Experimental Study of Linear Equalization Combined with MLSE at 10.7 Gbps

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Abstract: We experimentally demonstrate that linear equalization combined with MLSE detection can reduce requirements for sampling speed and number of states versus a stand-alone MLSE detector without linear equalization.

OCIS codes: (060.2330) Fiber optics communications, (060.4510) Optical communications

1. Introduction

Maximum likelihood sequence estimation (MLSE) has long been recognized as a method that could effectively increase the dispersion tolerance of multi-Gb/s direct-detection single mode fiber (SMF) optical links [1]. In recent years, performance of MLSE at 10.7 Gbps to mitigate impairments on these channels has been well studied. The availability of chipsets based on SiGe analog-to-digital converters (ADCs) and CMOS digital signal processing (DSP) engines have facilitated real-time experiments investigating performance in the presence of chromatic dispersion (CD), self-phase modulation (SPM), polarization mode dispersion (PMD), and other impairments [2,3, and references therein].

The seminal paper on MLSE [4] described an optimal receiver for linear intersymbol interference channels in the presence of additive Gaussian noise. That optimal receiver includes a front-end filter that is matched to the transfer function of the linear channel, a T-spaced sampler that converts the continuous-time matched filter output to discrete-time samples spaced at the symbol period, a linear (discrete-time) transversal filter, and a back-end Viterbi decoder. The optimal receiver for a nonlinear ISI channel is more complex [5], but it also includes a transversal filter (actually, a bank of such filters) before the Viterbi decoder.

A word about terminology: while the MLSE receiver described in communications theoretic literature usually includes a transversal filter preceding the Viterbi decoder, the optical communications community usually does not include the transversal filter when referring to an MLSE receiver. Following common practice in optical communications, we will refer to the communications theoretic MLSE receiver as a receiver that combines linear equalization with MLSE.

Relatively few studies have addressed linear equalization combined with MLSE detection for optical fiber channels [6,7]. The experimental work referenced in [2,3] focused on an MLSE receiver without a transversal filter. To our knowledge, this is the first real-time experimental study of combined linear equalization and MLSE detection for an intensity modulated, direct detection (IMDD) single mode fiber application. We investigate performance sensitivity to the length of the transversal filter and sampling rate.

2. Receiver Architecture

This experimental study is enabled by a transceiver chip with architecture described in [8]. The receiver consists of a monolithic CMOS chip with a front-end programmable gain amplifier, synchronous (baud-spaced) analog to digital conversion with an effective number of bits (ENOB) of 5.8, a transversal filter (also called a feed-forward equalizer, or FFE) with a selectable number of taps, and a Viterbi decoder with a selectable number of states (either 4 or 8). The embedded signal processing includes all-digital timing recovery to optimize sampling phase, a digital AGC algorithm, and LMS adaptation of the FFE and channel model of the Viterbi decoder [8].

3. Experimental Setup

The experimental setup is shown in Fig. 1. The pulse pattern generator fed a 2^{31} PRBS pattern at 10.7 Gbps to a deserializer which in turn drove the electrical parallel input of a commercial 300-pin zero-chirp MSA transponder. The tunable source of the MSA transmitter produced an NRZ optical signal at 1549.7 nm with an extinction ratio of 13.2 dB. Fiber spans of approximately 50 km of standard SMF were interspersed with EDFAs. Launch power into each span was approximately +3 dBm. The chromatic dispersion of each span was measured, with an average value of 16.6 ps/(nm km) for the entire link. ASE was added at the end of the fiber link and excess ASE was filtered with a 14 nm CWDM bandpass filter. An ASE filter with .315nm bandwidth was used prior to the PIN/TIA receiver, which received an optical input power of -10 dBm. The MLSE chip received the differential electrical signal from the PIN/TIA, except for the reference CDR measurements. For the reference CDR measurements, the PIN/TIA output was routed to the BERT receiver, which has an internal CDR. For these measurements, the threshold of the BERT receiver was manually optimized to give the best BER.

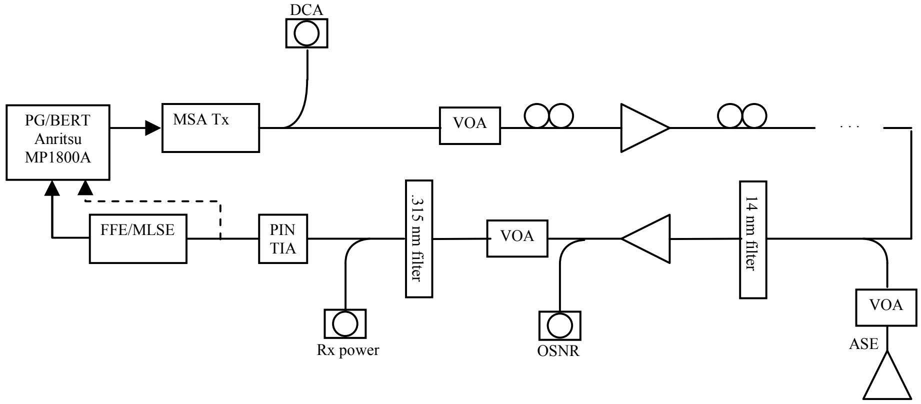


Fig. 1. Experimental Setup

4. Results

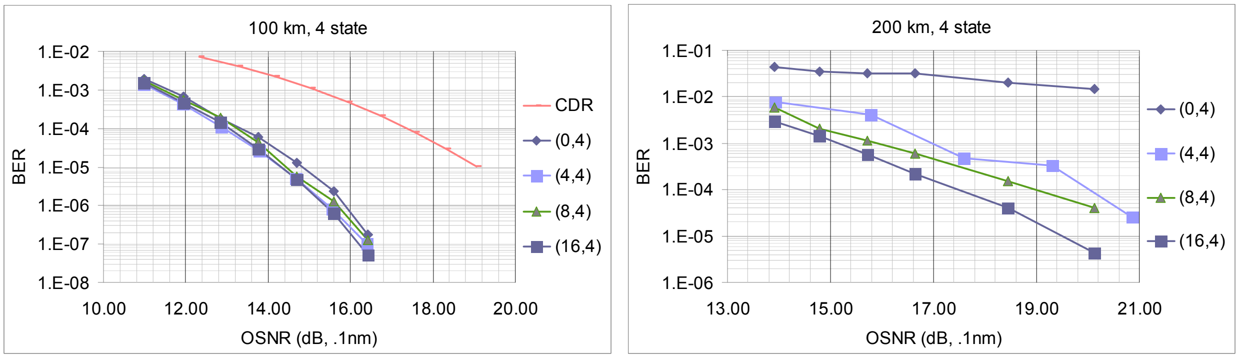


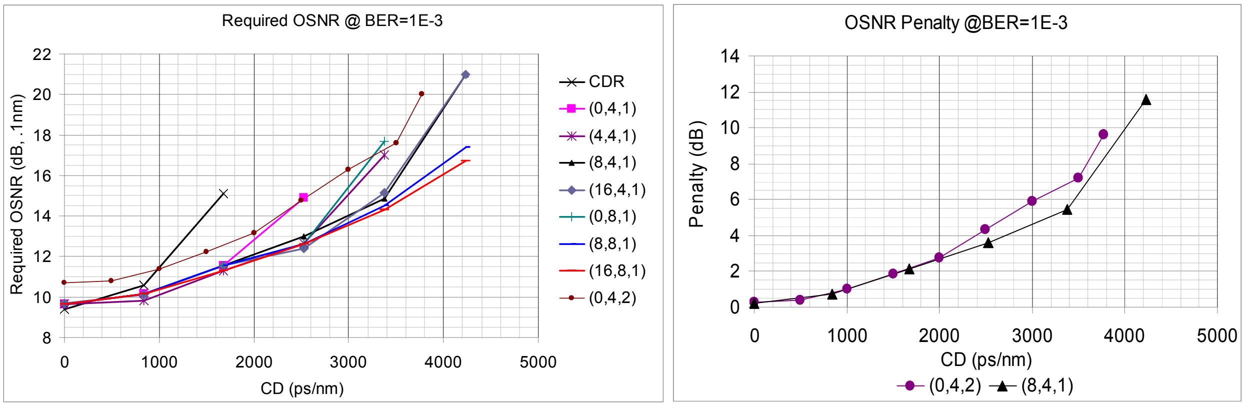
Fig. 2. Four-state results at 100 km and 200 km

Fig. 2 shows results for 4-state MLSE at 100 km and 200 km, where (*m*,*n*) indicates *m* FFE taps and *n* states. (0 FFE taps means that the FFE is bypassed.) The reference CDR curve is shown for 100km, but the CDR could not achieve lock at 200 km. The 100 km case shows that the 4-state MLSE offers a significant advantage over the CDR, but it shows little dependence on the number of FFE taps. The case is very different at 200 km, where the 4-state MLSE without linear equalization could not get below a BER of 1E-2. OSNR for a given BER improves significantly as the number of FFE taps is increased. Similar dependence on FFE length is observed for the 8-state MLSE at 200 km.

Fig. 3a shows required OSNR at a function of chromatic dispersion to achieve a BER of 1E-3. Here *p* in (*m*,*n*,*p*) indicates the number of samples per bit, where *p*>1 indicates oversampling. Data for the 4-state MLSE with *p*=2 is from [3].We highlight a few observations for this application (CD tolerance of IMDD NRZ):

- Little is gained by increasing beyond 8 taps in the FFE.
- To a certain extent, the FFE can be traded off against the number of states (compare (4,4,1) with (0,8,1)).
- Inclusion of an FFE mitigates the need for oversampling (compare (8,4,1) with (0,4,2)). The CDR back-to-back OSNR requirement was different in the two experiments, hence there may be differences in the optical link that do not reflect the MLSE performance (e.g., extinction ratio). We therefore normalize out that

requirement in Fig. 3b. The resultant penalty is the required OSNR minus the back-to-back OSNR requirement for the reference CDR of the respective experiment.



(a) (b)

Fig. 3. Performance at BER = 1E-3. (a) OSNR requirement for various combinations of FFE length, MLSE states, and oversampling ratio. (b) OSNR penalty for oversampled MLSE without FFE and synchronously sampled MLSE with FFE.

5. Discussion and Conclusions

While the IMDD SMF channel departs from the linear ISI channel with additive Gaussian noise described in [4], the transversal filter preceding the Viterbi decoder nevertheless plays an important role in maximum likelihood sequence estimation. The Viterbi algorithm relies on independence of the noise samples (see the discussion of Eq. 58 in [4]). The FFE in principle whitens the noise that is colored after the front end continuous time filter (be it a matched filter or otherwise). We say “in principle” because the FFE may not be long enough to truly whiten the noise, but by minimizing the mean squared error it moves in that direction. The FFE also plays a role in tailoring the residual channel response (after the FFE) to the memory of the finite-complexity Viterbi decoder that follows.

Any practical MLSE receiver realized at multi-Gbps rates involves a compromise of cost, complexity, power consumption, and size. Realizing a front-end matched filter is usually impractical; realizing a bank of matched filters (part of the optimal receiver for a nonlinear channel with additive Gaussian noise [5]) is even more so. Oversampling the received signal helps when high frequency components (above ½ the bit rate) are present. But oversampling, depending on the data rate, may force one into a different technology for the analog-to-digital converter (for example, SiGe BiCMOS instead of conventional CMOS). As CMOS technologies shrink, sampling rates exceeding 25 Gsamples/second become more feasible in standard CMOS. Such rates can be used to oversample at 10 Gbps, or they can be used for synchronously sampled MLSE to support (D)QPSK-based 40 Gbps or polarization multiplexed (D)QPSK-based 100 Gbps. In this study, the synchronously sampled MLSE detector combined with linear equalization performed as well or better than an oversampled MLSE detector without a transversal filter (for a given number of states). Moreover, the linear equalizer may reduce the number of states required in the Viterbi decoder to achieve a given level of performance. The combination of linear equalization with MLSE detection has been shown to effectively enable dispersion compensation in a synchronously sampled CMOS receiver at rates exceeding 10 Gbps.

6. References

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