to guarantee the Hermitian symmetry and ensure that there are guard bands on either side of the OFDM subcarrier band, a Fast Fourier Transform (FFT) size of 512 and a cyclic prefix length of 128 are used. The generated electrical OFDM signal has a bandwidth of 2.5 GHz.

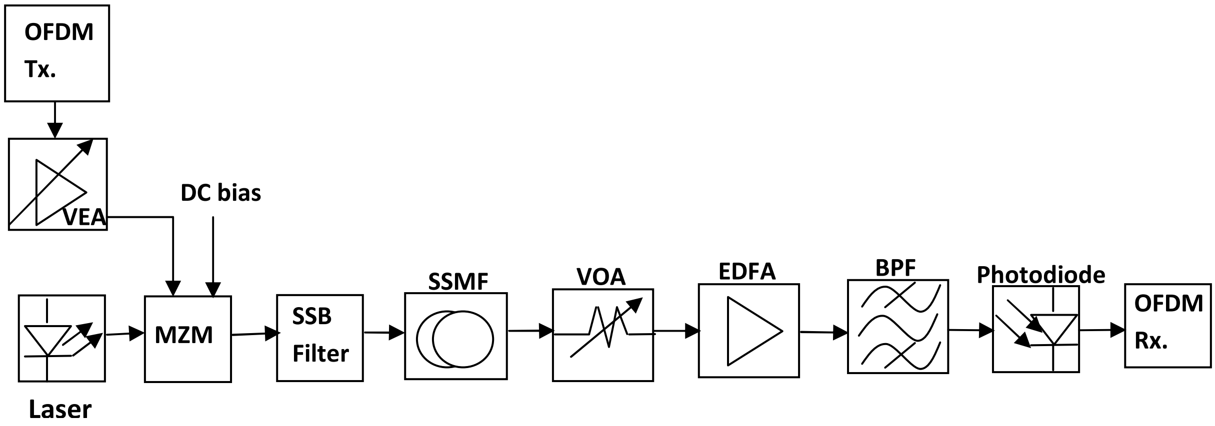

Fig.1: Direct-Detection Optical OFDM setup

Consequently, with these simulation parameters, the data rate of the generated electrical OFDM signal is 4 Gb/s. A variable electrical attenuator (VEA) is placed at the output of the OFDM transmitter to allow variation of the amplitude of the electrical drive to the MZM. A double-sideband optical OFDM signal is generated at the output of the MZM. To prevent sideband cancellation due to chromatic dispersion when the optical signal impinges on the photodiode, one of the sidebands of the optical OFDM signal is filtered off using a 7-GHz Single Sideband (SSB) filter [7]. The optical OFDM signal is sent through 140km of Standard Single Mode Fibre (SSMF) and amplified appropriately using an Erbium Doped Fibre Amplifier (EDFA). The receiver OSNR is tuned by varying the attenuation of the VOA in steps of 1 from 1 dB to 10 dB. A 10-GHz raised-cosine optical filter is placed at the output of the EDFA to carry out Amplified Spontaneous Emission (ASE) noise filtering before the OFDM signal is directly detected by a PIN Photodiode.

3. Simulation Results

For the simulation, 128000 bits are transmitted, resulting in 1000 OFDM data symbols. A training symbol of a known bit sequence is inserted every 20 data symbols to carry out equalisation of the received symbols. We first fix the amplitude of the driving OFDM signal and vary the D.C. bias to the MZM, V_b from the most linear point, the quadrature point, to V_π, the null point. It should be noted that $V_b = \frac{V_\pi}{2}$, and V_π is the voltage required to switch the MZM off. V_π is chosen to be 10v for all simulations. As the value of V_b is increased and approaches V_π, the power of the optical carrier reduces, implying more power in the optical OFDM sideband and consequently, better SNR.

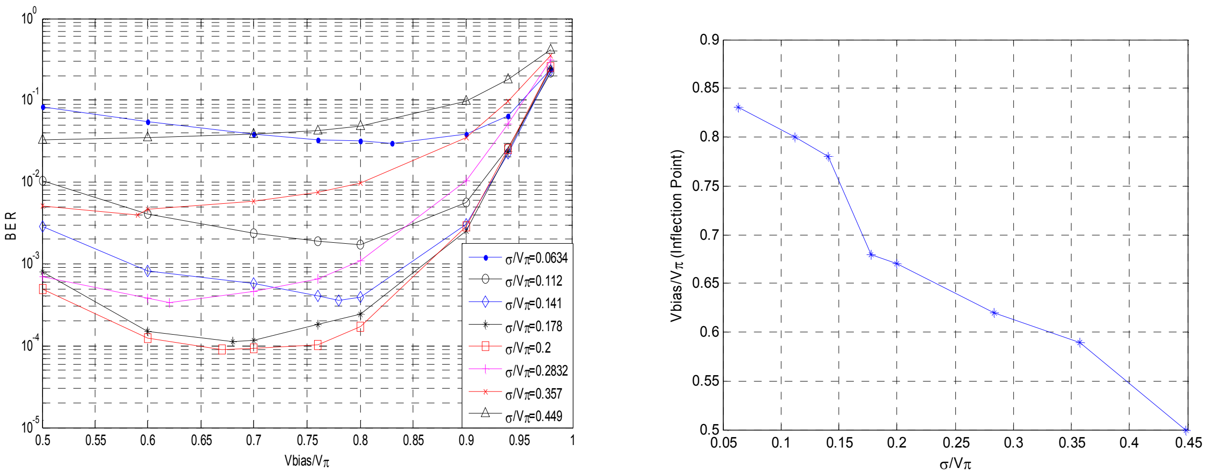

Fig. 2 (a): BER vs. V_b/V_π for different values of normalised standard deviation σ of the driving OFDM signal.

(b): Inflection point vs. V_b/V_π for different values of normalised standard deviation σ of the driving OFDM signal

Since the amplitude distribution of the driving OFDM signal is approximately Gaussian, its r.m.s voltage equals the standard deviation [8]. Using the VEA, we attenuate and later amplify the driving OFDM signal to obtain different values of standard deviation. For each value of normalised standard deviation (σ/V_π), we plot the Bit Error Rate (BER) against varying values of the normalised bias (V_b/V_π) as shown in Figure 2(a). For each of the curves in Figure 2(a), we can see that the Bit Error Rate (BER) reduces with increasing values of V_b until it gets to a point, the so-called inflection point, when it starts to increase. At this inflection point, the signal begins to suffer distortion due to the non-linear characteristic of the MZM. Figure 2(b) shows that this inflection point is dependent on the amplitude of the driving electrical OFDM signal. The higher the amplitude of the driving signal, the sooner the non-linearity is encountered and the lower the inflection point. For a standard deviation of the driving signal equal to 0.0634, the inflection point is around 0.83, compared to a lower inflection point of 0.59 when the standard deviation is increased to 0.357.

Figure 3 shows the spectrum of the received electrical OFDM signal. Here, for a fixed value of normalised standard deviation of the driving signal equal to 0.199912, when the MZM is biased at the non-linear portion of the MZM characteristics (normalised bias value of 0.9), the amplitude of the Intermodulation distortion products is much larger than when the MZM is biased at quadrature with a normalised bias of 0.5.

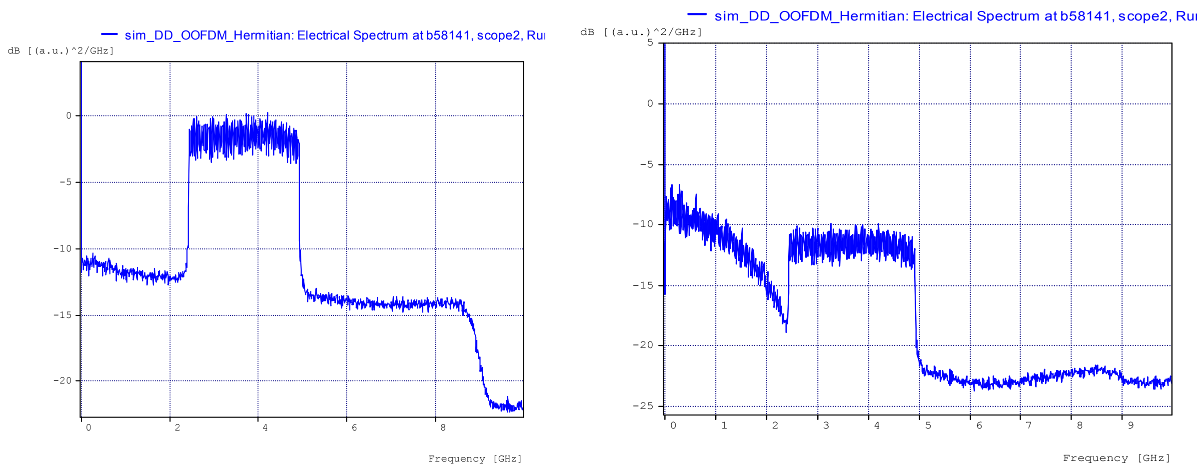

Fig. 3 (a): Received Electrical spectrum for V_b/V_π = 0.5 with normalised standard deviation (σ/V_π) of 0.199912.

(b): Received Electrical spectrum for V_b/V_π = 0.9 with normalised standard deviation $(\sigma/V_\pi)$of 0.199912.

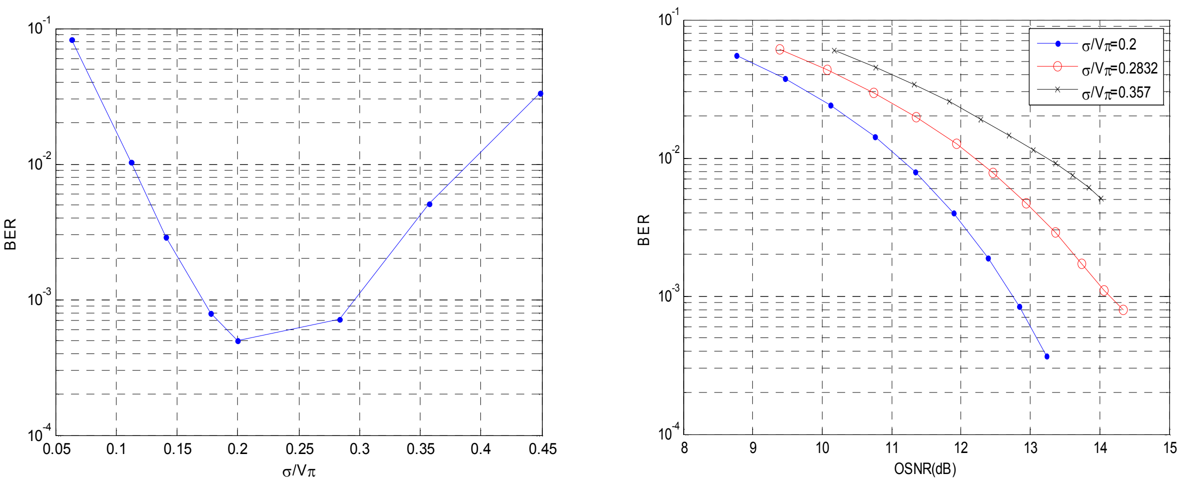

Fig. 4 (a): BER vs. normalised standard deviation $(\sigma/V_\pi)$for fixed normalised bias $(V_b/V_\pi)$of 0.5

(b): BER vs. OSNR for different values of normalised standard deviation (σ/V_π) of driving signal and fixed normalised bias (V_b/V_π) of 0.5

Conversely, we fix the bias and then increase the drive to the MZM. For each value of drive, we obtain the BER. Figure 4(a) shows us a plot of the BER against normalised drive for a fixed normalised bias of 0.5. For very low drive values, the BER is high because there isn't enough power in the OFDM sideband compared to the optical carrier. However, as the amplitude of the drive is increased, there is now more power in the OFDM sideband and the BER reduces up to the inflection point and then starts to increase. This is because for very high drive amplitudes, the driving signal encounters the non-linear part of the MZM characteristic and suffers significant non-linear distortion, resulting in increased BER. This is confirmed in Figure 4(b) where the plot of the BER against the Optical Signal-to-Noise Ratio (OSNR) for different values of normalised MZM drive shows that for a particular value of OSNR, for instance 12 dB, the BER increases as the drive amplitude increases. The BER is 0.0034, 0.0117 and 0.0227 for values of normalised standard deviation of the driving signal equal to 0.2, 0.2832 and 0.357 respectively. This is because for normalised drive values of 0.2832 and 0.357, the OFDM signal has already started encountering the non-linear portion of the MZM characteristics, resulting in increased BER. Consequently, with the fixed value of bias, provided the non-linear distortions do not cause significant degradation, as the drive is increased, the receiver sensitivity increases.

4. Conclusion and Future Work

This paper has studied the impact the non-linearity of the MZM characteristic has on the BER of a direct-detected optical OFDM signal. We have clearly illustrated that the bias point of the MZM as well as the amplitude of the drive to the MZM have significant impacts on receiver sensitivity. So, with proper biasing and selection of appropriate drive to the MZM, the receiver sensitivity can be improved. For future considerations, the number of subcarriers and the modulation scheme will be varied to see how a variation in these parameters influence the non-linear distortion caused by the MZM.

5. References

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