Subcarrier Selection for IM/DD OFDM Systems

Henning Paul, Karl-Dirk Kammeyer

Department of Communications Engineering, University of Bremen, 28359 Bremen, Germany,
✉ paul@ant.uni-bremen.de, ✉ kammeyer@ant.uni-bremen.de

Abstract *Subcarrier selection mitigates the need for suppression of one sideband at the transmitter side for Intensity Modulation/Direct Detection OFDM systems caused by group velocity dispersion of the fiber and thus reduces optical hardware efforts.*

Introduction

In recent years, Orthogonal Frequency Division Multiplexing (OFDM) has been proposed for high-speed transmission over optical fiber due to the ease of equalization of the group velocity dispersion dominated optical channel. These efforts can be separated into two different approaches: Coherent optical systems[1] are as well subject of investigations as Intensity Modulation/Direct Detection (IM/DD) systems[2]. There also exists a hybrid approach with complex valued modulation at the transmitter but Direct Detection at the receiver[3] - this approach shall be numbered among the IM/DD systems, since it shares the advantage that no local laser at the receiver is needed.

IM/DD systems have the advantage of a lower optical hardware complexity and shall be the subject of this work. These systems, however, require the suppression of one sideband of the double sideband transmit signal in order to avoid power fading, which causes severe signal distortions[4,5]. OFDM is often praised for its ability to equalize frequency selective channels, but another advantage is the ability to treat every subcarrier separately: In wireless and wireline applications, it is common practice to apply different powers and modulation alphabets to different subcarriers in dependence on the channel transfer function, which is known as "power loading" or "bit loading", respectively. In digital subscriber line (DSL) circuits subcarriers are omitted if they suffer from strong external interference (or might cause interference to others). This technique is now applied to optical Double Sideband (DSB) transmission, where only the OFDM subcarriers with channel coefficients above a certain threshold are used for data transmission and the others are omitted. This technique shall be called "subcarrier selection" in the following.

System model

The equivalent baseband transfer function[6] of a DSB optical IM/DD system can be described by

$$\tilde{H}(j\omega) = H_0 \mathrm{e}^{-j\tau\omega} \cos(b_2\omega^2), \qquad (1)$$

which exposes zeros at $\omega = \pm\sqrt{\nu\pi/b_2 + \pi/(2b_2)}$, $\nu \in \mathbb{N}$, i.e. with decreasing spacing. This transfer function is evaluated at frequency positions $n \cdot 2\pi\Delta f$ for N_c subcarriers $n = 0 \ldots N_\mathrm{c} - 1$, while the subcarrier spacing Δf is gained from the relation

$$\Delta f = \frac{1}{T_\mathrm{c}} = \frac{R}{\eta_\mathrm{S} \cdot \eta_\mathrm{CP} \cdot \log_2 M \cdot N_\mathrm{c}}, \qquad (2)$$

with T_c being the OFDM core symbol duration, R the desired bit rate, M the modulation alphabet size, η_S the subcarrier selection ratio and η_CP the efficiency loss caused by the cyclic prefix. The left plot in Fig. 1 shows the magnitude of the estimated channel coefficients for a DSB IM/DD system with 1023 independent subcarriers (the DC carrier is unused), $\eta_\mathrm{CP} = 0.8$, 42.8 Gb/s bit rate and 80km of SSMF using QPSK modulation in the noise-free case sorted in descending order, the right plot shows a histogram of the magnitudes. The channel estimation has been averaged over 32 least squares estimations with different, random training symbols. The Mach-Zehnder modulator (MZM) was operated in the quadrature point, the OFDM signal was scaled to a standard deviation of $\sigma = 0.2V_\pi$ and clipped in the turnaround points of the MZM's characteristic.

The distribution of channel coefficients shows that

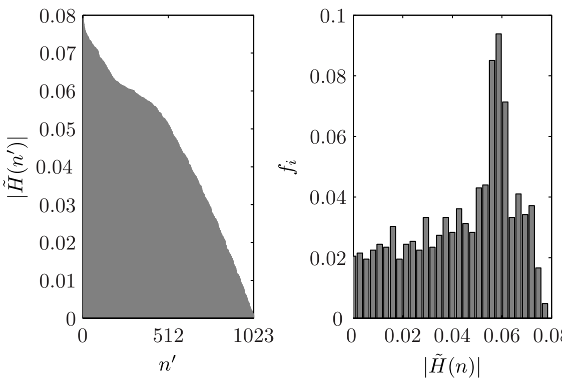

Fig. 1: Estimated channel coefficients: Magnitudes in descending order (left), histogram of magnitudes (right).

the largest 50% of the channel coefficients have a magnitude which is suitable for data transmission and don't cause an overly large SNR loss. Fig. 2 verifies this assumption: The resulting average bit error rates of a DSB IM/DD system with $N_\mathrm{c} = 2048$ and 256, 512 and 768 information bearing subcarriers chosen out of 1023 independent subcarriers, corresponding to $\eta_\mathrm{S} = 0.25, 0.5, 0.75$. The bit rate was fixed to 42.8 Gb/s, $\eta_\mathrm{CP} = 0.8$ was chosen, QPSK was used for transmission over 80km of SSMF. It can be seen that $\eta_\mathrm{S} = 0.25$ and $\eta_\mathrm{S} = 0.5$ perform similarly, with a slight advantage

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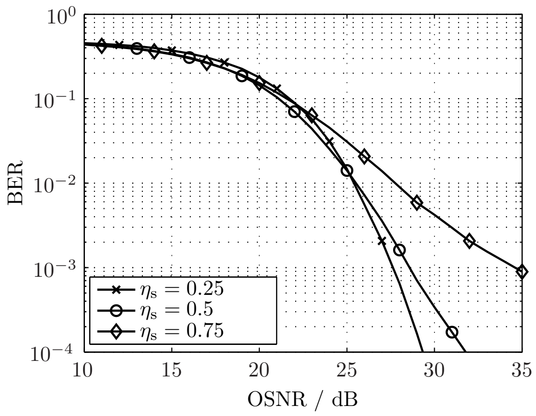

Fig. 2: Bit error rates for $\eta_S = 0.25, 0.5, 0.75$

for $\eta_S = 0.25$, while $\eta_S = 0.75$ requires a significantly higher OSNR at a BER of 10^{-3}. Because of the better bandwidth efficiency, $\eta_S = 0.5$ would be preferred in a practical system.

Note that (1) is a linear phase transfer function, which means that with phase shift keying (PSK) modulation on the subcarriers, no equalization is required if synchronization is established – apart from a phase offset common to all subcarriers.

Operation point dependency

In order to decrease the OSNR requirement for a BER of 10^{-3}, the bias and standard deviation of the modulator input are varied. Previous investigations[7,8] showed that a bias of $0.7V_\pi < V_{\text{bias}} < 0.9V_\pi$ and a standard deviation of $0.2V_\pi < \sigma < 0.3V_\pi$ represented the best tradeoff between received signal power and interference in the electrical domain. In Fig. 3, using $\eta_S = 0.25$

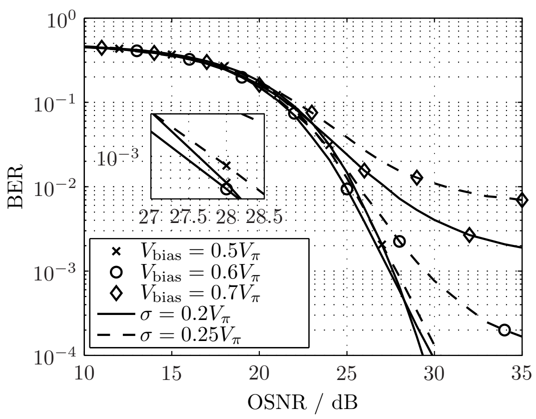

Fig. 3: Bit error rates for different biases and standard deviations

the bias was varied from $V_{\text{bias}} = 0.5V_\pi$ to $0.7V_\pi$, for both $\sigma = 0.2V_\pi$ and $\sigma = 0.25V_\pi$, but in the interesting region of BER=10^{-3}, best performance is achieved for $\sigma = 0.2V_\pi$ and $V_{\text{bias}} = 0.6V_\pi$, with only a small advantage over $V_{\text{bias}} = 0.5V_\pi$, i.e. biasing in the quadrature point. For larger standard deviations and biasing outside of the quadrature point, the system becomes interference limited, as can be seen by the error floors developing for $V_{\text{bias}} = 0.7V_\pi$.

Subcarrier selection with guard band

In connection with SSB modulation, a spectral offset of the information carrying band from the carrier has been proposed[3], a guard band into which the intermodulation products between the subcarriers are falling. A similar technique can also be applied in combination with subcarrier selection: E.g. for $\eta_S = 0.25$, the 256 subcarriers with largest coefficient magnitude are not selected out of all 1023, but only out of the upper 512; the lower 512 subcarriers (including the DC subcarrier) are unused. Fig. 4 shows the bit error rates for a sys-

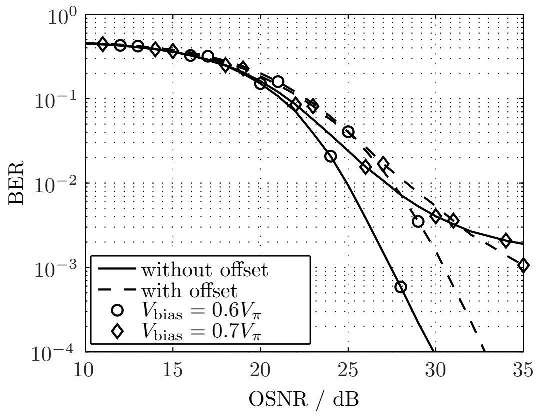

Fig. 4: Bit error rates with and without spectral offset for different biases

tem with identical parameters as above, $\sigma = 0.2V_\pi$ and $\eta_S = 0.25$ with and without use of a spectral offset. From the error floor behaviour of $V_{\text{bias}} = 0.7V_\pi$ for OSNR larger than approximately 30dB, it can be seen that the spectral offset reduces the interference caused by intermodulation, but at the price of an OSNR loss. This is caused by the fact that the subcarriers selected out of 512 in average have a smaller coefficient magnitude than if selected out of 1023.

Conclusions

We have shown that at the expense of an OSNR loss and increased bandwidth, the need for optical sideband suppression can be circumvented by subcarrier selection. As a by-product, equalization is simplified due to the linear phase nature of the equivalent baseband channel.

As a perspective for future work, subcarrier selection allows the usage of unused subcarriers for reduction of the peak-to-average-power-ratio and thus reducing the effects of clipping.

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