50G PON FEC Evaluation with Error Models for Advanced Equalization

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Abstract: Post-equalization bit-errors from ISI-impaired 50G PON transmission experiments are modeled using Fritchman's Markov chain. LDPC FEC evaluation with this error model reveals a 0.3-0.6 dB optical power penalty for equalizing ISI including 83 ps/nm dispersion.
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1. Introduction

Hard-decision input low-density parity-check (LDPC) codes have been adopted for forward error correction (FEC) in several modern communications systems such as the IEEE 802.3ca 25 Gb/s passive optical network (PON) [1]. The binary symmetric channel (BSC) model is predominantly used for FEC performance evaluation with hard decision inputs. Nevertheless, in order to assess FEC performance in more realistic conditions with correlated errors, the 802.3ca LDPC code was also evaluated in a burst error channel modeled using the 2-state Gilbert-Elliot (GE) Markov chain that emulated the error behavior at the decision feedback equalizer (DFE) output prior to FEC decoding [2].

The ITU-T is currently developing a 50 Gb/s per wavelength PON standard using binary non-return to zero (NRZ) signaling, where the wavelength of 1342±2 nm and a reach of 20 km have been agreed upon for downstream transmission; this corresponds to a worst-case chromatic dispersion (CD) of 74 ps/nm [3]. To keep costs low, leveraging components from the data center eco-system such as the lower bandwidth 25 Gb/s class components is key [4]. At the same time, 50G PON must minimally offer a similar range in optical budgets as previous lower rate systems. Consequently, at these high symbol rates, complex receiver equalization schemes such as maximum likelihood sequence estimation (MLSE) or continuous-time linear equalizer (CTLE) with DFE are necessary to combat the inter-symbol interference (ISI) introduced by limited bandwidth components as well as reduced tolerance to CD [3].

In this paper, we perform 50 Gb/s PON transmission experiments with advanced equalization schemes, and characterize the error correlation at the equalizer output using the relative probabilities of consecutive error events, also referred to as error-clusters. A sub-class of Fritchman's Markov-chain models (FMMs) [5] is used as a generative model that fits the measured error-cluster probabilities. Errors generated by these models are then used to evaluate the performance of an LDPC code down to the target bit-error rate (BER) of 1E-12.

2. *N*-state Fritchman's Markov chain model for consecutive errors

Error-cluster probabilities have been previously used to characterize the error behavior of PON systems [2,6]. The 2-state GE Markov chain used to model the error-cluster distribution (ECD) at the output of a DFE [2] is capable of modeling a constant ratio between probabilities of consecutive errors for an arbitrary average probability of bit error. However, this model is not adequate to represent more complex ECD behavior. In fact, the GE model can be considered as a special case of the error generating model using partitioned Markov chains first proposed by Fritchman [5]. The FMM has been extensively used in wireless communications to model the error-free run distribution (EFRD), i.e., gap between two error events, and ECD [7].

In this paper, we consider an LDPC code similar to that of [1] for 50G PON and focus on accurate modeling of the ECD at the input to the LDPC decoder (i.e., after equalization). Note that more complex modeling using both ECD and EFRD simultaneously is possible but not pursued here. Consequently, an *N*-state FMM having a single good (error-free) state G, and *N*-1 bad (error) states, $B_i, i \in 1, \dots, N-1$. is considered. Further, the model is constrained such that: (a) the good state is only allowed to transition to the first bad state B_1 or to itself, (b) each of the *N*-2 bad states $B_i, i \in 1, \dots, N-2$, can transition to G, to itself, or to the next bad state B_{i+1}, and (c) the last bad state B_{N-1} can transition only to itself or to G. A transition to a bad state results in a bit error (binary '1'), while a transition into the good state indicates the absence of an error (binary '0'). Such an *N*-state FMM can be shown to accurately model the ECD up to length *N*-1 and the asymptotic slope as the cluster length tends to infinity. For this study, it is adequate to limit N to 4 based on the measured data. The 4-state FMM is shown in Fig. 1(a). We can show that the probability of an error-cluster of length n, i.e., a sequence of exactly n 'ones' bookended by 'zeros', denoted as p_n is given as

$$p_1 = (1-g)(1-\varepsilon_1-b_1);\ \ p_2 = (1-g)[b_1(1-\varepsilon_1-b_1)+\varepsilon_1(1-\varepsilon_2-b_2)];$$

$$p_n = b_1 p_{n-1} + (1-g)\, b_2^{n-2}\varepsilon_1(1-\varepsilon_2-b_2) + (1-g)\,\varepsilon_1\varepsilon_2(1-b_3)\sum_{i=0}^{n-3} b_2^i b_3^{n-3-i}, n \geq 3\,. \qquad (1)$$

The parameters b_i and ε_i model the relative cluster length probabilities with respect to p_1 and may be determined by curve fitting techniques [7]. The parameter g serves as a normalizing factor to ensure that the desired average BER, P_e, is met. Given $P_e, b_i, \varepsilon_i, i = 1,2,3$, the value of g is determined by

$$g = 1-\left((1-b_1)(1-b_2)(1-b_3)P_e/\left((1-P_e)(1-b_2-b_3+b_2b_3+\varepsilon_1-b_3\varepsilon_1+\varepsilon_1\varepsilon_2\right)\right). \qquad (2)$$

Also, the 2-state GE model of [2] is obtained from the 4-state FMM by setting $\varepsilon_1 = \varepsilon_2 = b_2 = b_3 = 0$.

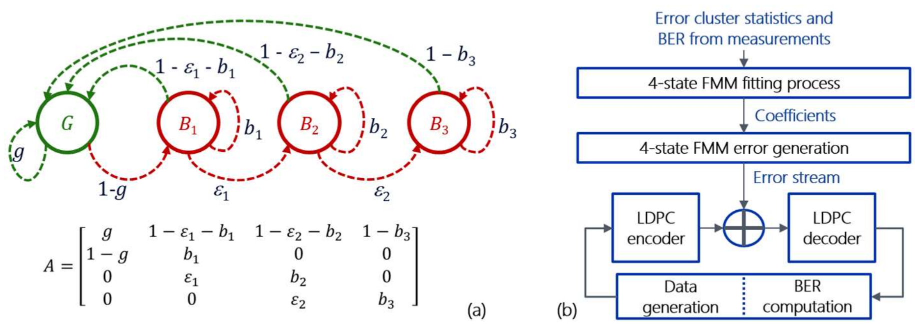

Fig. 1(a). 4-state Fritchman's Markov model and its transition matrix A. (b) Error modeling and simulation process.

3. 50G PON measurements with equalization, error modeling, and LDPC simulation results

Figure 2(a) shows the experimental setup for optical transmission measurements with 50 Gb/s NRZ signaling at 1342 nm using a 25 Gb/s class avalanche photo diode (APD) trans-impedance amplifier (TIA) receiver. Measurements are performed for both back-to-back (b2b) transmission and transmission over 30 km of our standard single-mode fiber (SSMF) corresponding to 83 ps/nm of dispersion, which covers the worst case for PON systems [3]. The received signal is equalized using either (a) a 3-tap MLSE or (b) a CTLE with 6-tap DFE (CTLE + DFE). Figure 2(b) shows the corresponding BER vs. received optical power (ROP); we see that for the typical LDPC hard decision BER threshold of 1E-2, the MLSE provides a gain of ~3 dB in the b2b case and ~3.4 dB for 30 km SSMF. A significant portion of the equalization is devoted to overcoming the bandwidth limitation; yet, the impact of CD is not negligible and leads to a 0.7 dB residual penalty after MLSE equalization. The CTLE + DFE performs slightly worse and provides a gain of ~2.8 dB for b2b and ~3.1 dB for 30km SSMF, and the residual CD penalty is ~0.8 dB.

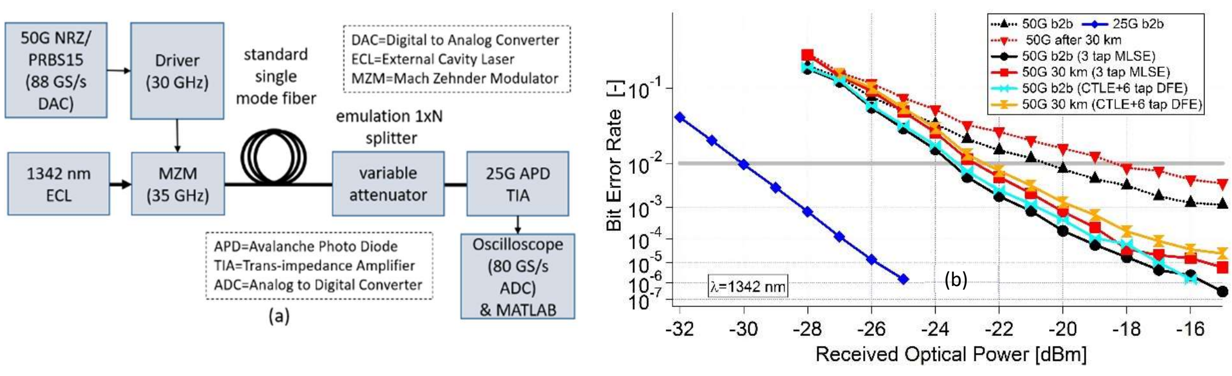

Fig. 2 (a). Experimental setup for 50G optical transmission at 1342nm. (b) BER vs. ROP with and without equalization.

Figure 3(a) shows the ECD normalized to the 1-error event probability as a function of the cluster length. Solid lines with filled markers indicate measurement data for points in Fig. 2(b) near or above the 1E-2 BER threshold for cases with and without equalization. All plotted measurement data correspond to 50 Gb/s experiments unless noted otherwise. When 25 Gb/s experiments are carried out with the same APD-TIA, the ECD of the b2b non-equalized received signal is very close to that of the BSC corresponding to the average BER, thereby indicating minimal correlation (ISI). On the other hand, with 50 Gb/s transmission, the ECD without equalization already deviates from that of the BSC ('30 km uneq' and 'b2b uneq' curves). After MLSE equalization, the probability of longer error-clusters increases significantly. This effect is even more pronounced with CTLE + DFE, where for example, after equalizing for 30 km transmission, the probability of 3-clusters roughly equals that of 2-clusters and probabilities of longer clusters decrease at a constant relative ratio of ~0.46. We fit these ECDs with the 4-state FMM and use the resulting FMM as a generative model to inject errors prior to LDPC decoding; this process is depicted in Fig. 1(b). In Fig. 3(a), dotted lines with like colors show the ECD of corresponding fits using the 4-state FMM obtained using Eq. (1). The fit parameters were manually determined, although curve fitting techniques may also be used to compute them. It is clearly seen that the 4-state FMM is capable of accurately capturing the relative behavior of error clusters of length 1 to 3, and then the asymptotic slope as the cluster length increases. Simulated ECDs for the BSC as well as the 2-state GE model with b = 0.5 are provided as dashed lines for reference.

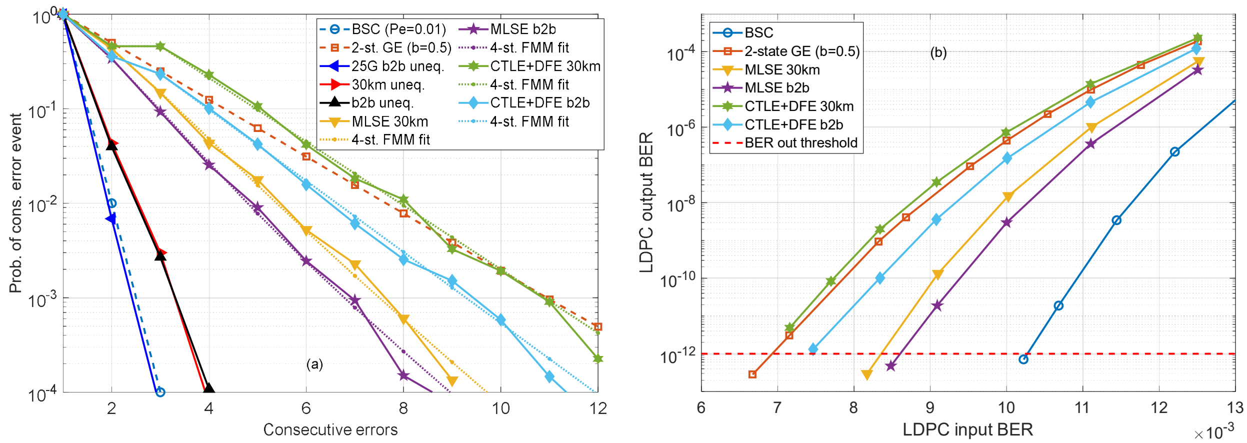

Fig 3(a). Probability of consecutive error events (normalized to 1-error event probability) vs. consecutive error length; measured results are shown with solid lines and solid markers. (b) Information bit BER after LDPC decoding vs. average BER at the decoder input.

Figure 3(b) plots the LDPC decoder output BER vs. input BER for a variant of the IEEE 802.3ca quasi-cyclic LDPC code [1] with a code rate of ~0.85. Each simulation point is based on 500 or more bit errors. In general, the ECD for a given equalization scheme varies as a function of the BER; however, these variations are observed to be minimal in the narrow window of BERs over which the LDPC code is evaluated; hence, a fixed set of FMM parameters (other than g) is used to generate each curve. With the BSC channel, the target output BER of 1E-12 is achieved at an input BER of 1.03E-2, while with the GE b = 0.5 channel, the input BER is 6.9E-3. For the 4-state fit to the 30 km MLSE measurements, the input BER is 8.3E-3; referring to Fig. 2(b), this reduction in input BER with respect to the BSC to achieve an output BER of 1E-12 translates to an optical power penalty (OPP) of 0.3 dB due to correlated errors at the output of the MLSE. Even in the b2b MLSE case, the required input BER is 8.6E-3; this translates to an OPP of ~0.15 dB. Similarly, with CTLE + DFE, the expected input BERs required to meet the target are 6.8E-3 and 7.4E-3 for 30 km and b2b, which translate to OPPs of ~0.6 dB and ~0.3 dB, respectively.

4. Conclusions

To our knowledge, this is the first time that consecutive error behavior at the output of different equalization schemes for 50G PON transmission experiments with transceiver bandwidth limitation and dispersion has been accurately represented using Markov models with more than two states. Evaluation of a variant of the 802.3ca LDPC code [1] using this model to generate errors shows optical power penalties of 0.3 dB and 0.6 dB for equalizing a 30 km transmission using MLSE and CTLE+DFE, respectively. This penalty should be included in the PON link budget calculation when comparing equalization schemes that introduce correlated errors at the LDPC decoder input.

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5. References

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