Are MLSE and nonlinear equalization required for optical single sideband modulation?

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ABSTRACT

Nonlinear equalizers based on nonlinear Volterra theory and maximum-likelihood sequence estimators (MLSE) are investigated to mitigate the nonlinear distortions resulting from the incomplete sideband suppression in optical single side band modulation (OSSB) systems. Through theoretical analysis and simulations, we demonstrate that electrical dispersion compensation (EDC) by using these nonlinear equalizers can achieve better performance compared to conventional analog equalizers including feedforward equalizers (FFE) and decision feedback equalizers (DFE).

Keywords: electrical dispersion compensation (EDC), nonlinear equalizer, maximum-likelihood sequence estimator (MLSE), feedforward equalizer (FFE), decision feedback equalizer (DFE), optical single sideband modulation (OSSB).

1. INTRODUCTION

Optical single sideband (OSSB) modulation format is considered as one promising candidate for next generation optical fiber networks [1, 2]. On one hand, OSSB can approximately double the spectral efficiency by preserving only one spectral sideband. On the other hand, chromatic dispersion of the fiber results in approximately linear distortion after direct detection in OSSB systems and therefore, linear transversal filter shows larger efficiency in electrical dispersion compensation (EDC) for OSSB than in on-off keying (OOK) systems [2, 3].

However, perfect sideband suppression can not be achieved and therefore, nonlinear distortions resulting from the interference between the main sideband and the vestigial sideband can not be mitigated by using simple linear equalizers, especially, in the presence of large dispersion. In this work, in order to clarify the impact of nonlinear distortions on the EDC performance, we investigate the following two kinds of nonlinear equalizers: (i) nonlinear feedforward and decision-feedback equalizer based on Volterra theory (noted as NL-FFE-DFE), (ii) maximum-likelihood sequence estimator (MLSE). Both of them will be compared to feedforward equalizer (FFE) as well as to conventional feedforward and decision-feedback equalizer (FFE-DFE).

2. ANALYSIS OF OSSB SYSTEM

We assume a typical 10Gb/s OSSB system setup illustrated in Fig.1. The OSSB signal is generated in two steps [2-4]. First, a conventional double sideband (DSB) signal is generated with a Mach-Zehnder modulator (MZM) (similar to OOK). Then the DSB signal is phase modulated by the Hilbert transformed electrical data signal through a phase modulator (PM). The Hilbert transformer (HT) is approximated by a third order FIR filter with a delay T=100ps [2-4]. OSSB format applies the same receiver as OOK. Linear standard single mode fiber (SSMF, dispersion coefficient D=17ps/nm/km) is assumed. The ASE noise from the EDFA dominates and other noises have been neglected. A 50GHz Gaussian optical bandpass filter (OBF) and a 7GHz third-order Butterworth electrical lowpass filter (ELF) are used before and after the photodetector, respectively. For the simulations, a pseudo random bit sequence (PRBS) with a length of 2^{10}-1 and non-return-to-zero (NRZ) coding are assumed.

The output electrical signal $i_{out}(t)$ after direct detection can be expressed in the frequency domain as [2]

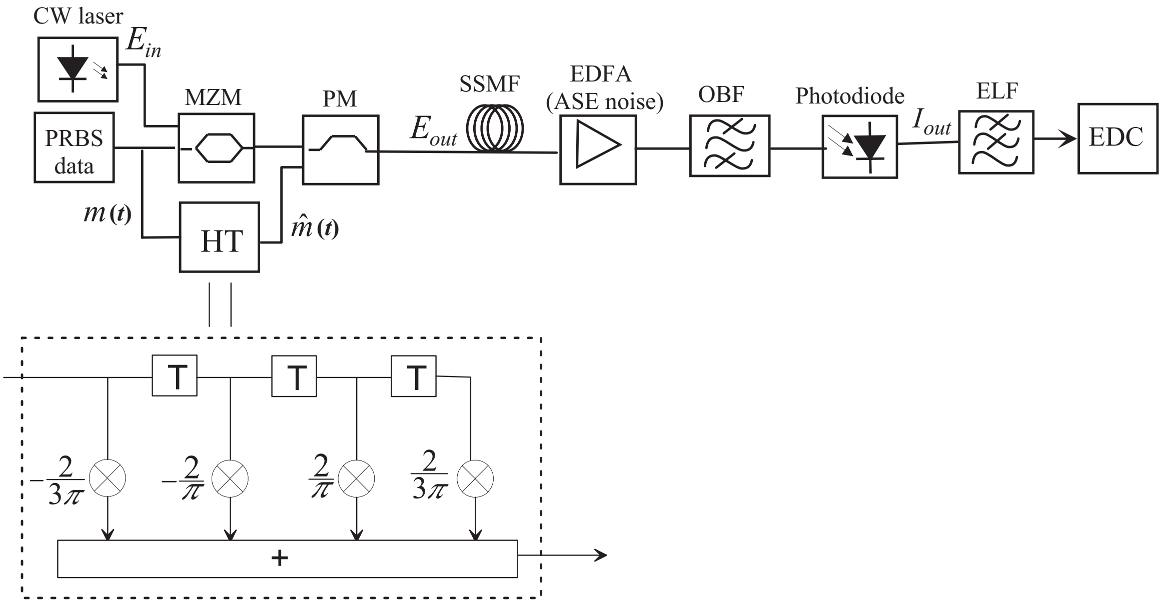

Fig.1: The OSSB system setup including EDC.

$$I_{out}(f)=\frac{R\left|E_{in}\right|^2}{2}\left\{\delta_0(f)+zH^*_{SMF}(f)M_L(f)+zH_{SMF}(f)M_U(f)+z^2\left[H^*_{SMF}(f)M_L(f)\right]*\left[H_{SMF}(f)M_U(f)\right]\right\} \quad (1)$$

with

$$M_U(f)=M(f)+j\hat{M}(f),\ M_L(f)=M(f)-j\hat{M}(f)$$

Where R is the photodetector responsivity and E_{in} is the CW laser field input. $H_{SMF}(f)$ is the transfer function of SMF and $H^*_{SMF}(f)$ is its complex conjugate. $M(f)$ and $\hat{M}(f)$ are the Fourier transforms of the transmitted signal $m(t)$ and its Hilbert transform $\hat{m}(t)$, respectively. $M_U(f)$ and $M_L(f)$ are the upper and lower sideband representations of $M(f)$. z is a parameter related to the modulation depth and extinction ratio. The first term on the right of equation (1) corresponds to the optical carrier. The second and third terms represent the beating between the optical carrier and each sideband. The phase information introduced by the fiber is preserved in the two terms and it can be compensated by using a transversal filter. However, the fourth term is the beating between the two sidebands and the phase is not preserved and therefore this term leads to nonlinear distortions. The nonlinear distortions directly depend on the value of z. A smaller z and thus a smaller extinction ratio result in less nonlinear distortions and larger dispersion tolerance, on one hand, but a larger b2b penalty, on the other hand. Therefore, on the trade off between the two effects, an extinction ratio of 8dB is presumed.

3. EQUALIZER STRUCTURES

In total, four kinds of equalizers are considered and their structures are assumed as follows: FFE(6) (6 delay-tap FFE), FFE(16)-DFE(2) (16 delay-tap FFE and 2 delay-tap DFE), NL(2,2)-FFE(4)-DFE(2) (4 delay-tap FFE and 2 delay-tap DFE, nonlinear order 2 for both FFE and DFE) and MLSE(n) (memory of n, n=2, 3 and 4). FFE(16)-DFE(2) with a high delay tap number and additional DFE part will be compared to FFE(6). The nonlinear equalizer NL-FFE-DFE can be considered as the extension from the conventional FFE-DFE by adding nonlinear terms considering the nonlinear distortions [5-7]. As an example, for illustration, a simple nonlinear equalizer with structure of NL(2,2)-FFE(1)-DFE(2) with oversampling of 1 is schematically shown in Fig.2. The nonlinear parts have been marked with dash line boxes. Obviously, it turns into a conventional FFE(1)-DFE(2) when these nonlinear coefficients are deleted. The parameters chosen for NL-FFE-DFE result from the trade off between performance and complexity. The memory of MLSE is limited to four to reduce complexity as well. Oversampling of 2 is assumed for all equalizers. Minimum mean square error rule is used to optimize the coefficients for delay-tap filter based equalizers (FFE, FFE-DFE and NL-FFE-DFE). MLSE is processed by the Viterbi algorithm based on a look-up table method by using Moto-Carlo simulations.

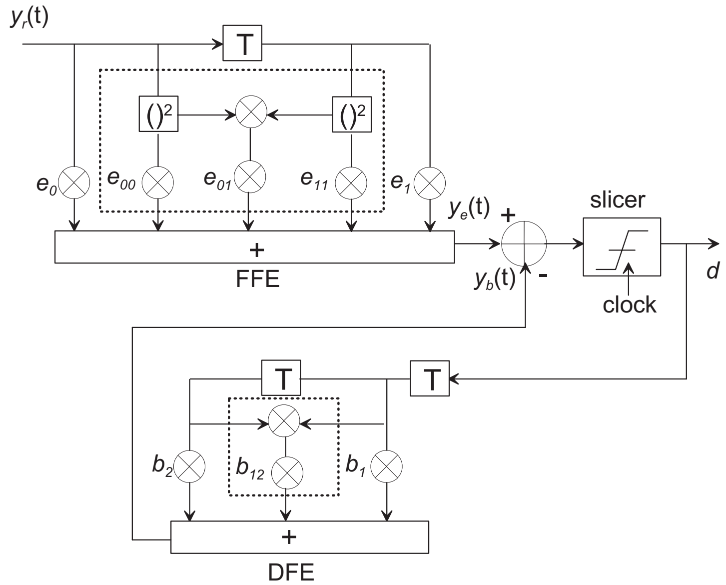

Fig.2: Setup of NL(2,2)-FFE(1)-DFE(2): nonlinear part of setup marked with dashed boxes.

4. RESULTS AND DISCUSSIONS

The required optical-signal-to-noise-ratio (OSNR) (in 0.1nm bandwidth) at a bit error ratio (BER) of 5×10^{-4} versus transmission distance with and without equalization is shown in Fig.3.

For both FFE(6) and FFE(16)-DFE(2), the transmission distance is extended from about 120km to about 260km at a target of 2dB OSNR penalty (compared to b2b). This improvement is much larger than that in OOK systems. Therefore, we have confirmed that linear equalizer can achieve good EDC performance in OSSB systems. More improvement can be achieved with a smaller extinction ratio.

However, NL(2,2)-FFE(4)-DF(2) shows larger improvement (near 400km transmission distance is observed at 2dB penalty) compared to FFE(16)-DFE(2). Note that further increased order for FFE-DFE shows negligible improvement within 2dB penalty. This has demonstrated that the nonlinear distortions caused by the interference of two sidebands, which degrade the conventional equalization performance, can be mitigated by nonlinear equalizers. Moreover, a NL-FFE-DFE with higher filter order and nonlinear order can achieve larger improvement. These conclusions can be further demonstrated by observing the signal eye-diagrams after 250km-transmission distance (without noise) with and without using equalizers shown in Fig.4.

Finally, MLSE with a large memory shows the best performance. For example, MLSE(4) can extend the transmission distance to more than 600km at 2dB penalty. Similar to NL-FFE-DFE, MLSE can take into account the nonlinear distortions. Additionally, MLSE does not suffer the noise enhancement, which is generally the problem encountered by delay-tap filter based equalizers including FFE, FFE-DFE as well as NL-FFE-DFE.

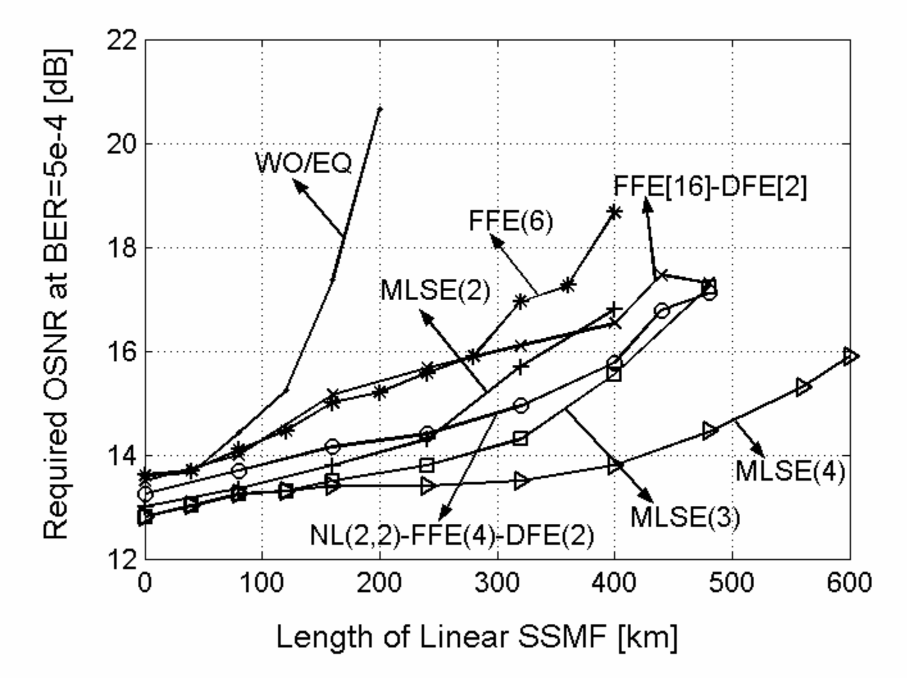

Fig.3: Required OSNR at BER= 5×10^{-4} versus the transmission distance over SSMF at 10Gb/s by using different equalization.

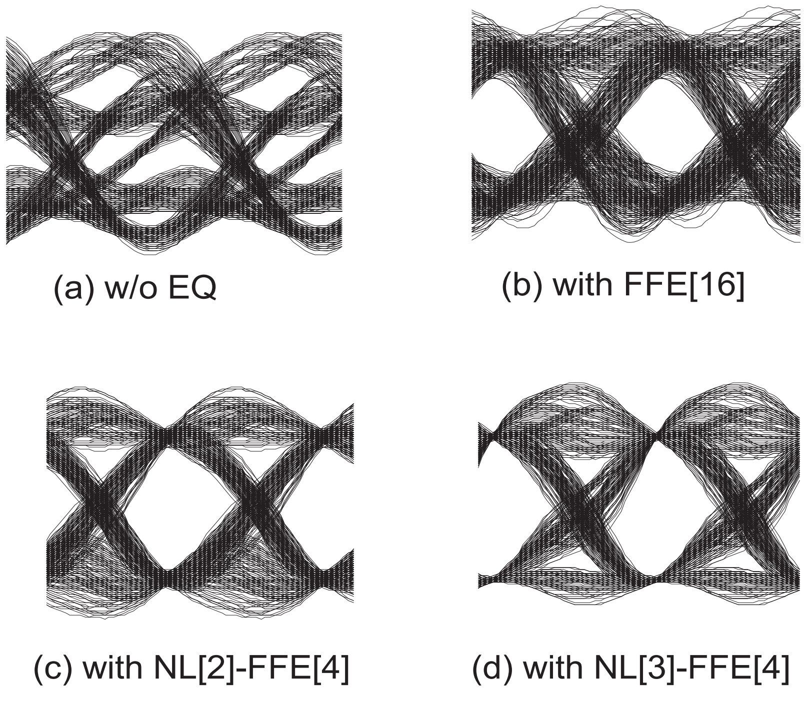

Fig.4: The received eye-diagrams of OSSB signal after 250km-transmission over SSMF at 10Gb/s with and without using equalization.

5. CONCLUSIONS

Through analysing the interactions of OSSB signal and chromatic dispersion, we show that EDC performance by using FFE/DFE is ultimately limited by the nonlinear distortions resulting from the incomplete sideband suppression and square-law direct detection. In contrast to linear equalizers, nonlinear equalizers including NL-FFE-DFE and MLSE have been demonstrated to mitigate this kind of nonlinear distortion and thus achieve further performance improvement. Thus MLSE and NL-FFE-DFE are beneficial in OSSB transmission systems as well.

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