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Electronic Equalization for Advanced Modulation Formats in Dispersion-Limited Systems

V. Curri, *Member, IEEE*, R. Gaudino, *Member, IEEE*, A. Napoli, and P. Poggiolini, *Member, IEEE*

Abstract—We investigate in this letter the use of electronic equalization on dispersion-limited systems for different modulation formats. Besides analyzing equalization on standard nonreturn-to-zero (NRZ) intensity modulation as a reference, we focus on two advanced modulation formats, duobinary (DB) and differential phase-shift keying (DPSK) which are recently gaining a lot of attention. We demonstrate that the introduction of an electronic equalizer strongly improves standard NRZ performance, whereas, it has a limited effect on DB and DPSK formats. Moreover, we give rules for the optimal choice of the equalizer transversal filter parameters, i.e., the number of taps and the delay between taps.

Index Terms—Adaptive equalization, dispersion equalization, intersymbol interference (ISI), modulation, optical fiber communications, Q factor.

I. INTRODUCTION

THE USE of electronic equalization as a way to mitigate the effects of intersymbol interference (ISI) in traditional communications systems (i.e., wireless and copper wireline systems) has been deeply studied, and an extremely large amount of literature is available [1], [2]. In general, all these techniques are based on the use of a transversal digital filter (which acts as a finite impulse response (FIR) filter) at the receiver with a proper choice of taps parameter. In early 1990s, Winters *et al.* [3] proposed for the first time the use of electronic equalization in optical communication system. This approach has recently gained momentum, as it is today seen as a cheaper (even though less performing) alternative to all-optical equalization. Several solutions have been proposed, mainly in order to reduce the system impact of chromatic dispersion (CD) [4], [6] and polarization-mode dispersion (PMD) [5].

Electronic compensation in optical systems still lacks a complete theoretical understanding. This is mainly due to the fact that the analysis carried out for equalization of linear channels in traditional communication systems [1], [2] cannot be directly applied to the optical environment, where CD and PMD are linear at the “optical” level, but (particularly for CD) become nonlinear at the receiver side after the photodiode “square-law” conversion [4]–[6].

In this letter, we focus on CD electrical compensation for systems limited by amplified spontaneous emission (ASE) noise,

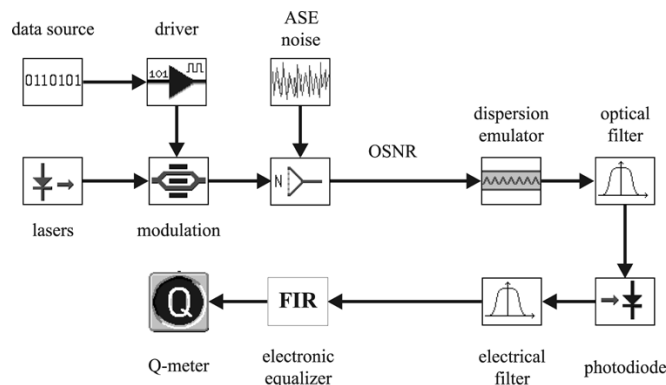


Fig. 1. Block diagram of the analyzed system setup.

focusing on advanced modulation formats. Recently, alternative modulation formats have been proposed in order to overcome linear and nonlinear propagation limits of standard NRZ. Among these formats, the most promising for an advantageous implementation seem to be the differential phase-shift keying (DPSK) [7] and the optical duobinary (DB) [8]. Anyway, the combination of advanced modulation formats with electronic equalization has not been deeply studied yet, at least to the best of our knowledge.

The purpose of this work is, thus, twofold. On one side, we analyze the impact of electronic equalization on DB and DPSK modulation formats, comparing the results to standard NRZ, which is taken as a reference. On the other side, we present a set of results on the optimization of equalizer transversal filter number of taps and delay between taps (for each modulation format).

This letter is organized as follows. In Section II, we describe the reference scenario and the equalizer scheme together with the algorithm used for the evaluation of the FIR filter coefficients. In Section III, we present the simulation results, demonstrating that the electronic equalization may strongly improve NRZ performance, but has a limited effect on systems based on DB and DPSK modulation formats. Finally, in Section IV, we draw the conclusions and envision possible evolutions of this work.

II. SYSTEM SETUP

We analyzed and simulated [9] the system scenario shown in Fig. 1, corresponding to an externally modulated system limited by the accumulation of ASE noise and by CD-induced ISI, while we neglect other effects, such as fiber nonlinearities. These assumptions are reasonable for high-capacity metro and extended metro links using single-mode fibers, a scenario that

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is today gaining increasing attention, due to the new optical market trends.

We considered an $R_b = 10$ Gb/s systems using a chirp-free external Mach–Zehnder amplitude modulator (MZM) at the transmitter side. For the three considered modulation formats, the MZM operates according to different driving schemes. Let V_{off} (V_{on}) be the driving voltage for a minimum (maximum) of the MZM transfer function, and $V_\pi = V_{\text{on}} - V_{\text{off}}$ the resulting ON–OFF voltage swing. In order to produce standard NRZ modulation, the MZM is simply driven between V_{off} and V_{on} voltages. For the DPSK modulation format, the input digital stream is first differentially precoded, then the MZM is driven between the two voltages $V_{\text{off}} \pm V_\pi$ [2]. This scheme yields a two-level phase modulation associated to “0” and “ π ” radians. To obtain a DB modulation, the input digital stream is processed by the DB precoder and then filtered using a narrow lowpass electric filter (five-pole Bessel filter with -3 -dB bandwidth equal to $0.25 \cdot R_B$) [8]. The filtered sequence is used to drive the MZM between the two voltages $V_{\text{off}} \pm V_\pi$ [8].

The modulated optical signal is sent to an optical channel affected by CD and ASE noise. For all modulation formats, results will be presented as a function of the optical signal-to-noise ratio (OSNR) (calculated over an optical bandwidth of 50 GHz) at the receiver input.

We assumed to use a standard optical receiver, based on a second-order super-Gaussian optical filter, having a -3 -dB bandwidth equal to $B_o = 40$ GHz, an ideal photodiode and a typical Bessel fifth-order electrical filter -3 -dB bandwidth $B_e = 0.75 R_B$ for NRZ and DPSK. For the DB format only, we used an electrical filter with $B_e = 0.5 R_B$, a value that, according to [8], optimizes DB tolerance to CD.

We analyze a standard equalizer structure based on a transversal FIR filter in a feedforward equalization configuration [1], i.e., a filter that, when receiving an electrical signal $x(t)$, generates at its output the signal

$$y(t) = \sum_{i=0}^{N_{\text{taps}}-1} C_i \cdot x(t - i\Delta T) \quad (1)$$

where N_{taps} is the number of taps, ΔT the delay between taps, and C_i the taps’ coefficients, which are optimized using the strategy described in the following section.

System performance was evaluated by using the Q factor¹ defined as $Q = \text{erfc}^{-1}(2\text{BER})$, where BER stands for the bit-error rate and $\text{erfc}^{-1}(\cdot)$ is the inverse of the complementary error function. In this letter, the Q factor is always presented in decibel units defined as $Q|_{\text{dB}} = 20 \log_{10}(Q|_{\text{linear}})$ [dB]. We spanned system parameters (OSNR and CD) in order to cover the 9–15-dB range for the Q factor.

III. SIMULATION AND RESULTS

As an optimization strategy, we used standard numerical optimization routines (such as the *quasi-Newton method* [10] and the *simplex search method* [11] implemented inside the commercial software Matlab) based on finding, for each system realization, the vector of taps coefficients C_i that maximizes the Q factor, i.e., that minimizes the BER.

¹The Q factor was optimized by choosing the optimum clock phase.

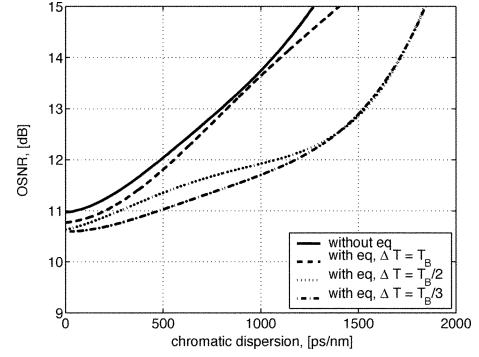


Fig. 2. OSNR versus D_{acc} at $Q = 17$ dB for the NRZ-OOK format. Different dotted curves refer to $\Delta T = T_B, T_B/2, T_B/3$, and $N_{\text{taps}} = 15$. The unequalized curve is shown as comparison.

Besides the tap coefficients, we also investigate different values for the delay ΔT and the number of coefficients N_{taps} . In particular, we explored $\Delta T = T_B, T_B/2$, and $T_B/3$ (where $T_B = 1/R_B$ is the bit duration) and $N_{\text{taps}} = 3, 7, 9$, and 15.

For each system setup, we performed an accurate time-domain simulation [9] of the signal propagation, then we optimized the equalizer FIR coefficient and obtain the resulting Q factor. The simulated digital stream was a $2^{13} - 1$ PRBS sequence. We explored accumulated CD values D_{acc} in the [0,4600]-ps/nm range, and $\text{OSNR} \in [9, 15]$ dB range. We presented all results showing the trace connecting all points giving rise to a Q factor equal to 17 dB (corresponding to $\text{BER} \sim 10^{-12}$) in the D_{acc} and OSNR plane. Basically, we show a plot of the OSNR required to get $Q = 17$ dB for each value of D_{acc} . We compared each system with and without equalizer.

We start by investigating, for the standard NRZ format, the influence of the tap delay ΔT and the number of taps N_{taps} . Results are shown in Fig. 2; the different curves refer to the unequalized system, and to the equalized system for $N_{\text{taps}} = 15$ (i.e., an extremely long transversal filter) and tap delays $\Delta T = T_B, T_B/2$, and $T_B/3$. Contrary to the typical results shown for example in [1], we show that $\Delta T = T_B$ gives poor performances, while a great improvement is obtained by using $\Delta T = T_B/2$. Moving to $\Delta T = T_B/3$ gives only marginal improvement, showing that for our considered setup $\Delta T = T_B/2$ is a good choice. We explain these results as follows. Most standard studies on equalization [1], [2] assume that a “matched” filter precedes the equalizer. In most cases, an integrate-and-dump filter with integration time T_b is assumed as a reference. In this situation, choosing a delay $\Delta T < T_B$ is useless, since the transversal filter acts on samples that are already correlated on a T_b time window by the filter preceding the equalizer. On the contrary, in our scenario, we assumed typical optical and electrical filters that are always significantly larger than a “matched” filter, and thus correlate the signal on a time window smaller than T_B , consequently justifying a tap delay smaller than T_b .

After setting $\Delta T = T_B/2$, we investigated the performance for different N_{taps} values. We show in Fig. 3 the results for the cases $N_{\text{taps}} = 3, 7, 11$, and 15. This figure shows that an FIR equalizer with more than seven taps does not increase performances. We notice here that a filter with seven taps and $\Delta T = T_B/2$ has a total “memory” equal to approximately 4 bits. We

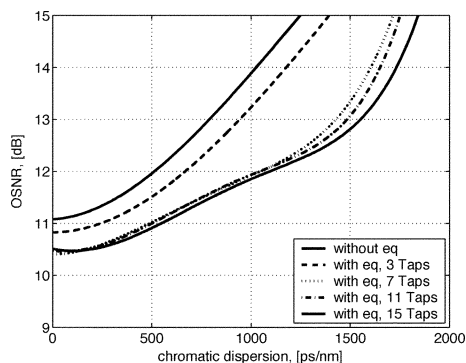


Fig. 3. OSNR versus D_{acc} at $Q = 17$ dB for the NRZ-OOK format. Different dotted curves refer to $N_{taps} = 3, 7, 11,$ and 15 , and $\Delta T = T_B/2$. The unequalized curve is shown as comparison.

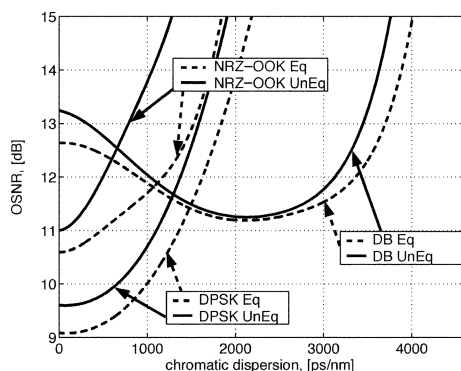


Fig. 4. OSNR versus D_{acc} at $Q = 17$ dB for the NRZ-OOK, DPSK, and DB format. Equalized results are obtained with $N_{taps} = 7$ and $\Delta T = T_B/2$ for NRZ-OOK and DPSK, and $N_{taps} = 15$ and $\Delta T = T_B/3$. The unequalized curves are shown as comparison.

observed that for high dispersion values, the seven taps coefficients are approximately symmetric with respect to the central taps, as can be expected from the symmetric nature of the dispersion impulse response. This physically means that the equalizer “handles” a time window with a range $\pm 2T_b$ around the sampling time of each bit.

Using these optimized parameters $N_{taps} = 7$ and $\Delta T = T_B/2$, Fig. 3 shows that electronic equalization can greatly improve performance for the standard NRZ format. We define the CD limit as the value giving a 2-dB OSNR penalty with respect to the back-to-back configuration; in Fig. 3, it can be observed that the back-to-back configuration requires an OSNR = 11 dB (in order to give a Q factor equal to 17 dB), so that the 2-dB OSNR penalty corresponds to the points of the curve that crosses the OSNR = 13 dB level. Using this reference, we observe an improvement from 750 ps/nm in the unequalized case to 1550 ps/nm in the equalized case, i.e., approximately a doubling of the dispersion limit.

Finally, we compared in Fig. 4 all the considered modulation formats with (dashed lines) and without (solid lines) equalization. This is the fundamental result of this letter, showing that, for DPSK and DB, electronic equalization does not significantly increase performance. Using the same reference introduced for NRZ, it can be seen that electronic equalization improves the dispersion limit by only 250 ps/nm for both DPSK and DB. The limited benefit given by electronic equalization on these two

modulation formats is not easy to be intuitively interpreted. A first observation is that both formats generate an electrical signal that, even *without* CD, shows a strong correlation over a one bit time window. This is due to the very narrow filtering at the transmitter side for DB, and by the receiver interferometric filter for DPSK. Moreover, in the case of DB, the format is *intrinsically* extremely robust to CD, as it has been shown in many papers, such as [8]. In fact, as shown in Fig. 4, it can be noted that the DB format, without equalization, reaches approximately the same performance of the back-to-back NRZ ($Q = 17$ dB with only OSNR = 11.2 dB) for $D_{acc} = 2200$ ps/nm. The corresponding eye diagram in this situation is nearly ISI-free, and thus, it cannot be significantly improved by equalization.

Finally, we notice that for all formats, and even without dispersion, i.e., in the back-to-back configuration, equalization improves performance of approximately 0.5 dB with respect to the unequalized system. This result can be explained by observing that, since our strategy optimizes taps coefficients using Q/BER as a target, it minimizes both ISI and noise. Thus, the resulting receiver equivalent filtering function tends to be closer to an ideally matched filter in the equalized case.

IV. CONCLUSION

For the first time, to our best knowledge, we have presented a comprehensive analysis of electronic equalization in connection to advanced modulation formats, showing that the use of electronic equalization based on FIR filter, while giving great benefit to standard NRZ, gives only limited advantages for DB and DPSK.

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