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Electrical Equalization for Advanced Optical Communication Systems

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Dedicated to Professor Edgar Voges on the occasion of his 65th birthday

Abstract **We investigate equalizers for electronic dispersion compensation (EDC) of dispersion limited optical fibre communication links in combination with different modulation formats. We show that the performance of conventional equalizers including feedforward equalizer (FFE) and decision feedback equalizer (DFE) are fundamentally limited by the nonlinearity of square-law detection of the photodiode in direct detection systems. Advanced modulation formats such as differential phase shift keying (DPSK) and optical duobinary further enhance this kind of nonlinearity and degrade further FFE/DFE performance. However, nonlinear FFE-DFE and maximum likelihood sequence estimation (MLSE) take into account the mitigation of nonlinear inter symbol interference (ISI) and hence can achieve much better performance. We show that in contrast to other modulation formats, optical single sideband modulation results in approximately linear distortions after detection and thus a simple linear FFE equalizer can achieve good compensation.**

Keywords **electrical dispersion compensation, decision feedback equalizer, maximum likelihood sequence estimation, nonlinear equalizer, modulation format.**

1. Introduction

The optical transmission channel in today's high capacity high speed lightwave communication systems is well understood and various system level models exist for the various kinds of impairments. Such knowledge is essential for designing advanced optical systems and software design tools are using these models. In this article we review the various possibilities for mitigating channel impairments by the use of equalizers in the electrical domain, after detecting the light signal by means of optical-electrical conversion. These electrical equalizers were originally considered as merely auxiliary devices [1], supporting powerful optical compensation techniques as e.g. the DCF (dispersion compensating fibre) for compensating chromatic dispersion (CD). However as electronic solutions have the potential of being eventually integrated on chip they are considered as very cost efficient [2]. Thus EDC has become an important issue, both economically and from the research point of view [3]-[8].

An equalizer tries to reconstruct the originally transmitted data sequence, e.g. by minimizing the ISI in each bit slot or by searching for a data sequence with maximum likelihood, whereas the various compensators compensate for one specific physical effect. Thus equalizers strive to simultaneously address signal distortions of various physical origin. For being practically efficient an adaptation algorithm must be used in order to take into account variable channel conditions.

Apart from equalization, other topics from digital communication theory have found their way into optical transmission. Among them are channel coding, OFDM (orthogonal frequency division multiplexing), and advanced modulation techniques.

We give an overview of equalization techniques at the receiver side by using different EDC solutions. These equalizers will be investigated and compared for modulation formats that are hot candidates for implementation in today's advanced transmission equipment: on-off keying (OOK), optical duobinary (ODB), differential phase shift keying (DPSK), and optical single sideband (OSSB).

2. Electrical Equalizers

We restrict ourselves on considering four kinds of electrical equalizers: (i) feedforward equalizer (FFE), (ii) feedforward-decision feedback equalizer (FFE-DFE), (iii) nonlinear feedforward-decision feedback equalizer (NL-FFE-DFE) and (iv) maximum likelihood sequence estimator (MLSE).

We assume that these equalizers operate in conventional receivers with direct detection of the received instantaneous optical power (squared envelope detection). In the case of DPSK this requires an optical phase-to-amplitude conversion (by a delay interferometer) prior to detection, and for OSSB we transmit sufficient carrier power (which reduces the extinction ratio), in order to enable direct detection.

An FFE is the simplest structure and the most cost-effective solution. It consists of a delay line filter (FIR filter) with filter coefficients that are adaptively adjusted to the channel impairments. For a linear transmission system, it is well known [9] that the ISI at sampling instant can be forced to zero, provided a tap spacing of at least $T/2$ (T is the bit duration) and a channel without zeros in its spectrum is given. Thus this type of equalizer is often called fractionally spaced zero forcing equalizer. The filter length, i.e. the number of filter-coefficients, is quite high for achieving sufficient performance improvement. The filter is always stable, independent of the choice of the coefficients.

With the DFE, previous bit decisions (after the nonlinear slicer) are used to eliminate the ISI caused by previous bits on the current bit to be detected. DFE is usually combined with FFE to mitigate the pre-cursor and post-cursor ISI simultaneously [9]. With a FFE-DFE the total number of filter coefficients is much less compared to the linear FFE for the same amount of ISI mitigation. However, one

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disadvantage of DFE is the error propagation due to its feedback structure.

In optical transmission, both above equalizers can only achieve limited performance due to the nonlinearity of square-law detection of the photodiode in direct detection systems [10]. Advanced modulation formats such as DPSK and ODB will further enhance this kind of nonlinearity as has been observed e.g. in [11],[12]. Therefore, a nonlinear FFE-DFE (NL-FFE-DFE) based on Volterra nonlinear theory is introduced [13], [14] to mitigate the nonlinear ISI. This kind of nonlinear equalizer has been shown to mitigate the chromatic dispersion in 10Gb/s ODB system [12] and to mitigate the intrachannel nonlinearity in 40Gb/s OOK systems [15]. In order to specify the parameters, we introduce the notation: NL[x,y]-FFE[m]-DFE[n], where x and y indicate the nonlinear order of FFE and DFE respectively and m and n are the respective filter orders. Finally, an optimum receiver for a nonlinear channel consists of a matched filter with symbol rate sampling, followed by Viterbi algorithm minimizing the error probability through selecting the most probable sequence (MLSE) [4],[5]. The matched filter, which is too complex to be implemented for high-speed optical receiver, is generally replaced with a low pass filter with successive oversampling.

3. System Setups and Parameters

We assume 10Gb/s data rate and non-retrun-to-zero (NRZ) pulse shape for all modulation formats. We consider pre-amplified reception where the ASE noise from the pre-detection EDFA dominates and therefore all other noises are omitted. A first order Gaussian optical bandpass filter with 3-dB bandwidth of 50GHz reduces noise and emulates a WDM channel filter. A Butterworth electrical lowpass filter with 3-dB bandwidth of 7GHz is applied before the equalizer. The channel is standard single mode fibre (SSMF) with dispersion coefficient of D=17ps/(nm km). The four modulation formats share the same channel but with different transmitter and receiver setups. For ODB, the transmitter consists of a pre-coder and Bessel low-pass filter with 2.5GHz bandwidth, as shown in [12] and the receiver is the same as with OOK. DPSK has the similar transmitter setup as OOK except with an additional differential pre-coder and a doubled drive voltage into the Mach-Zehnder modulator. The balanced receiver setup as shown in [11] is used for DPSK. The OSSB signal [16]-[18] is generated in two steps. First, the conventional double sideband (DSB) signal is generated, then the DSB signal is phase modulated by the Hilbert transformed electrical data signal. The Hilbert transform is approximated by a FIR filter [16]. The receiver for OSSB is the same as with OOK.

4. EDC Performance for Different Modulation Formats

As mentioned earlier, the envelope detection in the optical direct receiver results in performance degradation of EDC as the overall behaviour becomes nonlinear even though we consider linear phase distortions by CD. I.e. the optical channel with CD can be described in the equivalent low-pass domain by a linear filter acting on the electrical field (square root of optical instantaneous power)

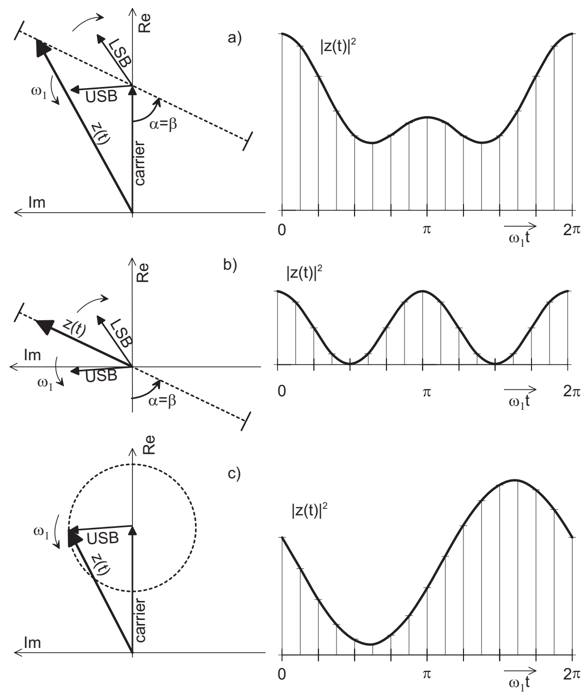

Fig. 1. Phasor diagram, showing upper and lower side bands (USB, LSB) of a single frequency component as well as the carrier and the resulting complex envelope z(t). Waveforms with distortions are shown on right hand side. a) OOK, b) ODB and DPSK, c) OSSB. Tip of phasor for z(t) moves along dotted line in a) b) or circle in c).

$$H(\omega) = |H(\omega)| \cdot \exp(-jb(\omega)) = C \cdot \exp\left(-j\beta_2 L\omega^2/2\right) \quad (1)$$

where C is a constant attenuation (normalized to $C = 1$), β_2 represents dispersion, L is the fibre length. It is well known [9] from traditional analog AM transmission that linear distortions in the channel result in general in nonlinear distortions, if envelope detection is used, whereas for synchronous detection only linear distortions occur. Therefore coherent optical receivers allow the efficient use of simple linear equalizer filters.

In order to estimate and to compare the (linear) EDC performance we consider what happens with a spectral component at specific frequencies within the modulation bandwidth for OOK, OSSB, ODB and DPSK after direct detection. Thus the following discussion shows how a single frequency component of the electrical field is converted in the electrical domain.

The complex envelope at receiver input for one spectral component ω_1 of the electrical field can be written as

$$\begin{aligned} z(t) &= 1 + a \cdot \frac{m}{2} \exp\left(j\left(\omega_1 t - \alpha\right)\right) \\ &\quad + b \cdot \frac{m}{2} \exp\left(j\left(-\omega_1 t - \beta\right)\right) \end{aligned} \quad (2)$$

The first term represents the carrier, the second is the upper sideband, the third is the lower sideband, m is the modu-

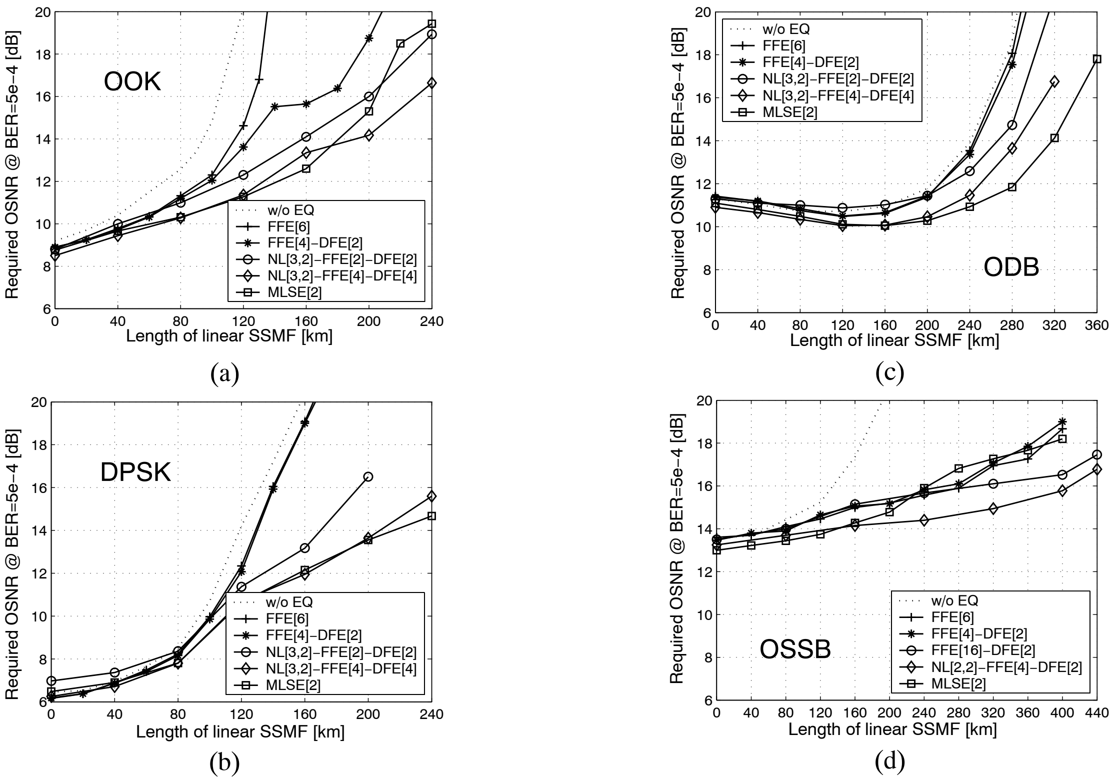

Fig. 2. Required OSNR at BER=5×10^{-4} versus length of SSMF with and without using equalization for a) OOK, b) DPSK, c) ODB, d) OSSB.

lation depth and

$$a = |H(\omega_1)| = b = |H(-\omega_1)| = 1$$
$$\alpha = b(\omega_1) = \beta = b(-\omega_1) = \beta_2 L \omega_1^2/2 \qquad (3)$$

The three terms in (2) can be conveniently represented in a phasor diagram as is depicted in Fig. 1.

For OOK both sidebands and the carrier are present. After taking the magnitude squared, we get:

$$|z_{OOK}(t)|^2 = 1 + \frac{m^2}{2} + 2m\, cos\alpha\, cos\omega_1 t + \frac{m^2}{2} cos2\omega_1 t \quad (4)$$

We conclude that due to the double frequency term we have nonlinear distortions. The linear part of this result suffers from pure amplitude distortions according to a $cos\alpha$ frequency response. A linear equalizer (FFE) tries to minimize the ISI due to this linear part. However as soon as (with increasing L) the first zero of the $cos\alpha$ frequency response falls into the signal bandwidth (this is the case for approx. 100km SSMF at 10Gb/s), equalization becomes difficult and FFE fails to work efficiently. For this critical case, we have $\alpha = \pi/2$ and in the phasor diagram, $z(t)$ moves along a horizontal straight line in fig 1a) and the waveform contains the double frequency distortion only; the contribution at ω_1 disappears completely.

The linear part in $z_{OOK}(t)$ results from the presence of the carrier. For ODB and DPSK we have carrier suppressed formats and therefore we get

$$|z_{ODB,DPSK}(t)|^2 = \frac{m^2}{2}(1 + cos2\omega_1 t) \qquad (5)$$

Thus the linear contribution at ω_1 disappears and we have basically nonlinear distortions (double frequency waveform in Fig.1b)) and we expect that equalizer performance is degraded even more.

Now for OSSB, we calculate the envelope by setting one of the sidebands in (2) to zero and keep the carrier, which is required for at least approximately detecting a SSB signal with an envelope detector

$$|z_{OSSB}(t)|^2 = 1 + \frac{m^2}{4} + m cos(\omega_1 t - \alpha) \qquad (6)$$

Apart from the DC component, we find solely a linear contribution at ω_1 , where only the phase is shifted according to the square-law frequency dependency (see (3)) of the dispersive fibre itself. Thus the post detection electrical equalizer should be implemented as a pure dispersive element with all-pass characteristic and linear group delay. Thus a linear equalizer is well suited for OSSB.

5. Simulation Results

Based on bit error ratio (BER) simulations with the Monte-Carlo method, we compare the required optical signal-to-noise ratio (OSNR in 0.1nm bandwidth) to achieve a BER of 5×10^{-4}, which is sufficient for error-free operation with forward error correction (FEC). The number of delay taps for the various equalizers is chosen considering a trade off between complexity and performance. The equalizer coefficients are optimized, based on

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minimum mean square error (MMSE) for FFE/ DFE and NL-FFE-DFE. Infinite resolution is assumed for MLSE, which is based on lookup table method by using the Viterbi algorithm [5]. Two samples per bit are assumed for all equalizers.

The results for OOK are shown in Fig.2a. The transmission distance is limited to less than 70km for a target OSNR penalty of 3dB and can be extended to about 100km by using either FFE[6] or FFE[4]-DFE[2]. However, both FFE and DFE show negligible performance improvement even with larger delay tap numbers. This shows the fundamental limit imposed by the nonlinear square-law detection of the photodiode. The NL-FFE-DFE accounts partially for this nonlinearity and can thus achieve much better performance compared to FFE-DFE. Moreover, we gain here 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 nonlinearity of photo detection. MLSE is outperformed by NL-FFE-DFE for larger distance due to the limited memory of 2 assumed for MLSE.

For DPSK and for ODB the results are given in Fig.2b and Fig.2c respectively. We confirm that DPSK based on balanced detection can achieve about 3dB sensitivity improvement compared to OOK for back-to-back (b2b) operation. As expected, ODB exhibits larger OSNR penalty for b2b. The optimum system performance is reached at transmission distance of around 100km. For DPSK and ODB, all EDC show relatively poor performance, especially at short transmission distances. Both FFE and DFE exhibit nearly no performance improvement. The main reason is the absence of the carrier as discussed above. Nevertheless, NL-FFE-DFE and MLSE both outperform FFE-DFE.

For OSSB, results are shown in Fig.2d. In order to obtain a good SSB signal, the extinction ratio should be chosen as a trade off between the single side band suppression and the b2b performance. For OSSB, chromatic dispersion results in basically linear distortions after detection and hence EDC performance is generally much less influenced by the square-law detection of photodiode. A simple linear FFE[6] can achieve good performance and extends the transmission distance from about 140km without equalization to about 300km at target of 3dB OSNR penalty, thus nonlinear equalizers are not as beneficial as in the other investigated modulation formats.

6. Conclusions

The nonlinearity of the square-law detection of photodiode in direct detection systems is the fundamental reason to degrade the performance for conventional equalizers including both FFE and DFE, especially for advanced modulation formats such as DPSK and ODB. We show that nonlinear equalizers such as NL-FFE-DFE and MLSE are required to achieve better performance because they can take into account the nonlinear distortion mitigation. Finally, we demonstrate that optical single sideband (OSSB) modulation results in approximately linear distortions in the electrical domain and hence linear equalizer alone can achieve good performance.

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