Joint Demapping and Decoding for DQPSK Optical Coherent Receivers

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Abstract: We present a low-complexity joint demapper-decoder scheme for coherent optical receivers with DQPSK modulation. The new technique reduces to 0.7dB the gap between QPSK and DQPSK in 100Gb/s coherent optical systems.

1. Introduction

Coherent detection based receivers with electronic dispersion compensation (EDC) are being considered for next generation optical transport networks (OTN) [1]. Quadrature phase shift keying (QPSK) modulation is the leading candidate for 40Gb/s and 100Gb/s OTN. However, QPSK may suffer from ±π/2 phase jumps or cycle slips (CS’s), which are induced by phase noise. These CS’s lead to catastrophic bit errors that cannot be corrected with forward error correction (FEC) codes. The use differential QPSK (DQPSK) modulation avoids the CS problem at the expense of some performance degradation.

Powerful FEC codes with iterative soft-decoding are required for ≥100 Gb/s coherent optical transmission systems. In DQPSK receivers, a demapper block is used to provide soft information to the iterative channel decoder. Traditional low complexity demappers are based on a serial concatenated architecture (SCA), as depicted in Fig. 1 [2]. However, as we shall show later, the performance of this suboptimal approach with DPQSK modulation is around 1.5 dB worse than that achieved with QPSK [3]. This performance degradation can be combated by using a turbo concatenated architecture (TCA) or a joint architecture (JA) (see Fig. 1). The use of these iterative decoding techniques based on the Bahl, Cocke, Jelinek, and Raviv (BCJR) algorithm, has been reported in past literature [4]. Unfortunately, the high complexity of BCJR-based iterative decoders makes prohibitive their implementation in multigigabit per second commercial optical receivers.

This paper presents a low complexity joint demapper and decoder (JDD) architecture for coherent DQPSK modulation. In order to reduce complexity, the proposed JDD is built upon the sum product algorithm (SPA) [5]. Although our JDD is general, we consider here its application with low density parity check (LDPC) FEC codes. The new JDD extends the Factor Graph (FG) of the LDPC code by including the minimum set of additional factor and variable nodes to represent the statistical relationship between blocks of coded bits and received signals. This way, the accuracy of the decoding process of bit blocks can be improved at every iteration over a joint factor graph that includes both the demapper and channel decoding functions. We analyze the JDD using DQPSK modulation with Gray mapping and an LDPC code with 20% overhead (OH) with net-effective coding gain (NCG) of 11.3 dB at a bit-error-rate of 10^{-15} [6]. Simulation results show that the new JDD improves significantly the performance of DQPSK, providing a 0.6 dB gain over the traditional SCA [2].

2. System Model

Figure 2-(A) shows the transmit system. The information bits b_k are grouped into blocks of K-bits, i.e., b ∈ {0,1}^K. Each data block b is encoded with an LDPC code obtaining an N-bit block c ∈ {0,1}^N where N is even. Codewords c are mapped into a sequence of N/2 QPSK complex symbols s, with s ∈ {1,i,-1,-i}^{N/2}. Finally, the components of the transmitted symbol block d is computed using differential modulation, i.e., d_k = d_{k-1}·s_k, where k = 1,...,N/2 and d_0 = 1. The discrete-time baseband receiver signal is given by

r_k = d_k + n_k

where k = 1,...,N/2 and n_k are independent identically distributed (iid) complex Gaussian random variables with zero mean and variance N_0.
These messages can be computed as:

\[ \Delta \phi = \sum_{n=0}^{3} \mu_{\psi_k}^{(y_k, y_{k+1})} \phi_{e^{i \phi}} \]

We derive a soft-input soft-output (SISO) joint demapper decoder by applying the SPA over the FG of the joint a posteriori probability (APP) mass function \( P(c | r) \) of the coded bits given the received symbols. Based on the Bayes rule, we get \( P(c | r) = f(r | c)P(c) \). Term \( f(r) \) can be neglected for detection, thus the soft decision can be performed over \( f(r | c)P(c) \). Since \( c \rightarrow s \rightarrow d \rightarrow r \) is a Markov chain, the probability density function \( f(r | c)P(c) \) can be expressed as:

\[ f(c | r)P(c) = \prod_{k=1}^{N/2} f(r_k | d_k) \prod_{k=1}^{N/2} f(d_k | c_{2k-1}, c_{2k}) \prod_{l=1}^{M} Q(c_{(i)}) \]

Figure 2-(B) shows the FG of \( f(r | c)P(c) \) according to eq. 2. The messages from node \( x \) to node \( y \) are denoted by the vector \( \mu_{x|y} \). The messages between nodes \( c \) and \( y \) are computed using the standard SPA for LDPC codes. The messages between nodes \( c \) and \( y \) are 2 dimensional vectors whose components \( \mu_{c|y}(b) \) for \( b \in \{0, 1\} \) represent bit probabilities. The messages between nodes \( \psi, d \) and \( \rho \) are 4 dimensional vectors whose components \( \mu_{\psi|d|\rho}(e^{i \phi}) \) for \( \phi \in \{0, \frac{\pi}{3}, \pi, \frac{2\pi}{3}\} \) represent symbol probabilities. The notation \( x(y) \) represents the two cases of equation, one case using \( x \) and other case using \( y \). These messages can be computed as:

\[ \mu_{d_k}^{\psi_k}(e^{i \phi}) = \sum_{n=0}^{3} \mu_{\psi_k}^{(y_k, y_{k+1})} \phi_{e^{i \phi}} \]

\[ \mu_{\psi_k}^{(y_k, y_{k+1})}(e^{i \phi}) = \frac{\mu_{\psi_k}^{(y_k, y_{k+1})} \phi_{e^{i \phi}}}{\sum_{n=0}^{3} \mu_{\psi_k}^{(y_k, y_{k+1})} \phi_{e^{i \phi}}} \]

\[ \mu_{\psi_k}^{(y_k, y_{k+1})}(e^{i \phi}) = \frac{\mu_{\psi_k}^{(y_k, y_{k+1})} \phi_{e^{i \phi}}}{\sum_{n=0}^{3} \mu_{\psi_k}^{(y_k, y_{k+1})} \phi_{e^{i \phi}}} \]

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where \( \Delta(n, m) = \frac{(m-n+2mn)\pi}{2} \).
4. Numerical Results

Figure 3 shows the BER versus the signal-to-noise ratio per bit ($E_b/N_0$) for the proposed JDD with DQPSK modulation. An LDPC code of length 24576 bits and rate 0.8334 is used. The number of iterations in the FG is set to 20. Perfect knowledge of the noise power $N_0$ is assumed at the receiver size. The performance of an SCA based on the soft DQPSK demapper defined by eqs. (4) and (5) in [2], as well as the performance with QPSK modulation and optimal demapping, are also presented for comparison proposes. At least, 1000 errors were counted at each simulation point. Note that JDD provides a 0.6 dB gain at BER=$10^{-4}$ respect to SCA. Furthermore, note that the gap between QPSK and DQPSK is reduced to 0.7 dB.

5. Conclusions

A new low complexity JDD scheme for coherent DQPSK modulation has been presented. An SPA-based demapper has been developed to reduce implementation complexity. Numerical results have shown that JDD outperforms traditional SCA. This good tradeoff between complexity and performance makes the proposed JDD an excellent alternative to improve the performance of DQPSK modulation in next generation optical transport networks.

References

1. D. Crivelli, H. Carter, and M. Hueda, “Adaptive digital equalization in the presence of chromatic dispersion, PMD, and phase noise in coherent fiber optic systems,” in “Global Telecommunications Conference (GLOBECOM), IEEE,” (2004).
2. M. Kuschnerov, S. Calabro, K. Piyawanno, B. Spinnler, M. Alfiad, A. Napoli, and B. Lankl, “Low complexity soft differential decoding of QPSK for forward error correction in coherent optic receivers,” in “Optical Communication (ECOC), 36th European Conference and Exhibition on,” (2010).
3. T. Mizuochi, Y. Miyata, K. Kubo, T. Sugihara, K. Onohara, and H. Yoshida, “Progress in soft-decision FEC,” in “Optical Fiber Communication Conference and Exposition (OFC/NFOEC), and the National Fiber Optic Engineers Conference,” (2011).
4. P. Hoeher and J. Lodge, “‘Turbo DPSK’: iterative differential PSK demodulation and channel decoding,” Communications, IEEE Transactions on 47, 837–843 (1999).
5. A. Worthen and W. Stark, “Unified design of iterative receivers using factor graphs,” Information Theory, IEEE Transactions on 47, 843–849 (2001).
6. D. Morero, M. Castrillon, F. Ramos, T. Goette, O. Agazzi, and M. Hueda, “Non-concatenated FEC codes for ultrahigh speed optical transport networks,” in “Global Telecommunications Conference (GLOBECOM), IEEE,” (2011).