Performance of Joint Iterative Detection and Decoding in Coherent Optical Channels

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Abstract: We show that a joint iterative detection and decoding algorithm compensates phase noise and laser frequency fluctuations in a 100 Gb/s coherent optical receiver with non-differential 16-QAM modulation, achieving 1 dB gain over existing solutions.
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1. Introduction

Multi-gigabit coherent fiber optic systems based on quadrature phase shift keying (QPSK) and M-ary quadrature amplitude modulation (M-QAM) are being considered to satisfy the projected increase on the bandwidth demand. In these devices, carrier phase recovery (CPR) algorithms are required to compensate effects such as laser phase noise and carrier frequency fluctuations [1–3]. However, since most of the M-QAM schemes considered for practical applications have rotational symmetry, errors in the carrier phase estimation may cause cycle slips (CS). After a CS occurs, all detected symbols are erroneous and they cannot be corrected by forward error correction (FEC) codes [1]. To counteract this catastrophic effect, *differential* modulation is typically used [1]. While this option mitigates the CS problem, its sensitivity in terms of signal-to-noise ratio (SNR) is worse than that achieved by non-differential schemes. To avoid the penalty of differential modulation formats, the use of pilot symbols has been proposed in previous literature [4, 5]. Although the catastrophic bit errors caused by CS's can be mitigated by pilot symbols [6], their occurrence cannot be avoided and performance degradation will be experienced in the presence of high laser phase noise power. This degradation, caused by practical limitations of an *explicit* CPR, is exacerbated by laser frequency instabilities introduced by mechanical vibrations, power supply noise, etc. [3]. These frequency fluctuations are modeled as a frequency modulation with a sinusoid of large amplitude (e.g., ~ 500 MHz) and low frequency (e.g., ≤ 35 kHz). It has been shown that the performance of explicit CPR such as Viterbi&Viterbi (V&V) or blind phase search (BPS) [2] is seriously degraded in the presence of high laser frequency fluctuations [3].

Recently, a V&V CPR followed by a turbo decoding stage has been proposed to combat phase noise in optical communications [7, 8]. In order to avoid the use of an explicit CPR stage, in this work we use a joint iterative detection and decoding (JIDD) algorithm proposed in [9] for satellite applications. The derivation of this scheme is based on the use of factor graph and the application of the sum product algorithm (SPA) framework, employing pilot symbols in combination with powerful FEC codes such as low density parity check (LDPC). Unlike previous turbo decoding techniques proposed for optical coherent communications, JIDD does not require an explicit CPR stage. This way, both (*i*) the performance degradation experienced by explicit CPR in the presence of frequency fluctuations, and (*ii*) CS's caused by errors in the carrier phase estimation are avoided. We present simulation results of post-FEC bit error rate (BER) for non-differential 16-QAM in a 100 Gb/s optical coherent system that uses the LDPC code with 20% overhead and net coding gain (NCG) of 11.3 dB at BER $= 10^{-15}$ proposed in [10]. Our study shows that JIDD with a pilot rate of 5% is able to completely compensate laser frequency fluctuations with amplitudes as high as 700 MHz and high phase noise as the present in non-linear operation[1]. Our results also show that gains higher than 1 dB can be achieved with JIDD over existing solutions such as [3] as a result of the modulation format (i.e., differential vs. non-differential).

2. The JIDD Algorithm

The received signal at the input of the carrier phase recovery can be expressed as

$$r_k = c_k e^{j\theta_k} + z_k \tag{1}$$

[1] It has been shown that the Wiener process can be also used to model nonlinear phase noise [11].

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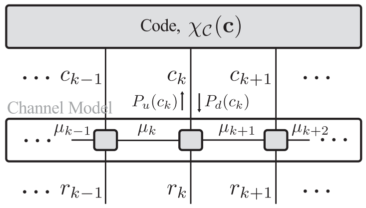

Fig. 1. Normal factor graph of JIDD.

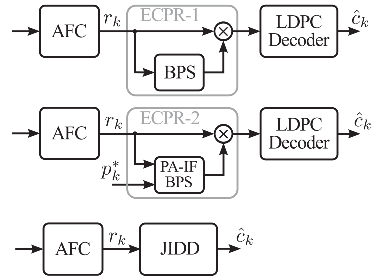

Fig. 2. Block diagrams of the CPR schemes.

where $c_k \in \mathscr{M}$ is the k-th transmitted M-QAM symbol with constellation $\mathscr{M}$, and θ_k is the total phase noise. Component z_k represents the amplified spontaneous emission (ASE) noise sample, which is modeled as a white complex Gaussian random variable with power $2\sigma^2$. Let $\Delta\nu$ and T be the total laser linewidth parameter and the symbol duration, respectively. The received phase θ_k can be expressed as

$$\theta_k = \theta_{k-1} + \phi_k + w_k \tag{2}$$

where w_k is a white real Gaussian process with variance $\sigma_w^2 = 2\pi\Delta\nu T$ [1]; $\phi_k = 2\pi T f_c + \Delta\Omega_k$ where f_c is the residual carrier frequency offset after the automatic frequency control (AFC). Term $\Delta\Omega_k$ represents the phase change generated by frequency fluctuations, which can be modeled as $\Delta\Omega_k \approx 2\pi A_p T \cos(2\pi T \Delta f_c k)$, where A_p and Δf_c are the amplitude and frequency of the modulation tone, respectively.

Denote $\mathbf{c} = \{c_0, c_1, \ldots, c_{K-1}\}$ with $c_i \in \mathscr{M}$ the coded symbol block of length K to be transmitted, and $\mathbf{r} = \{r_0, r_1, \ldots, r_{K-1}\}$ the received symbol block. In the following analysis, ϕ_k is assumed to be constant in a symbol block (i.e., $\phi_k = \phi$, $k = 0, \ldots, K-1$). To implement the *maximum-a-posteriori* (MAP) detector, the *a posteriori probability* (APP) $P(c_k|\mathbf{r})$ must be evaluated. Towards this end, JIDD uses the *sum-product algorithm* (SPA) on a *factor graph* (FG) to evaluate the joint APP distribution function

$$p(\mathbf{c}, \theta, \phi|\mathbf{r}) \propto \chi_{\mathscr{C}}(\mathbf{c}) \prod_k p(r_k|c_k, \theta_k)\, p(\theta_k|\theta_{k-1}, \phi)\, p(\phi) \tag{3}$$

where $\chi_{\mathscr{C}}(\mathbf{c})$ is the code indicator function defined as 1 if $\mathbf{c}$ is a codeword of the channel code $\mathscr{C}$ constructed over the constellation $\mathscr{M}$ and 0 otherwise; $\theta = \{\theta_0, \ldots, \theta_{K-1}\}$ is the sequence of the channel phase noise. The normal factor graph of the JIDD algorithm is depicted in Fig. 1 (see [9] for more details).

3. Numerical Results

We investigate the performance of the JIDD algorithm in the presence of laser phase noise and frequency fluctuations. We consider a non-dispersive optical channel, a baud rate of $1/T = 32$ Giga-baud with 16-QAM modulation (i.e., the bit rate is 128Gb/s). We use the LDPC code with 20% overhead and net coding gain of 11.3 dB at BER $= 10^{-15}$ proposed in [10]. We focus our study on the post-FEC BER as a function of the signal-to-noise ratio per information bit (E_b/N_0), which considers the penalty caused by the code overhead and the pilot symbols. Simulation results for JIDD are analyzed and compared to those of two alternative solutions based on an explicit carrier phase recovery denoted as *ECPR-1* and *ECPR-2* (see Fig. 2). ECPR-1 is the BPS carrier recovery algorithm [2] with differential modulation. On the other hand, ECPR-2 is a pilot-aided scheme that employs an interpolation filter followed by BPS with non-differential modulation [12]. ECPR-1 and ECPR-2 use an LDPC decoder with 50 iterations, while JIDD employs 20 inner iterations for each update of $P_d(c_k)$ from $P_u(c_k)$ and 50 outer iterations of $P_d(c_k)$ in each codeword. Equally spaced pilot symbols of the highest amplitude allowed by the constellation are used. Several values of the pilot rate (P_R) are considered for the pilot-aided schemes with non-differential modulation (i.e., JIDD and ECPR-2). Results without laser phase noise and frequency fluctuations are also included for comparison purposes. This scheme (denoted as *Ideal CPR*) uses an LDPC decoder with 50 iterations.

The robustness of JIDD in the presence of laser frequency fluctuations is analyzed in Fig. 3(a). We consider $\Delta\nu =$ 500 kHz, $\Delta f_c = 35$ kHz, and $A_p = 500$ MHz. Notice the drastic performance degradation achieved by both ECPR-1 and ECPR-2. In this case, JIDD with $P_R = 5\%$ is the only scheme that achieves an acceptable performance with ~ 0.5 dB penalty. Fig. 3(b) shows the penalty versus the frequency amplitude A_p for JIDD with $\Delta f_c = 35$ kHz, $\Delta\nu = 250$

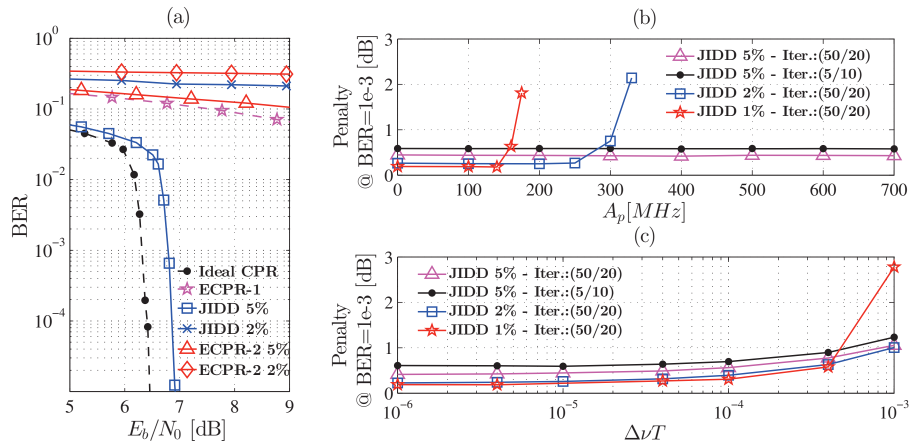

Fig. 3. Performance of JIDD. Label "*Iter.: (A/B)*" denotes *A* outer iterations with *B* inner iterations.

kHz, $P_R = 1$, 2, and 5%. Notice that frequency amplitudes as high as $A_p = 700$ MHz can be tolerated by JIDD with $P_R = 5\%$. Furthermore, note that the extra degradation of JIDD with $P_R = 5\%$, 10 inner iterations, and 5 outer iterations is only ~ 0.2 dB. Fig. 3(c) investigates the tolerance to the laser phase noise in the presence of frequency fluctuation with $A_p = 140$ MHz and $f_c = 35$ kHz. In this case, note that the performance of JIDD is practically insensitive to laser phase noise when $\Delta\nu T < 2\times10^{-4}$ (e.g., $\Delta\nu < 6.4$ MHz at $1/T = 32$ Giga-baud).

4. Conclusion

The excellent performance of JIDD in high-speed transmission over optical channels with laser frequency fluctuations and high phase noise (as experienced in nonlinear operation [11]) has been demonstrated. We realize that, unlike previous turbo decoding techniques proposed for optical coherent communications, the JIDD-based decoding scheme does not suffer from CS's caused by explicit CPR.

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