Ultra-Low-Complexity MAP Demapper for Bandwidth-Limited Pluggable Coherent Optics beyond 800G

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Abstract: We reveal the benefit of adding a MAP demapper in bandwidth-limited coherent systems, and study a simplified MAP algorithm achieving a comparable performance with the conventional MAP for 100-GBd 16/64-QAM with more than 8-fold complexity reduction. © 2022 The Author(s)

1. Introduction

The deployment of coherent technologies has been gradually extended from optical transport network to shorter-reach scenarios like datacenter interconnect and metro access at around 100 km. As the 400ZR coherent interface achieved a big success over the past few years, the optical internetworking forum (OIF) has recently announced the start of the 800G coherent project aiming to define interoperable 800G line specifications for the next generation [1]. Considering 400ZR operates at around 60 GBd with dual-polarization (DP) 16-ary quadrature amplitude modulation (QAM), an 800G transceiver would require a higher symbol rate beyond 100 GBd [2,3] using 16-QAM or even higher-order modulation. Due to component bandwidth limitations, it is usually more challenging to maintain the signal integrity when pursuing higher symbol rate. Moreover, there exist various impairments which are severer at higher frequencies, like the finite efficient number of bits (ENoB) of digital-to-analog converters (DAC) and the driver modulator nonlinearity. The ultimate solution to approach the capacity of such colored signal-to-noise ratio (SNR) systems (*i.e.* SNR varies with frequency) would be the multicarrier signaling by adapting the power and modulation format of each subcarrier with its underlying channel condition [4-7]. However, the single-carrier QAM format may be preferred for 800G coherent pluggables because it realizes a smooth upgrade from 400ZR without redesigning the DSP (digital signal processing) ASIC (application specific integrated circuits) for multicarrier. The bandwidth constraint results in a non-flat noise power spectral density (PSD) for a single-carrier signal after the linear feed-forward equalization (FFE), which deteriorates the symbol decision performance. Such an issue has been prominent in the development of 200G per lane IM-DD (intensity modulation direct detection) optics using 100-GBd 4-ary pulse amplitude modulation (PAM-4), and the 800G pluggable MSA (multi-source agreement) group has suggested an additional equalizer using the hard-decision (HD) output maximum likelihood sequence estimation (MLSE) to enhance the PAM-4 decision [8]. Following a similar idea, in this paper, we apply a low-complexity maximum a posteriori probability (MAP) decoder in a bandwidth-limited 100-GBd 16/64-QAM coherent system with a line rate of 800G/1.2Tbps, that demaps symbols to both HD bits and log-likelihood ratios (LLRs) suitable for soft-decision (SD) forward error correction (FEC). With respect to the FFE-only receiver, the extra MAP demapper achieves around 2-dB optical SNR (OSNR) sensitivity gain, which is promising to be implemented in future low-cost 800G coherent receivers to enhance the system margin.

2. Reduced-complexity M-BCJR algorithm

For a bandwidth-limited system with colored SNR, it is known that partial-response (PR) signaling can improve the symbol decision performance. The simplest PR filter has two taps with an impulse response $1 + \alpha D$, where D denotes one tap delay and α is the weight. A common duobinary signal has $\alpha = 1$, but the optimum α for a particular system would deviate from 1 depending on its frequency response. A PR filter can be deployed either at the transmitter as a pre-equalizer [9], or at the receiver as a noise whitening filter (NWF) [10]. Despite its location, the filter induces inter-symbol interference (ISI) that shall be removed by a post-equalizer like a MAP or MLSE decoder. The computational complexity of a MAP/MLSE decoder is predominantly determined by the number of states per trellis stage $N_{states} = X^L$, namely, $O(X^L)$, where X is the alphabet size of the modulation and L is the memory length of the PR filter. For a complex-valued 2-D format like QAM, X can be treated as the 1-D alphabet size by decomposing the complex-valued signal to two real-valued ones. Assuming a coherent system requires 2 or 3 taps of PR memory, the decoder is simple for 4-QAM, but may burn substantial DSP power for higher-order formats like 16/64-QAM being considered in 800G+ coherent optics. While MAP/MLSE has been utilized in recent coherent experiments [11] to approach the extreme performance, we mainly focus on its complexity reduction in this paper and study if it can be simplified for the low-cost coherent pluggables. We exploit a reduced-state MAP decoder based on the BCJR algorithm named M-BCJR [12]. M-BCJR limits N_{states} to a fixed number M by discarding non-significant states with low probabilities at each trellis stage. We reveal below M can be much smaller than X^L, leading to a greatly reduced complexity $O(M)$.

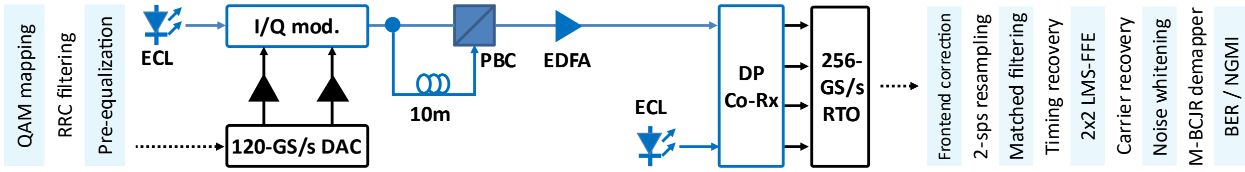

Fig. 1. Experimental setup. RRC: root-raised cosine filter; ECL: external cavity laser; mod.: modulator; DAC: digital-to-analog converter; PBC: polarization beam combiner; EDFA: Erbium-doped fiber amplifier; DP: dual-polarization; Co-Rx: coherent receiver; RTO: real-time oscilloscope; sps: sample per symbol; LMS: least mean square; FFE: feed-forward equalizer; NGMI: normalized generalized mutual information.

3. Experimental setup

We study the M-BCJR algorithm in a 100-GBd coherent system with the experimental setup illustrated in Fig. 1. The electrical signal is generated by a pair of 8-bit CMOS DACs sampling at 120 GSa/s, and then amplified by a pair of 55-GHz RF amplifiers. The signal drives a single-polarization $LiNbO_3$ I/Q Mach-Zehnder modulator (MZM) with a 3-dB bandwidth of around 35 GHz and a smooth decay of frequency response to beyond 50 GHz. The light source is a 1550-nm external cavity laser (ECL) with <100-kHz linewidth and 16-dBm output power. The DP signal is emulated by polarization combining the modulator output with its 10-m decorrelated copy. The signal is back-to-back (BtB) tested with amplified spontaneous emission (ASE) noise loading for OSNR sensitivity measurement. The signal is intradyne detected by a standard coherent receiver with >70-GHz bandwidth, whose outputs are digitized by a 4-channel 100-GHz real-time oscilloscope (RTO) sampling at 256 GSa/s.

The offline transmitter DSP maps the bits to 16/64-QAM symbols, and then perform Nyquist pulse shaping using a root-raised cosine (RRC) filter at 2 sample per symbol (sps) with a roll-off factor of 0.01. The 100-GBd signals are resampled to 120 GSa/s and pre-equalized before loading to the DAC. As the receiver has >70-GHz bandwidth, the bandwidth constraint is mainly induced by the transmitter. Without pre-equalization (PE), the accumulated power attenuation at the spectrum edge of 50 GHz is close to 30 dB. We use a linear PE whose coefficients are optimized to maximize the overall SNR, which is not a zero-forcing filter to avoid noise enhancement at low-SNR frequencies [13]. The received spectra comparison with and without PE is similar to what was reported in [6]. The receiver performs routine offline coherent DSP as illustrated in Fig. 1. We use a complex-valued 2×2 least mean square (LMS) FFE at 2sps for channel equalization. The equalizer then down-samples the signal to 1sps for the following carrier recovery and BCJR decoding. The BCJR demapper outputs the LLR of bits. We evaluate the system performance using both HD and SD FEC metrics. For HD-FEC with the metric of bit error rate (BER), we take the signs of LLR as the HD of bits. For SD-FEC, we calculate normalized generalized mutual information (NGMI) from the LLR as the SD metric.

4. Results and discussions

To reveal the colored-SNR effect due to the bandwidth limit, we calculate the noise in the 100-GBd 16-QAM system by comparing the baseband signal $d(t)$ after QAM mapping and the recovered signal $s(t)$ after equalization and carrier recovery, namely, $Noise = s(t) - d(t)$, and illustrate the noise PSD in Fig. 2(a). Clearly, the noise power is enhanced for higher frequency, leading to around 12-dB difference between DC and the Nyquist frequency of 50 GHz. The signal $s(t)$ should pass through a NWF for the subsequent MAP demapping, and a longer NWF can achieve higher degree of whitening at the cost of longer ISI memory. We try both 2-tap (*i.e.*, $1 + \alpha D$) and 3-tap NWFs whose filter coefficients are extracted by the auto-regressive spectral estimate of the noise PSD [10]. In Fig. 2(a), the 2-tap NWF has greatly shrunk the PSD fluctuation to around 4 dB, and the 3-tap NWF only brings marginal improvement. Fig. 2(b) compares the OSNR sensitivity of the 100-GBd 16-QAM signal with and without MAP demapping. Despite the error floor, the MAP demapper brings a substantial OSNR gain of around 2-3 dB. The extra gain of the 3-tap decoder is marginal with respect to the 2-tap one, which is predicted by the comparison of whitened noise PSD in Fig. 2(a). A 2-tap BCJR decoder should calculate $N_{states} = 16$ probabilities per trellis stage for 16-QAM. We use the M-BCJR concept explained in Section 2 to simplify the decoder. Surprisingly, using an extremely small $M = 2$, M-BCJR can achieve a BER performance almost overlapping with that of the full-state BCJR.

Fig. 3(a) shows the OSNR sensitivity for the 100-GBd 64-QAM system. The MAP demapping gain is slightly smaller than that for 16-QAM. For ZR applications over around 100 km, the system OSNR is usually at or above 35 dB. The MAP demapper provides about 2-dB OSNR gain for 64-QAM at this region. Like what we observed for 16-QAM, the extra gain of the 3-tap decoder is marginal, and M-BCJR can achieve a similar BER performance with BCJR using $M = 2$. As the 64-QAM signal exhibits >1e-2 BER, it is more suitable to use SD than HD for FEC decoding. Fig. 3(b) shows the NGMI for the (M-)BCJR decoder with 2-tap memory to reveal the SD performance. M-BCJR is known to degrade the LLR quality because it frequently produces empty likelihoods $\mathcal{L}_{\pm 1}$ which leads to infinite LLRs without reliable estimate of their magnitudes. This is clearly indicated by the corrupted NGMI of M-BCJR when $M = 2$ in Fig. 3(b). This issue can be alleviated by increasing M, which retains more probabilities at each

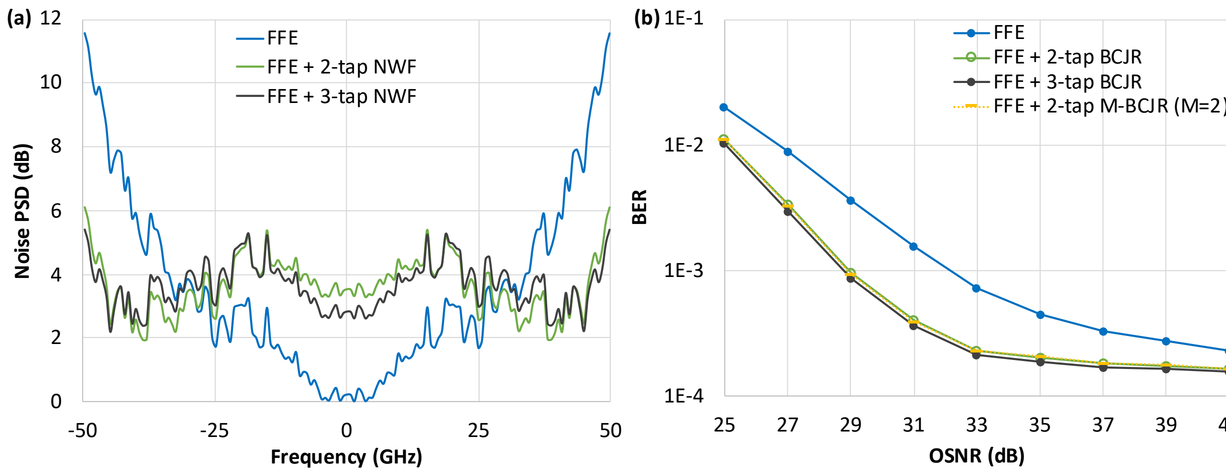

Fig. 2. 100-GBd 16-QAM: (a) noise power spectral density (PSD) without or with noise-whitening filter (NWF); (b) OSNR sensitivity.

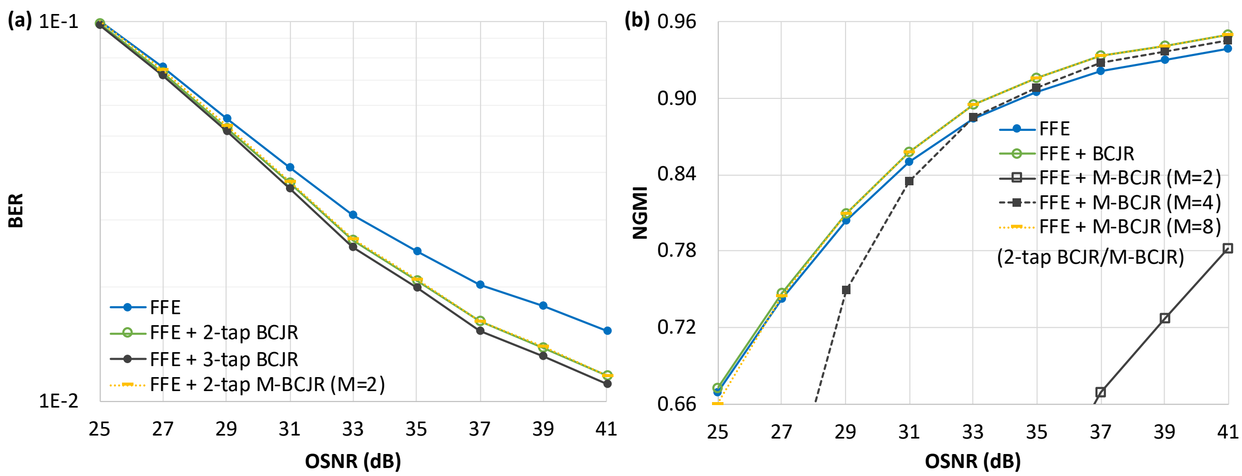

Fig. 3. 100-GBd 64-QAM OSNR sensitivity characterized by (a) BER and (b) NGMI. All the (M-)BCJR decoders in (b) have 2-tap memory.

trellis stage to better estimate the LLR magnitude. In Fig. 3(b), $M = 4$ greatly improves the NGMI at the high OSNR region, and $M = 8$ almost results in the same NGMI performance as the full-state 2-tap BCJR with $N_{states} = 64$.

5. Conclusions

We demonstrate around 2-dB OSNR sensitivity gain in an 800G-class coherent system using a simple MAP demapper as a post-equalizer. The M-BCJR algorithm can effectively reduce the computational complexity of the BCJR decoder for both HD and SD FECs, making it suitable to be implemented in future low-cost coherent optics beyond 800G.

6. References

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