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Numerical analysis of 50 Gbaud homodyne coherent receivers relying on line-coding and injection locking in lasers

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ABSTRACT

We present a numerical analysis of 50 Gbaud coherent detection enabled by injection locked lasers and line coding. The coherent receiver was tested with respect to an ideal receiver for two higher order modulation formats (16-QAM, QPSK) and under diverse operating regimes relating to the slave laser linewidth properties, the injection level and the frequency detuning between the incoming signal and the slave laser. The impact of the slave laser properties and line coding techniques on the receiver performance is highlighted showing that the technique could be used as a practical solution in order to enable low-cost and short reach $n \times 100$ Gb/s Ethernet communication systems with the potential of flexibility in terms of the data rate.

1. Introduction

The use of coherent detection for the support of long-haul high capacity optical communication links is nowadays the unique roadmap for all system vendors. People from both academia and industry judge that transmission should take place in the optical domain, however the processing required to extract complex modulation formats should be completely carried out digitally in the electronic domain. This approach is currently known as “digital coherent detection” and assigns carrier synchronization, linear impairments compensation and even nonlinear impairments partial compensation at the electronic backend of the receiver enabled by powerful analog to digital converters (ADCs) and complex digital signal processing (DSP) modules. This approach is definitely very reliable, however it is limited in bandwidth, it is power greedy and expensive, so up to date its use is foreseen only for the long-haul part of the optical network [1]. The penetration of coherent detection into metro and access links could be radical and viable if part of the functionalities of the coherent receiver were transferred to the optical domain using real-time analog photonic processing. Indeed, the cost per bit should be affordable for telecom operators in metro and access networks, and the existing digital technology is still expensive for short term commercialization at high baud rates [2]. Homodyne detection provides the simplest DSP solution to optical coherent detection and minimizes the receiver bandwidth requirements. In homodyne coherent detection, the phase and frequency recovery of transmitted data is very important for carrier synchronization. Phase synchronization has been realized with digital phase estimation schemes [3,4]. However, as the modulation complexity increases, computational complexity becomes too high to realize carrier synchronization with digital signal processors. On the other hand, analog phase synchronization techniques, such as optical phase-locked loop (OPLL) [5] and injection locking [6–8] schemes are potentially agnostic carrier recovery techniques to the order of the modulation format.

In this work we study an optical coherent receiver which utilizes injection locking in lasers in order to accomplish carrier synchronization in the optical domain. Since phase modulation provides carrier suppressed signals, we have adopted the use of line coding firstly proposed in [6] for 10 Gbaud PSK signals in order to acquire a residual carrier for the locking process. Our analysis relies on the use of a reliable model and aims at identifying the impact of the laser linewidth, the injection strength and the line coding technique on the performance of the receiver for 50 Gbaud QPSK and 16-QAM tributaries. The technique can be harmonically combined with optical dispersion compensation which is proved to be more energy efficient compared to digital solutions especially when the wavelength division multiplexed comb consists of a high number of channels [9]. The transfer of critical processing procedures at the optical level would substantially reduce the cost per bit of coherent transceivers making them attractive solutions for metro and access applications. Although the strong advantage of the technique is the possibility of high baud rate operation without requiring high speed, high resolution ADCs and DSP, the technique could be also combined with DSP as well if one aimed at offloading the carrier synchronization process from the DSP preserving the rest functionalities.

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2. Numerical analysis and results

The conceptual scheme of the receiver is presented in Fig. 1.

A coupler divides the incoming modulated signal; one part of the signal goes directly to the receiver, the other part is filtered by an optical bandpass filter (OBPF) so as to remove the largest part of the modulation spectrum before the optical injection. The slave laser becomes phase locked to the incoming signal with a phase synchronization error which depends on the linewidth properties of the laser and the injection strength.

The lasers are modeled based on the well-known rate equations for the complex slowly varying amplitude of the electrical field E and the carrier number inside the cavity N given below [10]:

$$\begin{aligned}
\dot{E}_m(t) &= \tfrac{1+i\alpha_m}{2}\left[G_m(t) - \tfrac{1}{t_{ph,m}}\right]E_m(t) + \sqrt{2\beta_m N_m(t)}\,\xi(t)\\
\dot{E}_s(t) &= \tfrac{1+i\alpha_s}{2}\left[G_s(t) - \tfrac{1}{t_{ph,s}}\right]E_s(t) + \sqrt{2\beta_s N_s(t)}\,\xi(t) + k_{ext}E_m e^{i\Delta\omega t}\\
\dot{N}_{m,s}(t) &= \tfrac{I_{m,s}}{q} - \tfrac{1}{t_{n,m,s}}N_{m,s}(t) - G_{m,s}|E_{m,s}(t)|^2\\
G_{m,s}(t) &= \tfrac{g_{m,s}[N_{m,s}(t) - N_{0m,s}]}{1+s_{m,s}|E_{m,s}(t)|^2}
\end{aligned} \tag{1}$$

where the index m,s denotes the corresponding parameter of the master and slave laser respectively, a is the linewidth enhancement factor, g is the differential gain parameter, s is the gain saturation coefficient, t_{ph} is the photon lifetime, t_n is the carrier lifetime, N_0 is the carrier number at transparency, $q = 1.602 \times 10^{-19}$ C and I is the bias current. Moreover, β is the spontaneous emission factor and $\xi(t)$ the spontaneous emission process (Langevin forces) modelled as a complex Gaussian process of zero mean and correlation $\langle \xi(t)\xi^*(u)\rangle = 2\delta(t-u)$ [10]. The model was numerically solved using the fourth-order Runge–Kutta algorithm.

For each of the two laser sources we consider a typical semiconductor laser with differential gain parameter $g = 4.0 \times 10^{-8}$ ps^{-1}, gain saturation coefficient $s = 5 \times 10^{-7}$, photon lifetime $t_{ph} = 3.2$ ps, carrier lifetime $t_n = 1.5$ ns, and the carrier number at transparency $N_0 = 2.1 \times 10^8$ and spontaneous emission factor $\beta = 2 \times 10^{-10}$ ps^{-1}. The parameter k_{ext} corresponds to the percentage of the external injection as it will be explained later. Linewidth enhancement factor a is the variable parameter in our analysis determining the phase noise features of the slave laser [10]. The expression of linewidth is $\Delta f_L = 4\beta\langle N\rangle(1+a^2)/4\pi\langle|E|^2\rangle$. Typical diode lasers with linewidth from 100 kHz to 1 MHz and relative intensity noise of 140 dB/Hz at 1 mW were considered.

Optical noise is generated assuming a typical optical amplifier characterized by amplified spontaneous emission described by a white Gaussian noise process with power spectral density per polarization equal to $S_{\mathrm{ASE}} = hfn_{sp}(G-1)$ where G is the gain of the amplifier, n_{sp} is the optical amplifier population inversion factor, h is the Plank constant, and f is the signal carrier frequency. The OSNR is defined as $\mathrm{OSNR} = P/2S_{\mathrm{ASE}}\Delta f$ where Δf is the optical bandwidth. The bit-error rate (BER) was calculated through error counting as a function of the optical signal to noise ratio (OSNR) of the signal calculated within 0.1 nm. In the case of QPSK signal, the outputs of the two balanced receivers carry typical NRZ On–off keying formats (real and imaginary part of the constellation). In this case, each bit is decoded by simply sampling each symbol at the middle point of the bit period and checking whether it is above or below threshold which is "0". In the case of 16-QAM, the two output signals follow the 4-PAM format. For the decoding of 4-PAM tributaries, our decision circuit consists of three thresholds, one between each pair of adjacent symbol levels per quadrature. The decision process takes place after the proper normalization of the signal power. Two line coding schemes were considered, namely 8B10B and 9B10B [11]. The first one is more redundant (actual bit rate = 80% of the line rate), and for this reason provides a stronger carrier for the phase synchronization. On other hand, the less redundant 9B10B modulation format improves the spectral efficiency, however at expense of the carrier synchronization performance. Table 1 summarizes the main properties of the numerical model and provides the critical parameters.

Fig. 2 shows the optical spectra for uncoded non-return to zero (NRZ) binary PSK modulation together with 8B10B and 9B10B coded streams obtained by using fast fourier transform (FFT). Line coding diminishes the low frequency components of the NRZ format. In that way the initial laser carrier can be revealed and used for analog carrier synchronization. 8B10B is more redundant than 9B10B, thus it provides higher carrier to noise (C/N) ratio. According to our calculations the C/N values for the three signals in a 2 GHz bandwidth around the carrier are the following: $(\mathrm{C/N})_{\mathrm{NRZ}} = -3.5$ dB, $(\mathrm{C/N})_{\mathrm{9B10B}} = 3.5$ dB and $(\mathrm{C/N})_{\mathrm{8B10B}} = 9.7$ dB. Therefore, with proper selection of the injection strength, both line-coding schemes provide the capability for efficient extraction of the signal carrier at the receiver.

It is worth observing the optical spectra of different modulation formats considering the same line coding technique. In Fig. 3 the optical spectra of 50 Gbaud BPSK and QPSK are depicted when 9B10B line coding is utilized. The QPSK is built as a superposition of two independent BPSK streams which are encoded with 9B10B each. It becomes evident that the distribution of the optical power is identical in both cases, thus meaning that the carrier recovery procedure relying on line-coding and injection locking is not differentiated with respect to the modulation format. The same conclusion is valid for QAM, if one takes into account that QAM can be seen as a superposition of two QPSK independent streams.

The next step of the present study is to evaluate the bit error rate performance (BER) as a function of the optical signal to noise ratio and the injection strength for different intrinsic linewidths of the slave laser. An optical filter of 2 GHz bandwidth is considered in order to remove the largest part of the modulated signal before injected into the slave. In Fig. 4 we study the effect of injection strength on the BER performance for both QPSK and 16-QAM streams at two constant OSNR values, for both line-coding techniques and two linewidth values of the slave laser. The incoming signal linewidth is equal to 170 kHz. The injection strength is

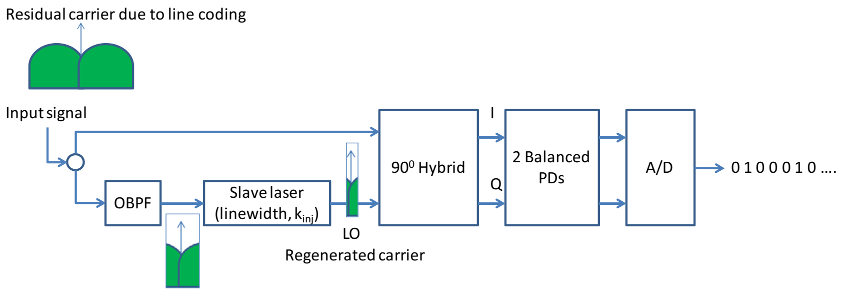

Fig. 1. Optical coherent receiver relying on injection locked local oscillators and line coding.