Experimental Investigation of Bit and Power Loading in 10 Gbit/s Next Generation Optical OFDM Access Networks

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***Abstract*— Orthogonal frequency division multiplexing (OFDM) based passive optical networks (PON) is a possible candidate for next generation optical access (NGOA) where due to cost constraints most likely intensity modulation (IM) and direct detection (DD) will be used. In combination with the dispersive optical channel it will result in a frequency selective system if double sideband (DSB) instead of the commonly employed single sideband (SSB) modulation is used. We will show experimentally that using bit loading (BL) and power loading (PL) can obviate the need for an optical single sideband filter (SSBF) therefore reducing the hardware expense in the cost sensitive access network.**

***Index terms*— OFDM, bit loading, power loading, EVM, DMT, SSB, DSB, PON**

I. Introduction

Due to an efficient equalization and high bandwidth efficiency orthogonal frequency division multiplexing (OFDM) has become an accepted technique in optical communication systems [1]. This paper shows the adaption of the well-known bit loading (BL) and power loading (PL) algorithms used in copper based discrete multi-tone (DMT) transmissions to an OFDM passive optical network (PON) scenario. To show the capability of BL and PL in optical transmission systems a double sideband (DSB) transmission with a dispersive optical standard single mode fiber (SSMF) of 50 km is compared to an optical OFDM single sideband (SSB) transmission system using direct detection (DD) [2]. In contrast to the established bit error ratio (BER) the error vector magnitude (EVM) is evaluated. The EVM gives more insight into the channel characteristics and converges faster in simulations and measurements without the need for error counting [3]. In addition EVM is used to estimate the signal to noise ratio (SNR) for PL purposes. Besides the implementation of BL and PL we will show that DSB transmissions can almost reach the performance of a SSB system at only a small optical signal to noise ratio (OSNR) penalty.

This paper is organized as follows: Section II gives a brief introduction into DSB transmissions with PF and section III introduces BL and PL using EVM as a figure of merit to compensate the negative influence of PF. Furthermore in section IV the used setup for simulations and measurements will be described followed by the presentation of the results. The last section will conclude this paper.

II. The Optical DSB Channel

The dispersive optical channel including DD with a single photo diode (PD) performs envelope detection according to a magnitude squared operation. The conjugate-complex allocation of the subcarriers of real valued OFDM (DMT) transmission results in nonlinear power fading. The baseband transfer function for such a dispersive channel is given by:

$$H(f) = |H_{const}| \cdot e^{-j\tau 2\pi f} \cdot e^{j \cdot b(f) \cdot L}\ , \qquad (2.1)$$

where constant phase factors and attanuation have been incorporated in the constant factor H_{const} and the phase response function $b(f)$ denotes the dispersive character of the fiber. By neglecting group and phase delay the phase response can be simplified to:

$$b(f) = -\frac{1}{2}\frac{\lambda_c^2}{2\pi c} \cdot D_1(\lambda_c) \cdot \left(2\pi f^2\right)\ . \qquad (2.2)$$

The frequency response magnitude for a power fading dispersive channel model using DD is derived by (2.3) and shown in Fig. 1:

$$\left|H(f)\right|^2 = \left|H_{const}\right|^2 \cdot \left|\cos\left(-j \cdot \frac{\lambda_c^{\ 2}}{c} \cdot D_1 \cdot L \cdot \pi f^2\right)\right|^2\ , \qquad (2.3)$$

where L stands for the fiber length (50 km) and D describes the dispersion coefficient (17 ps/nm/km for SSMF) [2].

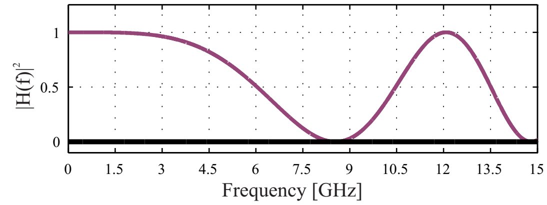

Fig. 1: Power fading described by the frequency response function in a dispersive channel between a frequency of 0 and 15 GHz for a 50 km SSMF (D = 17 ps/nm/km)

From formula (2.3) it follows that for the given parameters we have a power fading (PF) null near 8.54 GHz, i.e. in the transmission band. To remove one sideband and thereby prevent destructive interference at the receiver a SSB filter can be used [4]. The baseband transfer function for a SSB channel is generally given by:

$$H(f) = H_{const} \cdot \exp\left(-j \cdot \frac{\lambda_c^2}{c} \cdot D_1 \cdot L \cdot \pi f^2 \right), \qquad (2.4)$$

where c is the speed of light in vacuum and λ_c describes the carrier frequency. D_1 stands for the dispersion parameter first order.

In this paper we apply BL and PL concentrate on DSB. Therefore SSB generation (e.g. with an optical filter) can be omitted.

III. Bit Loading and Power Loading

EVM is a figure of merit, which describes the difference vector between the received data symbol d_{RX} and transmitted reference symbol d_{TX}. This vector is typically measured in phase and magnitude given by:

$$EVM(i) = \left| IQ_{err,i} \right| = \sqrt{I_{err,i}^2 + Q_{err,i}^2}\ , \qquad (3.1)$$

where i indicates the subcarrier. The general EVM evaluation is depicted in Fig. 2.

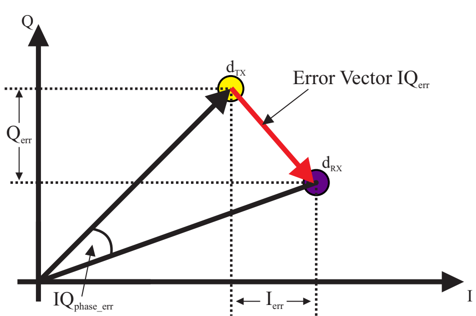

Fig. 2: Error Vector Magnitude

EVM is typically given by the root mean square (RMS) operation over the measured symbols. If we assume a channel with Gaussian noise we can approximate the SNR from the EVM [5]:

$$SNR \approx \frac{1}{EVM^2} \qquad (3.2)$$

This estimation results in a carrier to noise ratio (CNR) for each subcarrier and can be used to distribute the power according to formula (3.3) or other commonly known optimization algorithms:

$$PL_{dB}(i) = 20 \cdot \log_{10}\left(\frac{\sum_{k=1}^{N} CNR(k)}{N} - CNR(i) \right) \qquad (3.3)$$

Utilisation of formula (3.3) results in the equal CNR for each subcarrier and therefore the same BER can be expected for each one. BL algorithms can be used to optimize data rate and / or transmission quality, due to an efficient allocation of transmitted bits per symbol to the subcarriers. An efficient allocation can generally be optimized to the following three criterias [6]:

1. Minimizing BER (constant bit rate and power),
2. Maximizing bit rate (constant power, target BER),
3. Minimizing power (constant bit rate, target BER).

By utilizing a BL scheme for transmission the allocation of power has to be corrected accordingly. In this paper BL is used to compensate the skipped subcarriers due to the power fading discribed in section II by allocating the same amount of bits to the less used subcarriers and bandwidth. PL is used to adjust the SNR to achieve equal BER for the used subcarriers and the therefore minimization of the used OSNR. The OSNR is a common figure of merit in optical communication systems and measured with respect to a fixed filter bandwidth of 0.1 nm.

IV. Measurements and Results

A. *System Model*

A PON scenario over 50 km SSMF is used and depicted in Fig. 4. The OFDM waveform is generated by offline digital signal processing (DSP) and fed to the high speed 10 GS/s digital to analog converter (DAC). Additional lowpass filters (LPF) are used to reduce the aliasing. The inherent magnitude squared operation nonlinearity due to the envelope detection of the PD in a DD optical receiver results in intermodulation products within the OFDM band depicted in Fig. 3.

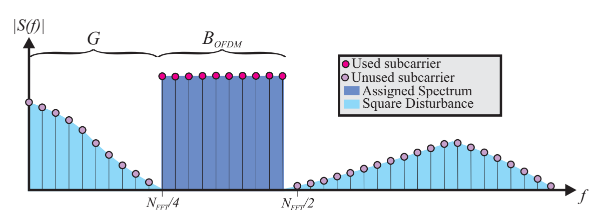

Fig. 3: OFDM bandwidth allocation with direct detection and MZM

Therefore a frequency gap G between the carrier and the OFDM band with a size equaling the used OFDM bandwidth B_{OFDM} is introduced, such that intermodulation products fall into this gap and the OFDM band is undistorted by intermodulation [7]. To realize the required gap an electrical Inphase-Quadratur-Modulator (IQM) transforms the complex valued electrical OFDM baseband signal to a real valued bandpass signal, using a local oscillator (LO). A Mach-Zehnder-Modulator (MZM) in push-pull mode is used to modulate the intensity of a DFB laser source emitting at 1539.69 nm. The resulting optical DSB signal is transmitted over 50 km SSMF. Furthermore a transmission with sideband supression using a tunable optical bandpass filter is realized to compare the DSB results with a SSB system.

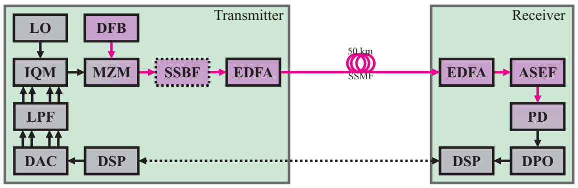

Fig. 4: Simplified measurement setup for a 50 km PON scenario with optional single sideband filter (dashed)

At the transmitter side an erbium doped fiber amplifier (EDFA) is used to compensate for the modulation loss and to boost the optical power for transmission. For the purpose of noise loading another EDFA is added at the receiver side. An addionally integrated optical bandpass filter is used to filter the noise caused by amplified spontaneous emission (ASE) from the EDFAs. The signal is directly detected by a photo diode (PD) and recorded with a 50 GS/s real time sampling oscilloscope for offline processing. The OSNR was varied at the receiver and in addition to the EVM meassurements the bit errors were counted for the different scenarios.

B. System Parameters

To transmit 10.3 Gbit/s 610 subcarriers realized by an IFFT with the length N_{FFT} of 1024 were used. Two symbols are used for synchronization according to Schmidl & Cox [8] and the equalizer (EQ) is trained by four reference symbols out of 30 data and the two synchronization symbols. The OFDM data subcarriers are allocated between 6 and 12 GHz and a gap from DC to 6 GHz has to be utilized. Therefore the LO is set to 9 GHz. The MZM is biased with 0.9 V_π and fed by a signal with a standard deviation of 0.1 V_π. The signal is clipped at 0.4 V_π in digital domain to avoid a high peak to average power ratio (PAPR). The application of linearization in terms of the cosine-shaped characteristic was renounced.

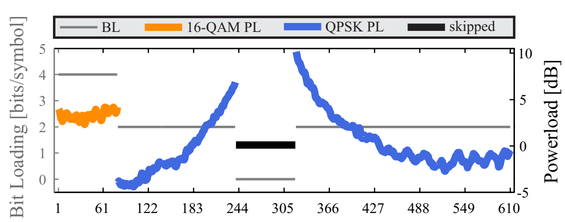

Fig. 5: BL and PL scheme for 610 used subcarriers for DSB transmission

Before measuring the BL scheme for the DSB transmission the PL schemes for the SSB and DSB transmission (depicted in Fig. 5) have to be extracted from the recorded EVM. Carriers exceeding an EVM of 0 dB (100%) are skipped, e.g. carriers 240 to 320 because of the excessive influence of PF. The threshold of 0 dB is choosen by experimental investigation. Therefore to transmit the same bitrates as in the QPSK SSB transmission the subcarriers with the lowest EVM (1 to 80) are loaded with a 16-QAM modulation format. Looking at the EVM after BL and before PL (magenta curve depicted in Fig. 6) the influence of the PF near the nulled subcarriers can be clearly noted.

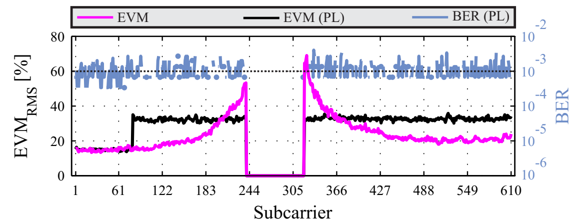

Fig. 6: Transmission performance by the mean of EVM and BER with and without PL / BL

C. Results

Applying the PL scheme (Fig. 5) calculated from the estimated CNRs from measured EVM the influence of the PF can be reduced (black) and the EVM can be set to the same level on all subcarriers with the same modulation format. The uniform BER reached by PL is given by the blue curve. To evaluate the achieved performance of the proposed scheme we measured the SSB transmission for comparison. According to earlier results [2], it was implemented using the optical bandpass filter. Additionally a SSB transmission using PL was also measured. The results of the different cases are depicted in Fig. 7, where the BER is plotted over the OSNR.

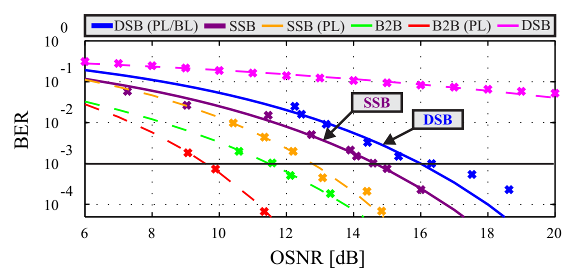

Fig. 7: BER vs. OSNR comparison of the different scenarios

The SSB transmission is superior to DSB with respect to the required OSNR for a BER of 10^{-3} and by using PL can be improved even further. On the contrary using a DSB modulation on its own does not enable a transmission. But introducing BL and PL and inserting nulls for the subcarriers near 8.54 GHz permits a transmission. A power change for a subcarrier results in nonlinear effects to all other used subcarriers. Practically these effects can be mitigated iteratively by an adaptive power loading scheme estimation. After about five optimization iterations of the PL algorithm a penalty of only 1.75 dB at a BER of 10^{-3} compared to the SSB transmission was achieved.

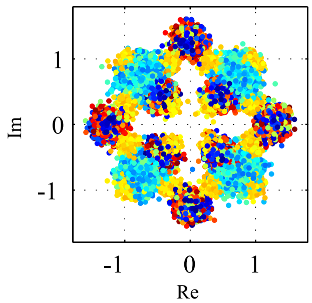

Fig. 8: Received constellation at increased bit rate of 15.9 GBit/s, 720 used subcarriers modulated with QPSK, 8-QAM and 16-QAM and SSB transmission

BL and PL is used not only to compensate PF but also to maximize datarate (as introduced in section III). By using 110 subcarriers more in the SSB system the datarate can be improved even further to about 15.9 GBit/s. The subcarrier expansion leads to more used bandwidth and by optimizing the bit loading scheme the spectral effiency is also improved. Hereto the electrical LO is set to 10.5 GHz to use the spectrum between 7 and 14 GHz. According to the given EVM the first 71 carriers are modulated with 8-QAM, the carriers 72 to 144 with 16-QAM, the carriers from 145 to 519 are modulated with 8-QAM as well and the last 100 carriers getting only a QPSK modulation. Fig. 8 shows the constellation at the receiver after equalization of all 720 used subcarriers. For this datarate improvement the BER is $5.57 \cdot 10^{-4}$ for an OSNR of 25.9 dB and a datarate of 15.9 GBit/s.

V. Conclusions

It was experimentally shown that using BL and PL by utilizing the EVM as figure of merit PF could be mitigated. It turned out that EVM is a convenient tool to meassure channel characteristics for OFDM transmission system. Even IQM imbalances could be mitigated using EVM as figure of merit.

Accepting an OSNR penalty of 1.75 dB makes a reduction in hardware effort possible, thereby further approaching the goal of a cost efficient PON for NGOA.

VI. References

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