Simplified Field Re-Construction and Adaptive System Optimization in Full-Field FFE

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Abstract: We simplify the implementation of full-field reconstruction and combine it with adaptive FFE. The adaptive algorithm incorporates self-equalization of system parameters and enables full-field FFE robust to sampling phase misalignment.

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1. Introduction

Direct-detection based full-field electronic dispersion compensation (EDC) is a promising candidate to balance the limited performance arising from loss of signal phase information in direct-detection EDC [1] and the increased complexity of coherent-detection EDC [2]. By extracting the intensity and instantaneous frequency information simultaneously using a single [3] or double [4] asymmetric Mach-Zehnder interferometer (AMZI), subsequent full-field chromatic dispersion (CD) compensation is possible. Previously, full-field EDC based on a dispersive transmission line method was demonstrated to recover a 10Gbit/s on-off keyed (OOK) signal after transmission over 496km of field-installed single mode fibre (SMF) [3]. However, the previous studies used static dispersion compensation where the compensation parameters were manually optimized, which is clearly not suitable for practical implementation. In this paper, we demonstrate a more practical implementation by simplifying the field reconstruction and simultaneously replacing the dispersive transmission line with a feed-forward equalizer (FFE). Manual adjustment of the compensator is replaced with adaptive optimization, and the additional degrees of freedom offered by full-field FFE allow a significant reduction in sensitivity to sampling phase misalignment.

2. Principle

A detailed description of full-field reconstruction is reported in [3]. A bias (λ) is added to the signal intensity $V_x(t)$, to significantly enhance the robustness to thermal noise and allow for AC coupling at the receiver. The signal $V_y(t)$, related to the instantaneous frequency of the signal multiplied by its intensity, is re-scaled (α) to correct for any gain imbalance between the $V_x(t)$ and $V_y(t)$ signal paths. We will show later that these parameters can be incorporated into the algorithm resulting in a self-adaptive system which is more robust to parameter errors.

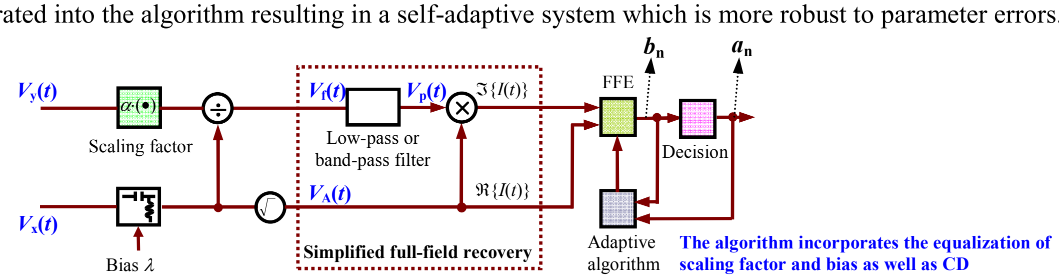


Fig. 1. Principle of simplified full-field reconstruction and adaptive parameter optimization. Optical front end is shown in Fig. 2.

Fig. 1 shows the principle of simplified full-field FFE. The estimated phase, $V_p(t)$, is typically obtained by integrating the estimated instantaneous frequency $V_f(t)$. In addition, the known amplification mechanism with a factor of $1/|\omega|$ for small ω values should be suppressed [3]. In previous works, an integrator and a high-pass filter were employed for phase estimation, which, as we will show, can be replaced by a single low- or band-pass filter with transfer function $H(\omega)\propto 1/(j\omega)$ for large ω (>several GHz) and $H(\omega)\neq\infty$ for ω=0. In this paper, we use a filter with transfer function of $H(\omega)=1/(1+j\omega RC)$ to emulate these filter specifications, where $1/RC=2\pi\times 1.25$GHz. This transfer function corresponds to a 1st-order RC low-pass analogue filter with a 3dB bandwidth of 1.25GHz.

The detected field is mathematically expressed as $V_A(t)e^{jV_p(t)}$. In this paper, we propose to truncate the Taylor series expansion:

$$\Re\{I(t)\} + j\Im\{I(t)\} = V_A(t)e^{jV_p(t)} = V_A(t)(1 + jV_p(t) - (V_p(t))^2/2...) \approx V_A(t)(1 + jV_p(t)) \tag{1}$$

where $\Re\{I(t)\}$ and $\Im\{I(t)\}$ represent the in-phase and quadrature components of the recovered full-field $I(t)$. This approximation induces a negligible performance penalty whilst simplifying the exponential term so obviating the requirement for complicated multipliers, lookup tables, and additional hardware [5].

The approximated field is then passed to the FFE, which might be implemented in either the digital or analogue domain. The FFE coefficients are optimized using a mean square criterion [6] such that the recovered signal, b_n, is

$$b_n = \sum_{k=-Nm}^{Nm} [\Re(I_{n-k/N}) f_{k/N} + j \cdot \alpha_{adap} \cdot \Im(I_{n-k/N}) f_{k/N}] + \lambda_{adap} \tag{2}$$

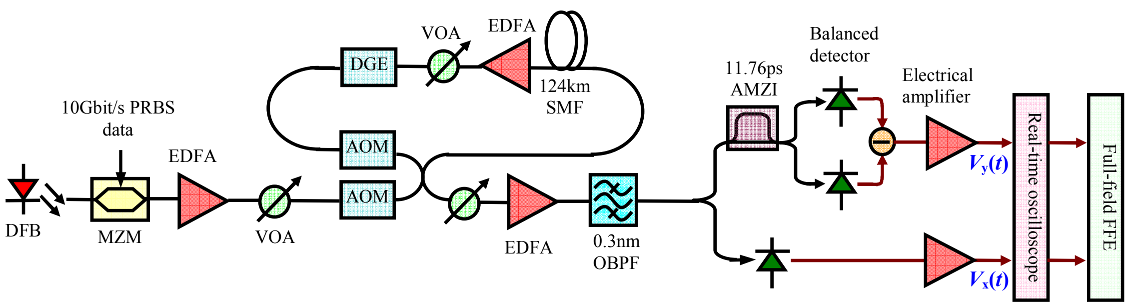
where $f_{k/N}$, $-Nm \le k \le Nm$, are the FFE coefficients with N being the sample number per bit and $2m$ being the memory length. $I_{n-k/N} = I((n-k/N)T)$ with T being the time period per symbol. Note that the linear approximation of the exponential in (1) results in V_f only impacting the imaginary part, and so any gain imbalance between the $V_x(t)$ and $V_y(t)$ analogue paths can be compensated by adding a scaling factor α_{adap} to the second term on the right-hand side of (2). Although α_{adap} and λ_{adap} are updated every bit in this paper, they could operate at a lower speed:

$$\alpha_{adap}{}^{(n+1)} = \alpha_{adap}{}^{n} + \Delta \cdot \sigma^{(n+1)}, \text{ with } \sigma^{(n+1)} = 0.8 \times \sigma^n + 0.2 \times (a_n - b_n) \cdot \sum_{k=-Nm}^{Nm} j \cdot \Im(I_{n-k/N}) f_{k/N} \text{ and } \sigma^1 = 0$$

$$\lambda_{adap}{}^{(n+1)} = \lambda_{adap}{}^{n} + \Delta \cdot \upsilon^{(n+1)}, \text{ with } \upsilon^{(n+1)} = 0.8 \times \upsilon^n + 0.2 \times (a_n - b_n) \text{ and } \upsilon^1 = 0 \tag{3}$$

where Δ, a parameter to control the update speed, also changes adaptively to ensure timely convergence [6]. a_n is the n^{th} decoded data (see Fig. 1), and is replaced by the training sequence during initial channel estimation.

3. Experimental Setup and Results



VOA: variable optical attenuator; EDFA: erbium doped fiber amplifier; AOM: acousto-optical modulator; DGE: dynamic gain equalizer

Fig. 2. Experimental setup

Fig. 2 shows the experimental setup. A 1557nm signal from a distributed feedback (DFB) laser was intensity modulated using a Mach-Zehnder modulator (MZM) giving a 6dB extinction ratio (ER) signal at 10Gbit/s with a 2^{11}-1 PRBS data (limited by the capacity of the off-line processing system). The OOK signal was transmitted over a recirculating loop comprising 124km of BT Ireland's field-installed single mode fiber (SMF) between Cork City and Clonakilty, County Cork, Ireland, with a signal launch power of around 0dBm per span. Although not explicitly depicted in Fig. 2, a 3.5nm band of amplified spontaneous emission (ASE) noise was transmitted with the signal to operate the loop amplifiers in saturation. At the receiver, the signal was pre-amplified and optically filtered using a 0.3nm optical bandpass filter (OBPF). The optical attenuator before the preamplifier was adjusted to vary the OSNR. Ten percent of the signal power was directly detected by a 10Gbit/s receiver and electrically amplified by a 12GHz electrical amplifier. The remaining signal was optically processed by an AMZI with an 11.76ps differential time delay and a $\pi/2$ differential phase shift (biased at quadrature), detected by a 43GHz balanced detector, and electrically amplified with a net amplification bandwidth of 15GHz. Both detected signals were sampled by a real-time oscilloscope at 50Gsamples/s with a resolution of 8 bits. In off-line processing, the signals were re-sampled at two samples per bit. 925,000 bits were used for full-field recovery and dispersion compensation using the principle described in Fig. 1. The first 80,000 bits were employed to emulate the training sequence for channel estimation. The initial FFE coefficients were set to compensate 0km CD and the memory length, unless otherwise stated, was 10, which resulted in a bit error rate (BER) close to the minimum value as shown in Fig. 3(a).

Fig. 3(b) verifies that full-field FFE with simplified full-field reconstruction induces negligible penalty at 496km compared to that in our earlier report [3]. The adaptive capability of full-field FFE for CD compensation is illustrated in Fig. 3(c), from which we found that the FFE coefficients converged rapidly from the initial values for

0km CD to optimal values during the first 2μs (~20,000 bits), and became steady thereafter. Note that other system parameters such as α and λ were optimized in Fig. 3(c), and otherwise, the required training time would increase. An 80k-bit training sequence was sufficient for all conditions studied in this paper.

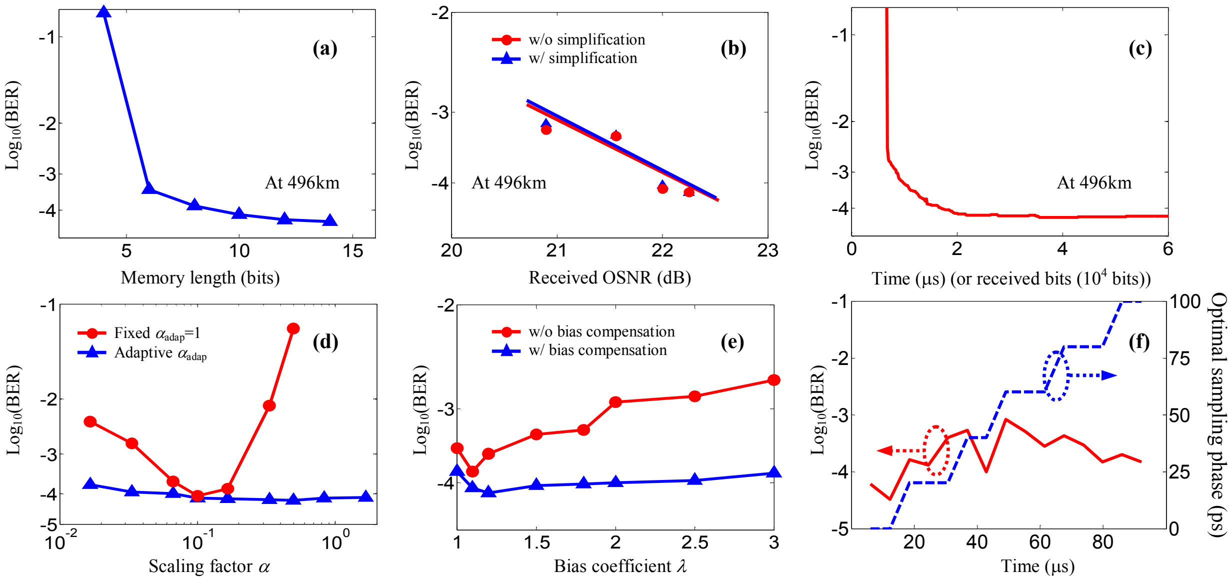


Fig. 3(a) Performance as a function of memory length of full-field FFE; (b) $\log_{10}$(BER) versus OSNR without (circles) and with (triangles) simplified implementation for full-field reconstruction; (c) Variation of $\log_{10}$(BER) versus time (or bits of training sequence) to illustrate the adaptive CD compensation; (d) Performance versus α without (circles) and with (triangles) compensation for gain imbalance; (e) Log_{10}(BER) versus bias coefficient without (circles) and with (triangles) compensation for bias-induced distortion; (f) Variation of optimal sampling phase and performance as a function of time when the sampling phase of full-field FFE is 0 ps. In (b)-(f), the memory length of full-field FFE is 10.

It is essential to optimize the scaling factor α, which arises from mismatched gain between the two receiver chains and is usually unknown in practice, since errors influence the system performance significantly. In Fig. 3(d), we observe that good performance can only be obtained at the optimum value of α without gain compensation (circles). However, adaptive imbalance compensation along with the FFE coefficients (triangles) gives a dynamic range of at least 20dB ([0.017 1.7]) for gain imbalance. The adaptive algorithm also compensates the distortion induced by improper setting of the bias added to $V_x(t)$ as shown in Fig. 3(e). Note that due to AC coupling of the receivers used in the experiment, the absolute bias value added to the signal intensity $V_x(t)$ was $-\lambda\cdot\min(V_x(t))$, where $\min(V_x(t))$ had a negative value and λ should be larger than 1 to avoid noise amplification [3]. From the figure, it can be seen that the adaptive algorithm results in full-field FFE more robust to the bias-induced distortion.

In Fig. 3(f), we illustrate the phase tracking capability of full-field FFE. The dashed line shows the optimum phase of the received data relative to the sampling time base, determined from the fixed dispersion transmission line method [3], and the solid line shows that the continuous adaptation of the FFE coefficients allows the BER to always be below 10^{-3} even for a sampling phase misalignment spanning an entire bit interval.

4. Conclusions

We have investigated full-field FFE in 10Gbit/s OOK-based 496km optical transmission systems, and proposed simplified full-field reconstruction and adaptive system optimization for practical implementation. We have also shown that full-field FFE can greatly enhance the robustness to the sampling phase misalignment. This work was supported by Science Foundation Ireland 06/IN/I969 and Enterprise Ireland CFTD/08/333. We thank BT Ireland for provision of the field-installed optical fibre.

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