Signal Processing in High-Speed Optical Communications and Impact on Electronic Subsystems

W. Rosenkranz, C. Hebebrand, A. Ali

Chair for Communications, University of Kiel
Kaiserstr 2
24143 Kiel, Germany

***Abstract*-The paper addresses modern design of optical communications transceivers for handling impairments of the optical high-speed long distance channel based on a digital signal processing approach. Electronic equalizers, advanced modulation formats, and optical OFDM transmission are considered.**

I. Introduction

Electronic signal processing is currently introduced in various subsystems of modern optical high speed transceivers. Traditionally electronic processing was basically limited to tasks like MUX/DEMUX, clock and data recovery and various synchronization loops as well as analog circuitry like modulator drivers or limiting amplifiers. In order to deal with advanced systems and with the need for improved performance at long reach and higher speed, additional signal processing requirements have appeared. Examples are FEC and electronic equalizers (EDC), electronic pre-compensation, differential encoders, clock and carrier recovery, and polarization control. Recent challenges employ pure digital processing, where ADCs and DACs are required, like OFDM (orthogonal frequency division multiplexing) modulation or MLSE (maximum likelihood sequence estimation) equalizers.

In this paper some of these signal processing algorithms, which may be used in advanced future optical communication systems are considered in detail and their impact on performance and cost in terms of implementation effort is reviewed. We also address the hardware challenges in terms of the subsystems needed, their complexity, and their necessary performance. One example is the characterization of the ADC-specifications required for successful operation of OFDM receivers.

II. Transmissiion Scenarios and Channel Impairments

A typical system setup for a high-speed optical WDM transmission network is shown in fig. 1. Whereas the link design is usually fixed and is in many cases designed for 10Gb/s on-off-keying (OOK) modulation with direct detection. For system upgrades the transmitter and receiver design may be optimized. Recent challenges arise as it comes to the transmission of 100Gb/s Ethernet data over a 100GHz or even 50GHz WDM grid on a link designed for the 10Gb/s data rate with standard single mode fiber (SSMF), dispersion compensation fiber (DCF), optical amplifiers and optical filtering.

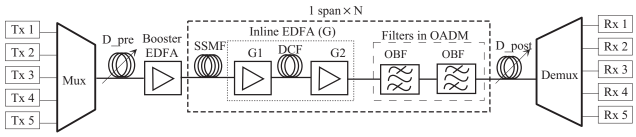

Fig. 1. WDM multi-span system setup.

The channel impairments which are considered are: chromatic dispersion (CD), nonlinear Kerr effect, influence of excess filtering (narrow bandwidth and phase response ripples), and polarization mode dispersion (PMD), noise effects, including nonlinear phase noise, and intermodulation effects due to the multiwavelength WDM.

III. Design and Performance of Traditional Equalizers for Various Modulation Formats

It is now quite common to use electronic equalizers for compensating for channel impairments. Both, FIR-filter based equalizers and sequence estimators (MLSE) are in commercial use at least for 10Gb/s systems. However the degree of performance gain depends heavily on the modulation format that is used.

Fig. 2 shows an electronic equalizer system with feed-forward and decision feedback structure, both based on FIR-filters, and both extended to nonlinear operation derived from Volterra series expansion [1].

As an example we show the performance of several such equalizer structures in the presence of chromatic dispersion in fig. 3 and fig. 4 for the conventional OOK and for optical single sideband (OSSB) modulation, respectively. As direct detection is considered, for OOK the loss of phase information, due to the magnitude squared operation of the photo detector, results in limited equalizer performance and only the nonlinear Volterra equalizer or the MLSE may mitigate partly this nonlinearity. However for OSSB it can

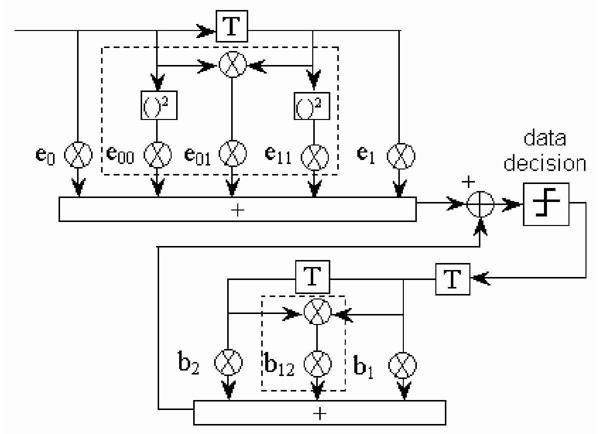

Fig. 2. Nonlinear extension of electronic FFE and DFE equalizer.

be shown, that the channel impairments like chromatic dispersion result in much less overall nonlinear distortions and primarily in linear distortions that can be mitigated by simpler linear equalizer design.

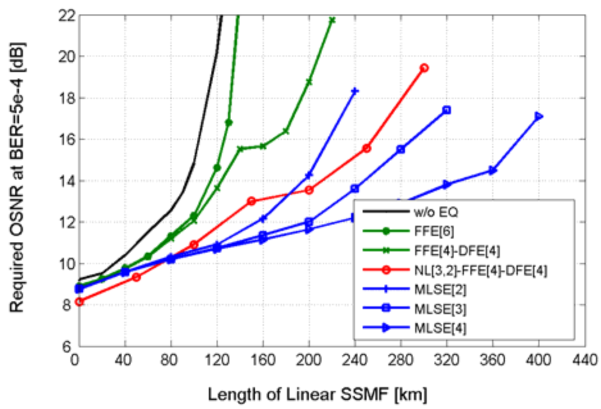

Fig. 3. Performance of various equalizers in a 10 Gb/s OOK modulated system

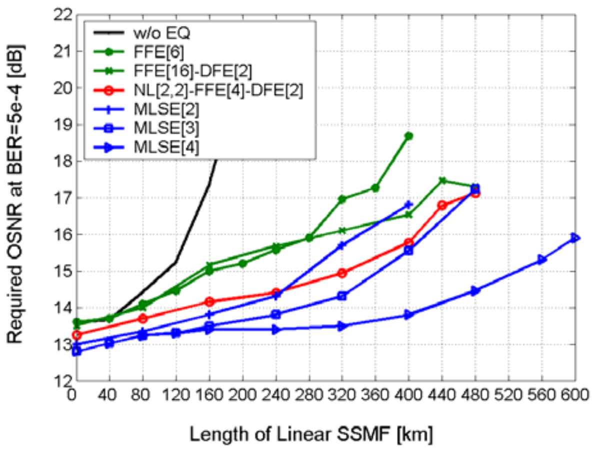

Fig. 4. Performance of various equalizers in a 10 Gb/s OSSB modulated system

IV. Electronic Equalizers in Coherent PSK-Receivers for Multilevel Modulation

In a second part we investigate electronic equalization in coherent receivers in combination with multi-level modulation and nonlinear fiber effects. The next bitrate in the Ethernet hierarchy is expected to be 100Gb/s, which results in 107…112Gb/s transmission data rate on the optical layer, as redundancy from FEC is considered. For this bitrate, multi-level modulation formats should be used to reduce the bandwidth requirements [2]-[4]. In conjunction with a coherent receiver, the multi-level formats can be demodulated in the electrical domain with digital signal processing (DSP), due to the availability of high-speed digital signal processors. Similarly carrier and phase recovery as well as the equalization can be achieved with DSP [5].

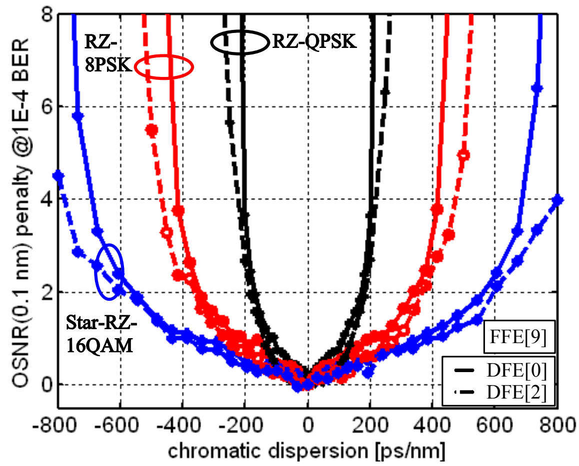

Fig. 5. Performance of a 9-tap linear equalizer for various multilevel modulation formats with coherent receiver at 107Gb/s assuming linear fiber (low launch power)

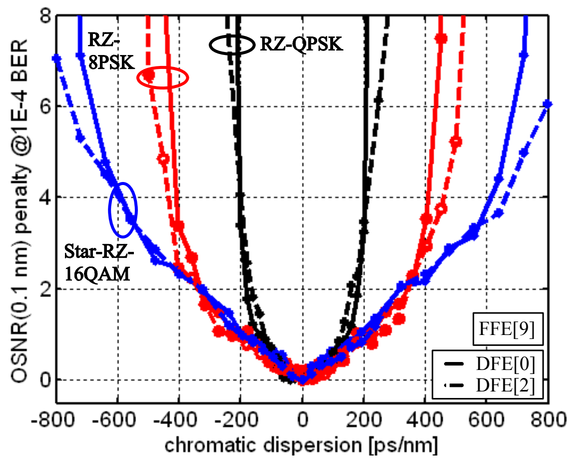

Fig. 6. Performance of a 9-tap linear equalizer for various multilevel modulation formats with coherent receiver at 107Gb/s, nonlinear fiber (5dBm launch power)

We propose a post detection equalizer design for complex multi-level modulation and coherent I/Q-detection. We investigate numerically the performance of electronic dispersion compensation (EDC) after coherent reception for RZ-QPSK, RZ-8PSK and Star-RZ-16QAM [2] at 107Gb/s for the linear and nonlinear (Kerr effect) channel. EDC is achieved by a zero-forcing (ZF) approach, using the minimum mean-square error (MMSE) criterion to derive the coefficients. We investigate the performance in terms of dispersion tolerance by Monte-Carlo simulations [2]. Results are summarized in fig. 5 for the linear low launch power input and for the nonlinear case with 5dBm launch power in fig 6. We conclude that even a 9 tap linear equalizer is well suited to compensate most of the CD. Also the nonlinear distortions are well mitigated as long as we consider pure phase shift keying (RZ-QPSK, RZ-8PSK). However for the Star-RZ-16QAM format (with additional amplitude modulated component) we conclude that the nonlinear resistance is poor. This is a result of the influence of nonlinear phase noise [2]

V. OFDM Modulation and Impairment Mitigation

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 [6-11] because OFDM can combat fiber chromatic dispersion [8] and has the inherent capability to use higher level modulation formats to increase spectral efficiency.

OFDM has been introduced in wireless communications mainly in order to easily combat the frequency selective fading wireless channel. Also in optical communications we can make use of the same concept. By considering the channel frequency response being approximately frequency independent over the narrow bandwidth of each OFDM subchannel, a simple "one-tap"-equalizer for each subchannel will be sufficient.

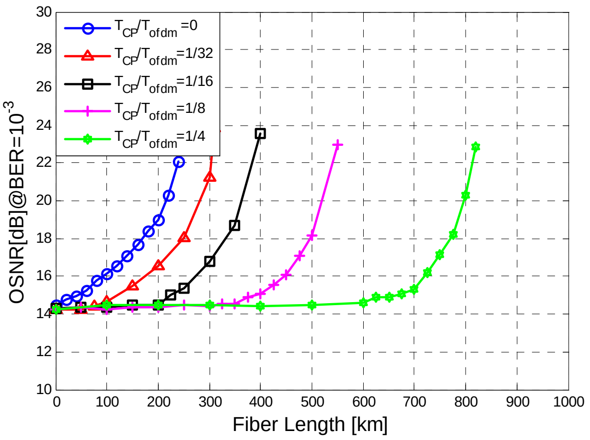

Fig. 7. Dispersion tolerance of optical OFDM transmission over SSMF with OFDM 1-tap equalizer and for various lengths of the guard interval. Data rate is 42.8Gb/s, 512 subcarriers, QPSK modulation.

In OFDM not only the simple equalizer, but also a guard-interval between the OFDM-symbols is required due to the channel memory. We show in fig. 7 the influence of guard-interval length and various other design parameters on the performance of OFDM for mitigating channel impairments, both for linear as well as nonlinear distortions.

Optical OFDM (OOFDM) itself offers different options for implementation. The demodulation can be realized either by means of direct detection (DD) or coherent detection (CO) using a local oscillator. 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 [6]. An alternative approach to overcome this limitation is the direct detection optical OFDM (DD-OOFDM) which is investigated here and shown in fig. 8. DD-OOFDM is combined with a single-sideband format (SSB-DD-OOFDM) [8]. In addition, in DD-OOFDM, a spectrally-inefficient frequency guard-band of width Wg between the optical carrier and the data signal, with a bandwidth equal to the signal bandwidth BOFDM, is typically needed to avoid the second-order intermodulation distortion near the optical carrier due to the square low photo detector [7,8]. Another issue is the nonlinearity, which is imposed by the external Mach-Zehnder modulator (MZM) [14]. The bias for the MZM has to be adjusted for optimally balancing the amount of nonlinear distortions and the carrier-to-sideband power ratio (PR).

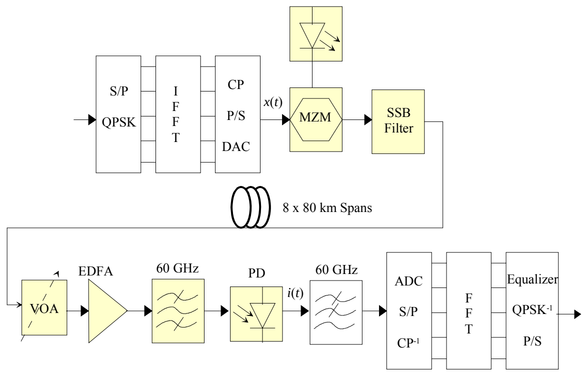

Fig. 8: DD-OOFDM Setup for 640km uncompensated 42.8Gb/s transmission

We show the dependency of the OFDM signal distortion and the receiver sensitivity on the MZM bias point. We propose a possibility of receiving the data signal with a reduced frequency guard-band. By simulation, we show that transmission of 42.8Gb/s over 640km of uncompensated standard single-mode fiber is possible.

Fig. 9 and fig. 10 show the results for back-to-back-case and for an uncompensated link of 8x80km of SSMF at 42.8Gb/s data rate. For Vbias/Vπ=0.5, a large amount of the frequency gap can be removed for the same receiver sensitivity. The increase of required Wg compared to the B2B-case is attributed to IMD. Increasing Vbias/Vπ from 0.5 towards 0.86 results in decreasing of PR and a graceful trade-off between spectral efficiency and sensitivity.

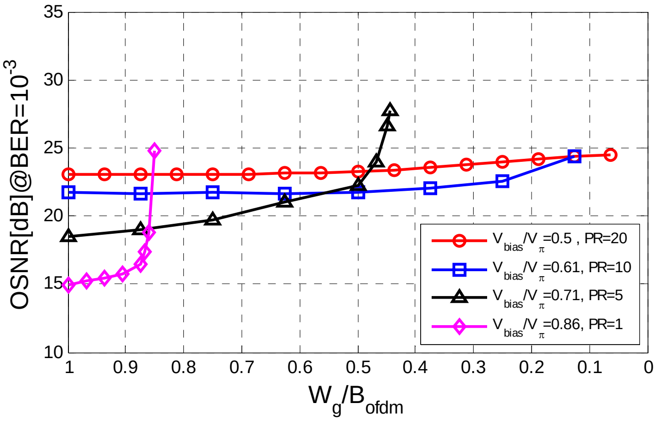

Fig. 9. Required OSNR as a function of frequency gap b2b transmission and various MZM biasing conditions.

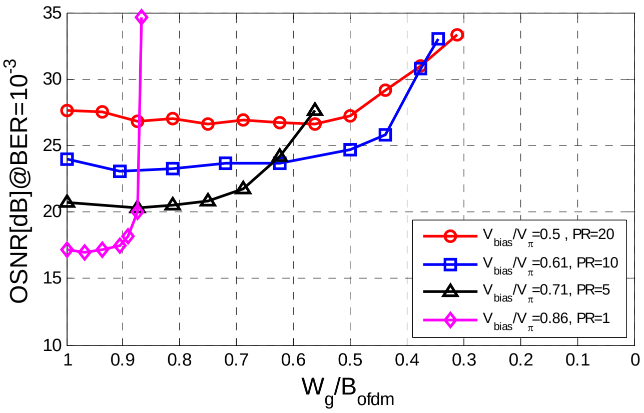

Fig. 10. Required OSNR as a function of frequency gap for 8x80 km SSMF and various MZM biasing conditions.

VI. Conclusions

We show how mitigation of optical channel impairments can be achieved by robust design of the overall transmission system. Apart from the direct use of subsystems like equalizers, many other design considerations may help to optimize the overall system resistance. We show that the choice of the modulation format is an important design issue in that respect.

Acknowledgment

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