Optical Fiber Technology 24 (2015) 5–14

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

On the performance of joint iterative detection and decoding in coherent optical channels with laser frequency fluctuations

Mario A. Castrillón [a],*, Damián A. Morero [b], Oscar E. Agazzi [c], Mario R. Hueda [a]

[a] Laboratorio de Comunicaciones Digitales, Universidad Nacional de Córdoba, CONICET, Av. Vélez Sarsfield 1611, Córdoba X5016GCA, Argentina
[b] ClariPhy Argentina S.A., Córdoba 5000, Argentina
[c] ClariPhy Communications, Inc., 7585 Irvine Center Drive, Suite 100, Irvine, CA 92618, USA

ARTICLE INFO

Article history:
Received 28 August 2014
Revised 8 April 2015
Available online 4 May 2015

Keywords:
Coherent detection
LDPC
Joint iterative detection and decoding
Phase noise
16QAM
DWDM

ABSTRACT

The joint iterative detection and decoding (JIDD) technique has been proposed by Barbieri et al. (2007) with the objective of compensating the time-varying phase noise and constant frequency offset experienced in satellite communication systems. The application of JIDD to optical coherent receivers in the presence of laser frequency fluctuations has not been reported in prior literature. Laser frequency fluctuations are caused by mechanical vibrations, power supply noise, and other mechanisms. They significantly degrade the performance of the carrier phase estimator in high-speed intradyne coherent optical receivers.

This work investigates the performance of the JIDD algorithm in multi-gigabit optical coherent receivers. We present simulation results of bit error rate (BER) for non-differential polarization division multiplexing (PDM)-16QAM modulation in a 200 Gb/s coherent optical system that includes an LDPC code with 20% overhead and net coding gain of 11.3 dB at BER = 10^{-15}. Our study shows that JIDD with a pilot rate $\leqslant 5\%$ compensates for both laser phase noise and laser frequency fluctuation. Furthermore, since JIDD is used with non-differential modulation formats, we find that gains in excess of 1 dB can be achieved over existing solutions based on an explicit carrier phase estimator with differential modulation. The impact of the fiber nonlinearities in dense wavelength division multiplexing (DWDM) systems is also investigated. Our results demonstrate that JIDD is an excellent candidate for application in next generation high-speed optical coherent receivers.

1. Introduction

Multi-gigabit coherent fiber optic systems based on quadrature phase shift keying (QPSK) and *M*-ary quadrature amplitude modulation (*M*-QAM) are currently being deployed in carrier networks. High spectral efficiency modulation and coding schemes are being considered to satisfy the projected increase of the bandwidth demand [2] and to enable advanced networking concepts such as the flexible grid and software defined optical networks. Carrier phase recovery (CPR) is a key function of intradyne coherent optical QPSK/*M*-QAM receivers [3,4]. In these devices, CPR algorithms are required to track effects such as laser phase noise and carrier frequency fluctuations [5].

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 [3]. To counter this catastrophic effect, *differential* modulation is typically used [3]. In this modulation technique, the information is transmitted as the phase difference between two consecutive symbols. Therefore, the effects of a CS do not translate into catastrophic bit error bursts. While this option provides a solution to the CS problem, its sensitivity in terms of signal-to-noise ratio (SNR) is worse than that achieved by non-differential schemes. For instance, a penalty of 1.2 dB has been reported for differential QPSK modulation [6]. To avoid the penalty of differential modulation formats, the use of pilot symbols has been proposed in previous literature [7–9] to prevent error propagation in non-differential modulation.

Although the catastrophic bit errors caused by CS can be mitigated by pilot symbols [10], their occurrence cannot be avoided and performance degradation will be experienced in the presence of high laser phase noise. This CS degradation caused by practical limitations of an *explicit* CPR is exacerbated by laser frequency

---

* Corresponding author.
E-mail address: acastrillon@efn.uncor.edu (M.A. Castrillón).
URL: http://lcd.efn.uncor.edu (M.A. Castrillón).

http://dx.doi.org/10.1016/j.yofte.2015.04.002
1068-5200/

instabilities introduced by mechanical vibrations including power supply noise [5]. These frequency fluctuations are modeled as sinusoidal frequency modulation of large amplitude (e.g., $\sim$500 MHz) and low frequency (e.g., $\leqslant$35 kHz).

In this work we investigate the performance of a joint iterative detection and decoding (JIDD) algorithm in optical systems based on pilot symbols and powerful FEC codes such as low density parity check (LDPC). JIDD uses the soft-output information on the coded symbols provided by the decoder and performs forward–backward recursions, taking into account carrier phase information. Although performance evaluation of JIDD has been addressed in the past (e.g., see [1] and references therein), its behavior in high-speed transmissions over optical channels with laser frequency fluctuations and phase noise has not been reported so far.

The JIDD technique analyzed in this work builds upon the algorithm proposed in [1] for satellite channels with random time-varying carrier phase and constant unknown frequency offset. We present simulation results of post-FEC bit error rate (BER) for non-differential polarization division multiplexing (PDM)-16QAM in a 200 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 [11]. 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 [5]. We highlight that this performance is achieved without the need of a traditional CPR stage such as the *blind phase search* (BPS) carrier recovery algorithm [4]. Furthermore, our results demonstrate that JIDD achieves gains higher than 1 dB over existing solutions based on an explicit CPR with differential modulation [5].

This paper is organized as follows. Section 2 investigates the impact of the laser frequency fluctuations in optical coherent receivers with LDPC codes and existing carrier phase recovery algorithms. The JIDD algorithm is investigated in Sections 3 and 4. The performance of the proposed receiver in the presence of nonlinear effects is analyzed in Section 5. Conclusions are drawn in Section 6. To facilitate the reading of this paper, abbreviations most frequently used are listed in Table 1.

2. Impact of laser frequency fluctuations in optical coherent systems with LDPC codes

Figs. 1 and 2 show a simplified model of the PDM coherent optical transmitter and receiver, respectively. The components in phase and quadrature of transmitted symbols for each polarization modulate the intensity and/or phase of corresponding output of the polarization beam splitter (PBS) of the transmitter laser (TL) through parallel Mach–Zehnder modulators (MZM) arranged in a Mach–Zehnder super-structure. Then, the modulated signals of each polarization are combined in the polarization beam combiner (PBC). The optical fiber introduces chromatic dispersion, polarization mode dispersion, as well as attenuation. Optical amplifiers (OA) deployed periodically along the fiber compensate the attenuation and introduce amplified spontaneous emission (ASE) noise. At the receiver, the optical signal is mixed with a local oscillator (LO) laser, the system operates with intradyne detection. The mixing of the received signal and LO with a 90° hybrid of 4 outputs (HY) gives the in-phase and quadrature components for each polarization, which are then fed to balanced photodiodes. This scheme allows suppressing the relative intensity noise (RIN). The TL and LO lasers can be either distributed feedback (DFB) or external cavity laser (ECL). The four signals are sampled twice per symbol period (i.e., the sampling rate is $2/T$ with T being the symbol duration) and fed into a digital signal processor (DSP). The DSP implements the main receiver functions, such as coarse carrier recovery (CCR), compensation of chromatic dispersion (CD) and polarization mode dispersion (PMD), timing recovery (TR), etc.

Table 1
List of commonly used abbreviations.

Acronym	Definition
ASE	Amplified spontaneous emission
BPS	Blind-phase search
CCR	Coarse carrier recovery
CD	Chromatic dispersion
CPR	Carrier phase recovery
DMT	Dispersion-managed transmission
DWDM	Dense wavelength division multiplexing
FDE	Frequency domain equalizer
FEC	Forward error correction
FFE	Feed-forward equalizer
GN	Gaussian noise
JIDD	Joint iterative detection and decoding
LDPC	Low density parity check
NLI	Nonlinear interference
PDM	Polarization division multiplexing
PLL	Phase-locked loop
PMD	Polarization mode dispersion
QAM	Quadrature amplitude modulation
S-JIDD	Simplified JIDD
UT	Uncompensated transmission

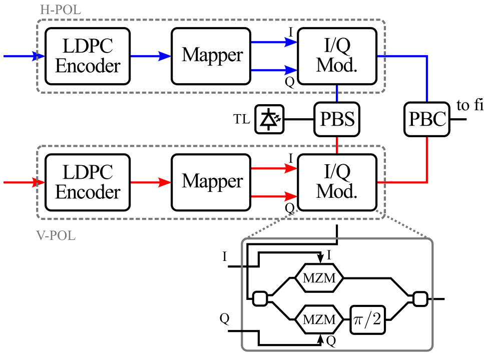

Fig. 1. Block diagram of PDM coherent optical transmitter with LDPC under consideration.

The CCR block estimates the carrier frequency offset (e.g., based on the spectral shift of the received signal) and compensates it in order to achieve a capture range of several GHz.[1] The chromatic dispersion is compensated typically by a frequency domain equalizer (FDE). The fiber length is automatically identified during the startup and the response of the filter is programmed accordingly. A $T/2$ *multiple-input multiple-output* (MIMO) feedforward equalizer (FFE) performs the polarization demultiplexing and the compensation of PMD and polarization-dependent loss (PDL). An adaptation algorithm is essential in optical channels since the receiver must track nonstationary effects (PMD, PDL, changes in the state of polarization of the TX or LO lasers, etc.). Towards this end, decision-directed LMS and/or the constant modulus algorithm (CMA) are typically used. A low latency phase-locked loop (PLL) is included to get tentative decisions required to implement the FFE adaptation algorithm [5,12]. Since most part of the carrier frequency offset has already been compensated by the CCR, the PLL is required mainly to track short-term frequency instabilities of the lasers as well as part of the phase noise [5]. To avoid the cycle slips introduced by the PLL in transmission with non-differential modulation, the signal not demodulated by the PLL is fed to the CPR. Therefore the CPR block must be able to track high-frequency laser phase noise, nonlinear phase noise as well as laser frequency fluctuations. Finally, the samples are processed by the soft decision demapper (SDD) which provides the soft information used by the iterative LDPC decoder to estimate the transmit bit.

---

[1] Due to the low bandwidth of the CCR loop, short-term frequency instabilities of the laser as well as correlated phase noise cannot be tracked.