DFE and BCJR Performance with SD FEC in 112 GBd PAM4 IMDD Systems

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Abstract: Soft information quality of different DSP schemes followed by hybrid soft/hard decision FEC is investigated. We demonstrate in simulations and experiments that BCJR achieves a significant gain over DFE by providing better soft information.

1. Introduction

Demands for faster data center (DC) links with ~40% annual bandwidth growth rate motivate research on ingenious switch architectures, high-bandwidth electrical and optical components, and overall integration. Depending on the link distance, future high-speed connections will require multilevel and multidimensional modulation formats, more sophisticated transmitters and receivers, and low-power advanced digital signal processing (DSP). The transition from intensity-modulation with direct-detection (IMDD) to coherent optical systems in longer links (> 3 km) might be delayed by another generation by using advanced DSP and FEC.

A new generation of 200Gbit/s/lane PAM4 optical transceivers will likely rely on new forward error correction (FEC) schemes [1], probably use advanced equalization methods based on maximum likelihood sequence estimation (MLSE) [2], apply an advanced clock extraction [3], upgrade existing standards [4], use semiconductor optical amplifiers (SOA) and a new frequency grid in WDM links, develop solutions to suppress/compensate multipath interference (MPI) and four-wave mixing (FWM) etc. As electrical links from the pluggable module to the switch ASIC affect performance, co-packaged optics (CPO) [5] may relax power requirements and increase E/O density when new symbol rates are considered. Next advanced generation of DC transceivers will likely carry 1.6/3.2T bits.

Advanced DSP algorithms will remain essential in balancing the performance of co-packaged optical channels and thus increasing the yield and lowering the cost of highly parallelized optical interconnects. 50GB PAM4 transceivers rely on linear feed-forward equalizers (FFE) while 100GBd transceivers have to use advanced equalization algorithms such as decision feedback equalizer (DFE) or maximum likelihood sequence estimation (MLSE). Additionally, the standard KP4 FEC seems to be weak and will be likely replaced by a novel FEC scheme. Different FEC codes have been proposed, however, a concatenated code using soft extended Hamming FEC and KP4 hard FEC [6] seems to be a good choice. The use of a soft-decision inner code requires MLSE to be replaced by a maximum a posteriori probability algorithm such as Bahl, Cocke, Jelinek and Raviv (BCJR) [7] or the BCJR simplification called MaxLogMAP (MLM) [8]. Due to strong intersymbol interference (ISI), DFE and BCJR/MLM will generate different soft information (log likelihood ratios, LLR) quality, which will result in different BER at the FEC output for the same pre-FEC BER. In this paper, we demonstrate that BCJR/MLM outperforms DFE at BER=1e-15 by 1.3 and 2.9 dB of optical sensitivity in simulations and experiments, respectively.

2. Simulation and experimental results

The simulation setup is presented in Fig. 1. The PAM4 symbols are filtered by a root-raised cosine (RRC) filter with a roll-off factor of 0.25. A 4^{th} order Bessel low-pass filter (LPF) s used to emulate the transmitter transfer function. An ideal electro-absorption modulated laser (EML) with infinite extinction ratio realizes the electro-optical conversion and a photodiode (PD) converts from optical to electrical signal and adds noise. The receiver LPF is identical to the transmitter one. After the RRC filter, three different equalization schemes are used. The first one is based on a 21-tap FFE and 1-tap DFE (more DFE taps bring only a negligible gain), the second one uses 21-tap FFE and BCJR based on Gaussian distribution to get LLRs, and the third one employs 21-tap FFE and the MLM using Euclidian distance for branch metric calculation. The last two methods use a 2-tap post filter ($1+\alpha D$) to whiten noise after the FFE block. The total transfer function results in FFE noise amplification that can be quantified by the parameter α. In simulations and experiments, this parameter is close to 0.6 and slightly depends on the input optical power (Pin). A Gray mapping is assumed to compute LLRs after the signal reconstruction blocks (DFE, BCJR, and MLM). The method described in [9] is used to estimate FEC performance without data encoding. Therefore, a scrambler after the signal reconstruction blocks is used to get the zero code word. Due to strong ISI, the LLRs after the equalization blocks are correlated. Therefore, an interleaver is required to improve the performance of the concatenated FEC code. The inner extended Hamming (128,120) code uses the Chase II decoding algorithm

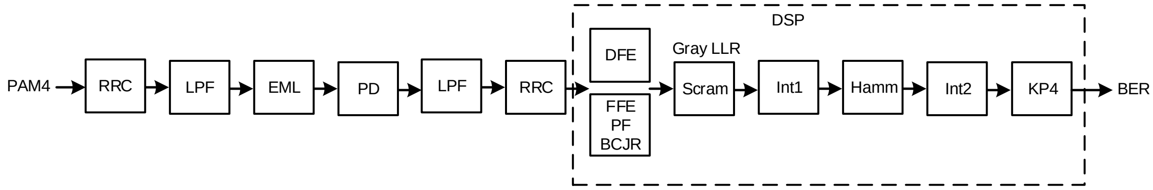

Fig. 1. Simulation setup. RRC – root-raised cosine filter with a roll-off of 0.25, LPF – 4th order Bessel low-pass Bessel, Scram – scrambler, Int – interleaver, Hamm – Hamming decoder

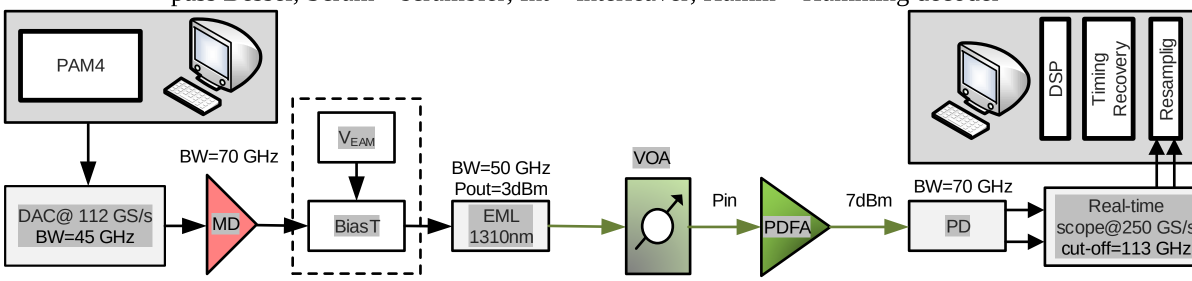

Fig. 2. Experimental setup. VOA – variable optical amplifier, PDFA – Praseodymium-doped fiber amplifier, EML – electro-absorption modulated laser, PD – photo diode, BW – bandwidth

described in [10] with five most unreliable bit positions. The first interleaver (Int1) is a row-column interleaver on PAM4 symbols with a depth of four, interleaving eight Hamming codewords [1]. The Hamming code outputs hard binary decisions that are still affected by correlated errors. Therefore, we use the second interleaver (Int2) that interleaves twelve KP4 codewords operating on KP4 symbols (KP4 symbol consists of ten bits) [6].

The input power is scanned in steps of 0.05 dB and 50 million symbols are processed per step. BER curves versus input power are shown in Fig. 3a. The BCJR and MLM achieve almost identical performance. The DFE performance without FEC lags behind BCJR/MLM by 0.75 dB at BER=4.85e-3 [1]. This gap is increased by 0.55 dB after the concatenated FEC at BER=1e-15 (obtained by using a linear tail extrapolation). The additional BCJR/MLM gain of 0.55 dB is due to better LLR quality. This is also visualized in Fig. 3c showing generalized mutual information (GMI) versus input pre-FEC BER. For the same (pre-FEC) BER, the BCJR/MLM consistently achieves larger GMI than the DFE. This is also visible in Fig. 3e, which shows the curves for BCJR BERout-Hamming BERout (BCJR: BCJR-Hamm in legend) and DFE BERout-Hamming BERout (DFE: DFE-Hamm). By comparing these two curves, one can note that for a pre-FEC BERin=1e-3 the BER after Hamming decoder achieves BERout~4e-5 in case of DFE and 7e-7 in case of BCJR.

The experimental setup is shown in Fig. 2 also including information about the 3dB-bandwidth of the components. The main bandwidth limitations come from the digital-to-analog converter (DAC) and the EML modulator. The EML bias variations were compensated by a DC tap included in the FFE along with the linear taps. The O-band EML output signal is attenuated by a VOA and then amplified by a PDFA, which is necessary because the PD does not include an electrical amplifier. After resampling, timing recovery is used to remove the clock offset and find the best sampling phase. After timing recovery, the signal is downsampled to 1 sps. The FFE consists of 41 linear taps and the DC tap to control DC variations. Nonlinear FFE taps did not bring any gain and therefore were excluded. Similar to simulations, a single tap DFE was enough to achieve good performance. The errors were much more correlated in experiments than in simulations. To get smooth BER curves we use longer interleavers of depth 256 Hamming codewords and 24 KP4 codewords for Int1 and Int2, respectively. BER versus input power is shown in Fig. 3b for the three considered equalization schemes. The BCJR/MLM outperform the DFE at a BER of 4.85e-3 by 1.3 dB that is 0.55 dB more than in simulations. The DFE performance penalty of 1.6 dB after FEC is also much higher than in simulations. The GMI vs input BER shown in Fig. 3d (experiment) is practically identical to the GMI in Fig. 3c (simulation). The GMI curves do not reflect error correlation, however, error correlation and error burst statistics are very critical for the DFE scheme, and probably longer interleavers may decrease the gap between DFE and BCJR/MLM, even though they cannot improve GMI. It is difficult to predict the pre-FEC threshold at output BER of 1e-15 based on tail extrapolation. For BCJR/MLM, simulation results are close to the theory and some published results [1]. However, experimental results show worse performance (lower pre-FEC BER threshold), which might be improved by clever interleaver design.

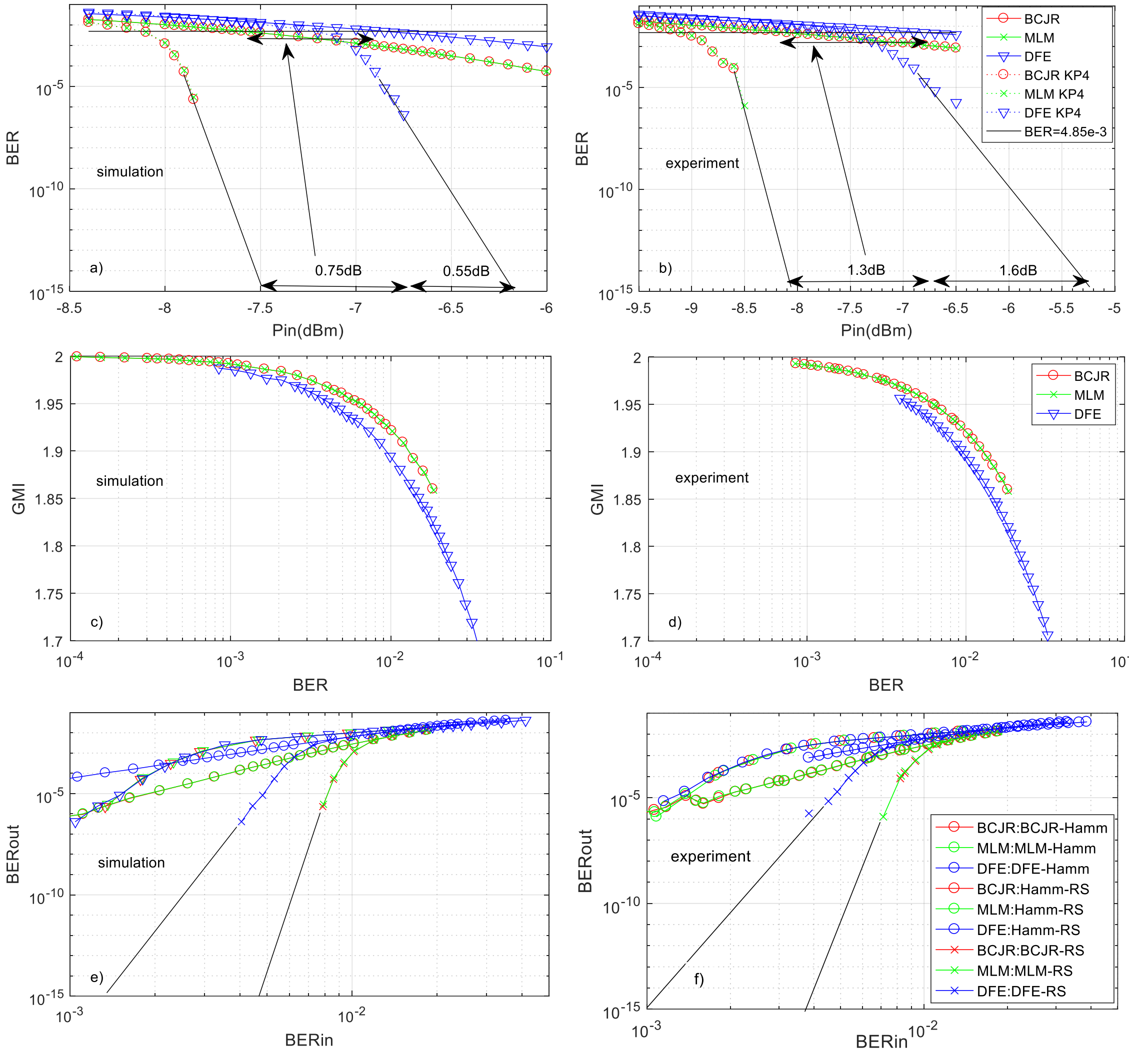

Fig. 3. a) BER vs Pin in simulations, b) BER vs Pin in experiments, c) GMI in simulations d) GMI in experiments, e) BERin vs BERout in simulations, f) BERin vs BERout in experiment

3. Conclusion

We studied the soft information quality for the DFE and BCJR/MLM equalization schemes. The BCJR/MLM significantly outperforms the DFE-based equalizer. The difference results in a performance gap of 0.55 dB and 1.6 dB in simulations and experiments, respectively.

4. References

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