Channel Matching: An Adaptive Technique to Increase the Accuracy of Soft Decisions

Reza Rafie Borujeny and Frank R. Kschischang
Department of Electrical and Computer Engineering
University of Toronto, Toronto, Ontario, M5S 3G4, Canada.
rafi@ece.utoronto.ca, frank@ece.utoronto.ca

Abstract: Nonlinear interference is modeled by a time-varying conditionally Gaussian channel. It is shown that approximating this channel with a time-invariant channel imposes considerable loss in the performance of channel decoding. An adaptive method to maintain decoding performance is described. © 2021 The Author(s)

1. Introduction

To meet the stringent reliability requirements of optical networks, some form of forward-error-correction (FEC) is usually employed. One important class of FEC schemes uses an inner low-density parity-check (LDPC) coded modulation scheme—which may suffer from an error floor—concatenated with an algebraic outer code. Two popular approaches used to achieve the required bit error rate (BER) seen by the outer code are bit-interleaved coded modulation (BICM) [1] and multi-level coding (MLC) [2].

It is well-known that the fiber nonlinearity causes inter-channel interactions that, eventually, cap the spectral efficiency of a wavelength-division multiplexed (WDM) system [3]. Each WDM channel leaks energy into neighboring channels which is impossible to perfectly mitigate due to the absence of the neighboring WDM channels at a given receiver. The resulting inter-channel interference is usually considered as a nuisance and is referred to as nonlinear interference noise (NLIN) [4]. Usually, NLIN is assumed to be additive and is modeled by a Gaussian random vector whose covariance is a function of the average power of the neighboring channels, the instantaneous power of the channel of interest, the modulation and demodulation format and the fiber parameters. Amongst other factors, the average power of the neighboring channels has the most significant contribution in the NLIN covariance [5]. At the same time, it is known that the average power of WDM channels can fluctuate [6, 7] which, in turn, causes fluctuations in the covariance of NLIN. If the fluctuations of the noise parameters are not properly taken into account, the soft information fed into the FEC decoder may be inaccurate. In this work, we study the importance of having accurate soft information on the performance of the decoder.

We take the inner MLC-based coded modulation scheme of [8] for our baseline system, although similar results are expected with BICM. We assume a time-varying conditionally Gaussian channel in which, conditional on the input, the noise covariance is a function of the average power of the WDM channels. We model the fluctuations of the average power through the second order statistics of the noise and consider the performance of the inner MLC scheme with two main strategies: with a fixed estimate of the NLIN power and with an adaptive estimate of the NLIN power. Our main finding is that if one does not adaptively match the soft information to the conditions of the channel, considerable degradations in decoding performance are caused. These results are also compared against a hypothetical genie-aided decoder having access to perfect channel state information.

It is shown that the simple strategy of re-estimating the noise covariance based on the currently decoded codeword can significantly improve the performance of the inner code. This simple idea is the main ingredient of turbo equalization [9] and has been previously used to compensate for channels with inter-symbol interference. This includes the compensation of intra-channel effects in optical fiber (see [10] and references therein) as well as inter-channel nonlinear equalization [11]. The application of turbo equalization for channel estimation has also been considered for some linear channels [12].

2. Simulation Setup and Channel Model

We simulate a single-polarization WDM system with five channels over a fiber of length 4500 km with the adaptive split-step Fourier method of [13]. In each run, the split-step model with periodic boundary conditions is solved for trains of 3600 symbols. It is assumed that each span of length $L_s = 50$ km is followed by an erbium-doped fiber amplifier (EDFA). The fiber loss is set to $\alpha = 0.2$ dB·km$^{-1}$. The nonlinearity coefficient is set to $\gamma = 1.27$ W$^{-1}$·km$^{-1}$ and the chromatic dispersion coefficient is set to $\beta_2 = -21.67 \times 10^{-24}$ s$^2$·km$^{-1}$. The amplified spontaneous emission (ASE) noise is assumed to be a circularly symmetric white Gaussian process with power spectral density $A_{\text{ASE}}^\text{EDFA} = (e^{\alpha L_s} - 1)h\nu n_{sp}$ where $h = 6.626 \times 10^{-34}$ J·s is Planck’s constant, $\nu = 193.41$ THz is the center frequency, and $n_{sp} = 1$ is the spontaneous emission factor. The channel spacing is assumed to be 50 GHz and a 16-QAM constellation is used. About 6.67% of the channel spacing is reserved for a guard band.

Root-raised-cosine pulses with 6.67% excess bandwidth are used for pulse shaping. As a result, the symbol rate per WDM channel is 43.95 Gsymbol · s⁻¹. At the receiver, the channel of interest—the center channel—is filtered and digitally back-propagated, and the result is passed through a matched filter. The obtained points are commonly back rotated to undo the effect of cross-phase modulation. All WDM channels are assumed to have the same average input power \( P_{in} \). The achieved mutual information under uniform input distribution is shown in Fig. 1b. With a maximum at \(-6.8\) dBm, this curve suggests that \( P_{in} \) must be set to the optimal value of \(-6.8\) dBm.

We model data transmission in a WDM system with a time-varying conditionally Gaussian channel with input random variable \( X \) and output random variable \( Y \). The input alphabet \( \mathcal{X} \) is the 16-QAM constellation in use, while the output alphabet \( \mathcal{Y} \) is the whole complex plane (see Fig. 1a).

Ideally, one wishes to operate on the optimal input power, or very close to it, so that the data rate can be maximized with aid of an appropriate choice of FEC. Because of the dynamics of the network, some power fluctuations may happen which in turn result in reductions in the achievable information rates. Our goal here is to capture such fluctuations and make sure that the FEC block is aware of them. This is achieved by re-estimating the noise parameters and making sure that the soft information used by the FEC decoder is accurate.

### 3. Multi-level Coding

We consider a similar MLC transmission scheme as in [8] with a 16-QAM constellation and an inner LDPC code of rate 0.63 which gives an overall inner coded modulation information rate of 3.63 bits per symbol. We study the performance of the inner coded modulation scheme under three scenarios, namely, obtaining noise covariance based on the optimal input power, a genie-aided decoder and an iterative channel estimation. We define the survivability of the inner coded modulation as the range of power fluctuations that it can tolerate while still maintaining the BER below a prescribed target BER. In our running example, the target BER is set to \(10^{-3}\). We compare these three decoding methods in terms of their survivability.

**Fixed Noise Covariance:** In this scenario, the inner decoder calculates the soft information based on the optimal input power, i.e., the noise parameters are those induced by the optimal input power. This means that the noise covariance is assumed to be fixed, despite the fact that the actual average power experiences fluctuations. The results are shown in Fig. 2b. When the receiver uses a fixed set of noise parameters based on the optimal power with a target BER of \(10^{-3}\), the MLC is successful as long as the average input power (in dBm) lies in \([-8.2, -5.2]\). That is, the survivability of this method is 3 dB.

**Perfect Channel State Information:** In this scenario, it is assumed that a genie provides the inner decoder with the true noise statistics. This corresponds to the availability of perfect channel state information at the receiver. The corresponding power interval that the MLC performs below the target BER of \(10^{-3}\) is \([-10.5, -4.2]\) dBm with a survivability of 6.3 dB, i.e., about 3.3 dB more survivability in comparison with having fixed estimates for the noise statistics. The results are shown in Fig. 2b.

**Channel Matching:** In this scenario, the inner code initially calculates soft information based on the optimal power. The decoded codeword is then remapped to the corresponding constellation points similarly to the way that the transmitter performs the mapping of the codeword to the constellation points. By considering the difference between these symbols and the actually received symbols, maximum likelihood estimates of the noise statistics are obtained. The updated noise statistics are then used to update the soft information fed to the decoder in a
Fig. 2: Structure of the adaptive decoder of this work is shown in (a). Performance of the inner coded modulation scheme, in terms of BER, is shown in (b).

turbo-equalizer fashion. Fig. 2a shows the structure of the turbo LDPC decoder used in this work. There are two parameters, namely $r_1$ and $r_2$, that determine the number of iterations performed: $r_1$ counts the number of iterations performed by the LDPC decoder before re-estimating the noise parameters while $r_2$ counts the number of “turbo” iterations performed to re-estimate the noise parameters. The performance of this method is illustrated in Fig. 2b. Depending on the choice of $r_1$ and $r_2$, different survivabilities can be obtained. This provides an interesting trade-off between decoding complexity and reliability. One can see that with 3 turbo iterations and 3 LDPC decoding iterations, the survivability is virtually identical to that of the genie-aided decoder.

References

1. G. Caire, G. Taricco, and E. Biglieri, “Bit-interleaved coded modulation,” IEEE Transactions on Inf. Theory 44, 927–946 (1998).
2. U. Wachsmann, R. F. Fischer, and J. B. Huber, “Multilevel codes: Theoretical concepts and practical design rules,” IEEE Transactions on Inf. Theory 45, 1361–1391 (1999).
3. R. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, “Capacity limits of optical fiber networks,” J. Light. Technol. 28, 662–701 (2010).
4. R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, “Accumulation of nonlinear interference noise in fiber-optic systems,” Opt. express 22, 14199–14211 (2014).
5. P. Poggiolini, “The GN model of non-linear propagation in uncompensated coherent optical systems,” J. Light. Technol. 30, 3857–3879 (2012).
6. P. M. Krumrich and K. Kotten, “Extremely fast (microsecond timescale) polarization changes in high speed long haul WDM transmission systems,” in Optical fiber communication conference, (Optical Society of America, 2004), p. F13.
7. D. Kilper, S. Chandrasekhar, and C. White, “Transient gain dynamics of cascaded erbium doped fiber amplifiers with re-configured channel loading,” in Optical Fiber Communication Conference, (Optical Society of America, 2006), p. OTuK6.
8. M. Barakat, D. Lentner, G. Böcherer, and F. R. Kschischang, “Performance-complexity tradeoffs of concatenated FEC for higher-order modulation,” J. Light. Technol. 38, 2944–2953 (2020).
9. C. Douillard, M. Jézéquel, C. Berrou, D. Electronique, A. Picart, P. Didier, and A. Glavieux, “Iterative correction of intersymbol interference: Turbo-equalization,” Eur. Transactions on Telecommun. 6, 507–511 (1995).
10. I. B. Djordjevic, L. L. Minkov, and H. G. Batshon, “Mitigation of linear and nonlinear impairments in high-speed optical networks by using LDPC-coded turbo equalization,” IEEE J. on Sel. Areas Commun. 26, 73–83 (2008).
11. O. Golani, M. Feder, and M. Shtaif, “NLIN mitigation using turbo equalization and an extended Kalman smoother,” J. Light. Technol. 37, 1885–1892 (2019).
12. S. Song, A. C. Singer, and K. Sung, “Soft input channel estimation for turbo equalization,” IEEE Transactions on Signal Process. 52, 2885–2894 (2004).
13. O. V. Sinkin, R. Holzlöhner, J. Zweck, and C. R. Menyuk, “Optimization of the split-step Fourier method in modeling optical-fiber communications systems,” J. Light. Technol. 21, 61–68 (2003).