Available online at www.sciencedirect.com
ScienceDirect
Int. J. Electron. Commun. (AEÜ) 63 (2009) 526–532
International Journal of Electronics and Communications
www.elsevier.de/aeue

Electrical and optical equalization strategies in direct detected high-speed transmission systems

Marc Bohn*, Chunmin Xia

Nokia Siemens Networks GmbH Co.KG, St.-Martin Street 76, 81541 Munich, Germany

Received 9 February 2009; accepted 31 March 2009

Dedicated to Prof. Dr.-Ing. Werner Rosenkranz on the occasion of his 60th birthday

Abstract

In this paper we give an overview of equalization technologies for adaptive compensation of dynamic distortions in high-bitrate optical transmission systems. In particular we focus on electrical and optical equalization strategies for direct detection transmission systems.

Keywords: Optical transmission; Electrical equalization; Optical equalization; FFE; DFE

1. Introduction

In today's high-bitrate transmission systems both linear and nonlinear distortions limit the system performance. The main linear distortions are chromatic dispersion (CD) and polarization mode dispersion (PMD) whereas the main nonlinear distortion is the Kerr effect of the transmission fiber. With equalization, the tolerance to these distortions can significantly be increased. However, as many distortions such as PMD are dynamic, an adaptive equalizer that automatically traces the distortions is required in order to guarantee a certain signal quality and thereby maximize the transmission distance.

Equalization can be carried out either in the electrical or in the optical domain. For direct detected transmission systems several electrical domain equalizers have been commercialized, such as the tapped delay line, decision feedback and maximum likelihood sequence estimation equalizer. The field of application for these kind of equalizers is seen from multimode fiber short links up to single mode fiber long haul links. Electrical equalizer concepts for direct detection transmission systems are reviewed and compared for different modulation formats in Chapter 2.

Although electrical equalizers offer a flexible, stable and cost-effective solution, in general they are limited in data rate due to the limitations of the electronics and the nonlinear characteristic of the photodiode. Moreover, due to the fact that with direct detection the phase and polarization information of the signal are lost, linear distortions in the optical domain turn into nonlinear distortions in the electrical domain. As a result the electrical equalization achieves generally a moderate performance improvement. In contrast to electrical equalizers, optical equalizers can use both phase and amplitude of the signal and thereby compensate more effectively for signal distortions. The adaptive optical equalization concept is discussed in Chapter 3 for a 40 Gb/s direct detected transmission system.

* Corresponding author.
E-mail addresses: marc.bohn@nsn.com (M. Bohn), chunmin.xia@nsn.com (C. Xia).

1434-8411/$ - see front matter
doi:10.1016/j.aeue.2009.03.007

2. Electrical equalization in direct detection transmission systems

In this section, an overview of four different electrical dispersion compensation (EDC) schemes will be given for direct detected 10 Gb/s transmission systems, namely feedforward equalizer (FFE), feedforward and decision-feedback equalizer (FFE-DFE), nonlinear FFE-DFE based on Volterra theory and maximum-likelihood sequence estimation (MLSE). Using numerical simulations, these EDC techniques will be compared for four kinds of binary modulation formats: on–off keying (OOK), optical duobinary (ODB), optical single sideband (OSSB) and differential-phase-shift-keying (DPSK).

For these simulations we assume a 10 Gb/s optically pre-amplified system with NRZ pulse shaping. The system setups (transmitter, receiver and channel) for all modulation formats are shown in Fig. 1. At the transmitter, all modulation formats are generated using a Mach–Zehnder modulator (MZM). For the generation of ODB a fifth-order Bessel electrical lowpass filter (ELF) is used with a 3 dB bandwidth of 2.5 GHz. A differential encoder is used for both ODB and DPSK to avoid an error propagation. The OSSB signal is generated in two steps. First, the conventional double sideband (DSB) signal is generated (similar to OOK). Then the DSB signal is phase modulated by the Hilbert transformed (HT) electrical data signal [1]. The HT is approximated by a FIR filter [1]. ODB and OSSB share the same receiver with OOK, while the DPSK receiver is based on balanced detection using a Mach–Zehnder delay-interferometer (MZDI). A third-order Butterworth ELF (3 dB cut-off frequency 7 GHz) is applied after detection for all receivers. Amplified spontaneous emission (ASE) from EDFAs is assumed to be the dominant noise source and therefore all other noise sources are omitted. Two Gaussian optical bandpass filters (OBF1 and OBF2) with the same 3 dB bandwidth (50 GHz) are assumed at the transmitter and receiver sides, respectively. Standard single mode fiber (SSMF) with a dispersion coefficient of $D = 17$ ps/nm/km is used for transmission fiber. The input power is kept to -2 dBm to neglect the impact of fiber nonlinearity.

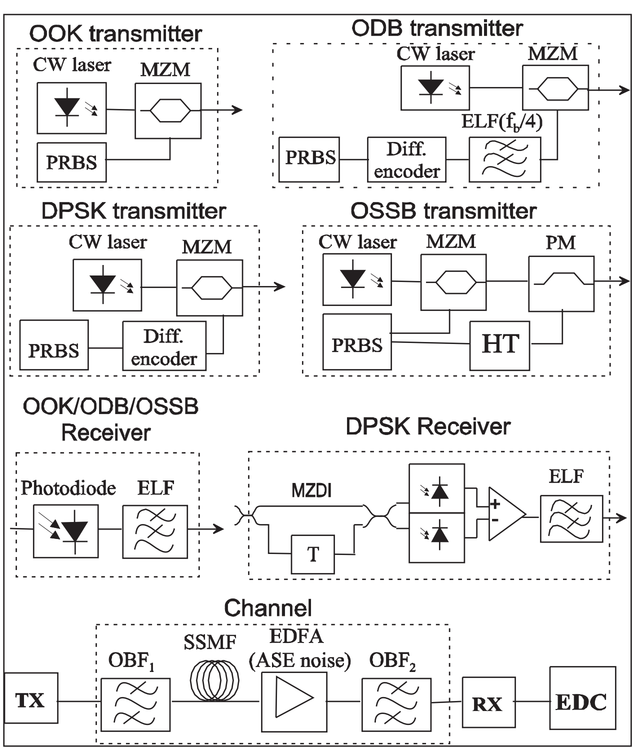

Fig. 1. System setups (transmitter, receiver and channel) for different modulation formats.

For the equalizers, we assume the following structures: a 6-delay tap FFE (FFE [6]), a 4-delay tap FFE and 2-delay tap DFE (FFE [4]-DFE [2]), a 4-delay tap FFE and 2-delay tap DFE with a nonlinear order of 3 and 2 for the FFE and DFE, respectively (NL [3,2]-FFE[4]-DFE [2]) and finally an MLSE with a memory of 2, 3, and 4, respectively (MLSE [2–4]). The orders of analogue equalizers determine the trade-off between performance and complexity. For the MLSE, a memory of 2 is chosen as default configuration as this MLSE is already commercially available. We will compare the performance of this MLSE to that of the MLSE [3,4]. The equalizer coefficients are optimized based on the minimum-mean-square-error (MMSE) for analogue equalizers (FFE, FFE-DFE and NL-FFE-DFE). An infinitive resolution is assumed for the MLSE, which is based on the lookup table method using a Viterbi algorithm. The probability density functions (PDF) are obtained by using Monto-Carlo simulations with a training bit sequence of a length of 1×10^6. A sampling rate of two samples per bit is assumed for all equalizers.

Fig. 2 shows the required OSNR for a BER of 5×10^{-4} versus the length of linear SSMF (i.e. only chromatic dispersion) with and without using equalization for different modulation formats.

The results for OOK are shown in Fig. 2(a). From this figure it can be seen that the feasible transmission distance is extended by both FFE and FFE-DFE by about 30 km at 3 dB required OSNR penalty. The limited increase in transmission distance is a result of the nonlinear distortions of direct detection. The NL-FFE-DFE accounts partially for this nonlinearity and can thus achieve much better performance compared to FFE-DFE [2–4]. Moreover, we can further improve the performance by increasing the number of delay taps. Both NL-FFE-DFE and MLSE take into account the nonlinear ISI mitigation and hence they are less influenced by the nonlinearity of photo detection.

The results for DPSK and ODB are given in Fig. 2(b) and (c), respectively. We confirm that because of the balanced detection DPSK achieves without equalization about 3 dB sensitivity improvement compared to OOK in back-to-back (b2b) configuration. As expected, ODB exhibits without equalization a larger OSNR penalty in b2b configuration. For DPSK and ODB, all EDC considered show a relatively