Effective homodyne optical phase locking to PSK signal by means of 8b10b line coding

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Abstract: We demonstrate a novel technique that allows effective homodyne optical phase locking to a phase shift keying (PSK) signal with a residual carrier. We exploit 8b10b coding of the signal in order to reduce its low frequency spectral content, suppressing the data-to-phase crosstalk effect. In a transmission experiment on a 10 Gb/s binary PSK signal (8 Gb/s before coding), we achieved transmission over 215 km of dispersion-compensated, installed single-mode fibre, with no penalty compared to back-to-back at a bit error ratio of 10^{-3}. The proposed solution is applicable to other modulation formats, including multi-level amplitude and/or phase modulation formats.

OCIS codes: (060.1660) Coherent communications; (060.2920) Homodyning; (060.5060) Phase modulation.

References and Links

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1. Introduction

Multi-level modulation formats, often combining amplitude and phase modulation, have recently been experiencing growing interest because they allow the channel capacity to be increased by improving the spectral efficiency of a transmission system. Coherent detection is the most promising detection technique for these formats. Direct homodyne detection appears in principle to be the most straightforward solution to achieve high spectral efficiencies with the lowest optoelectronic and electronic bandwidth requirements, enabling demodulation to baseband without further processing. However in this case, an optical phase lock loop (OPLL) has to be used in order to lock the local oscillator (LO) laser to the frequency and phase of the transmitter laser [1]. Unfortunately an OPLL is not easy to implement from discrete components due to the constraints imposed by the loop delay, which restricts the loop bandwidth, thus imposing a constraint on the summed linewidth of the transmitter and LO lasers [2]. This makes the use of a conventional OPLL impractical.

Recently, a novel scheme based on an optical injection phase locked loop (OIPLL) has been demonstrated [3,4], which overcomes the above limitation by combining optical injection locking with low-bandwidth (few kHz) electronic feedback to give a wide bandwidth OPLL with large tracking range, enabling the LO to be phase locked to the transmitter laser

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with low phase error variance even when lasers with summed linewidth of a few MHz are employed. Low-penalty demodulation of amplitude shift keying signals at 10 Gb/s was demonstrated using this OIPLL receiver [3]. However, the technique becomes more involved for phase shift keying (PSK) signals, which usually have no residual carrier to which the LO laser can be injection locked. In [4] an unmodulated pilot carrier was transmitted together with the signal in the orthogonal polarisation state and used to lock the LO. Although this approach proved to be very effective, it limited the system capacity since, by using both signal states of polarisation (SOPs), it cannot be extended to polarisation-multiplexing schemes. Furthermore, a practical implementation would require very precise control of the phase relationship between the SOPs at the input of the receiver, which is very difficult to achieve for long transmission distances due to the random nature of polarization related effects in a single-mode fibre. A more straightforward solution could be to reduce the phase deviation of the PSK from π radians, thus giving a residual carrier that is co-polarised with the signal, to which the OPLL might be locked [1]. However, data-to-phase crosstalk on the LO, resulting from the OPLL tracking components of the PSK modulation that fall within its bandwidth, would still result in an unacceptably large phase error variance between the signal and the LO. In this paper we demonstrate the use of the OIPLL homodyne coherent receiver to demodulate binary PSK data by introducing an effective solution to suppress the data-to-phase crosstalk effect. The technique is free from the previous limitations, i.e. it does not require a pilot carrier on the orthogonal SOP and keeps high phase stability. We exploit the well-known 8b10b coding scheme, widely used in Gigabit-Ethernet (GbE) [5], in conjunction with a reduction of the PSK phase deviation, which gives a residual carrier. The 8b10b coding greatly decreases the power spectral density of the transmitted signal around the carrier frequency, thus allowing locking of the LO to the residual carrier with reduced phase error variance compared to operation without coding. Transmission of a 10 Gb/s PSK signal (corresponding to a data rate of 8 Gb/s before coding) over more than 200 km of dispersion-compensated, installed standard single-mode fibre (SMF) is demonstrated, with no penalty compared to back-to-back operation at a bit error ratio (BER) of 10^{-3}, proving the effectiveness of the proposed technique.

2. Experimental arrangement

The experimental arrangement used to validate the proposed technique is shown in Fig. 1. The output of a DFB laser (operating at 1566.34 nm to match the wavelength of the LO laser) was phase modulated by a $LiNbO_3$ phase modulator (PM). The modulator was driven either by a 10 Gb/s pseudo-random binary sequence (PRBS, length: 2^7-1) or by the same sequence encoded using the 8b10b algorithm. A short PRBS was used to avoid long runs of ‘ones’ and ‘zeros’ introducing patterning in the case of the unencoded data, in order to allow a more direct comparison with the 8b10b coded data, which by design contains no more than five bits of the same type in sequence. By varying the peak-to-peak driving voltage we could change the phase deviation of the optical PSK signal generated. The modulated signal was then transmitted either over a 40 km spool of standard single-mode fibre in the laboratory or through the installed network. At the receiver site, the signal was passed through a polarisation tracker, whose function was to provide a constant state of polarisation at the input of the OIPLL receiver, and noise loaded to enable evaluation of the system performance at different optical signal-to-noise ratios (OSNRs).

The OIPLL receiver structure is also detailed in Fig. 1 (inset). The input signal and LO are combined in a $LiNbO_3$ 90° optical hybrid, one output of which (I) is used to recover the demodulated data while the other (Q) output gives a phase error signal. Balanced photo-detectors give a high common mode rejection ratio, suppressing directly detected signals and common-mode noise contributions. Phase locking of the LO laser to the residual carrier in the input signal is achieved by a combination of optical injection locking of the LO laser and low bandwidth electrical feedback. Under the conditions used, the optical injection locking tracks phase variations within a bandwidth of several hundred MHz, which is much larger than can be achieved with an OPLL using electrical feedback alone. This allowed the transmitter and

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LO semiconductor lasers, which have a combined linewidth of 2.8 MHz, to be phase locked together with a phase error variance of less than 10^{-2} rad^2, measured over the frequency range 1 kHz to 10 GHz, when no modulation was applied. To maintain the optical injection locking at its optimum operating point, even if the laser frequencies drift, the error signal from the Q output of the optical hybrid is fed back to tune the frequency of the DBR LO laser by adjusting its gain-section current. The effective bandwidth of this electrical OPLL is a few kHz. An additional control loop, with a bandwidth of a few Hz, is used to track slow variations in the path lengths due to environmental changes by driving a piezo-electric fibre stretcher (PZT).

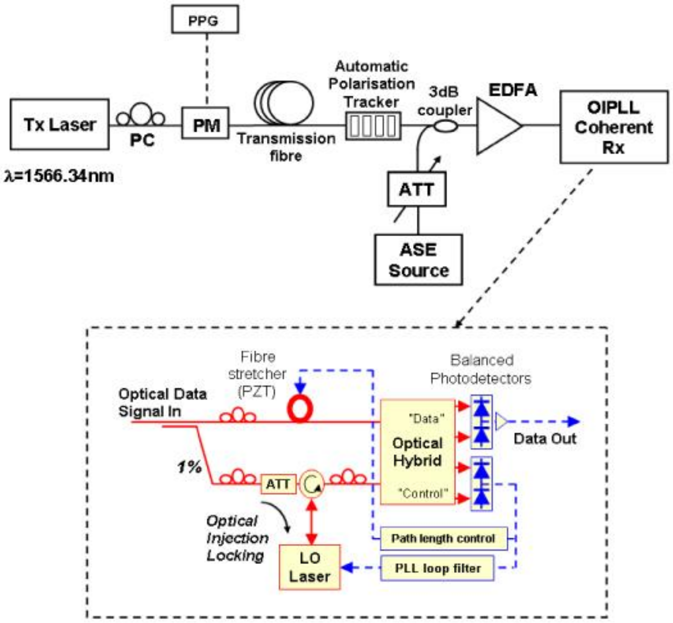

Fig. 1. Experimental arrangement and OIPLL architecture (inset).

3. Receiver performance

We first characterised the receiver in the back-to-back condition. Figure 2 shows the received back-to-back eye diagrams for the demodulated 10 Gb/s binary PSK signal when modulated by (a) the standard 2^7-1 PRBS and (b) the 8b10b encoded version. The reported eye diagrams were both taken for a peak-to-peak phase deviation (α) of approximately 2.4 rad. Larger values of α did not allow stable locking, as the residual carrier power was then too low. A phase deviation of 2.4 rad p-p was therefore considered to give the optimum balance between maximising the eye amplitude while leaving enough residual carrier power for stable phase locking. The phase deviation was estimated from the measured peak-to-peak modulator drive voltage and the nominal value of V_π for the phase modulator. In Fig. 2c and 2d we also report the RF spectra of the demodulated data at the receiver output corresponding to the above two cases. These spectra were obtained by detuning the LO to give demodulation to an (unlocked) intermediate frequency of 10 GHz. Comparison of the spectra clearly shows the reduction in low-frequency spectral components in the case of the 8b10b coding. The corresponding improvement in eye opening due to the reduction in data-to-phase crosstalk with the 8b10b coding is clearly observed in the back-to-back eye diagrams.

We then performed BER measurements on the received signal. In the case of the unencoded 2^7-1 PRBS, an error floor was observed at a BER of 10^{-3}, which is unacceptable for system operation. On the other hand, the 8b10b coded signal gave much improved BER performance, as shown by the results in Fig. 3, with BER below 10^{-10} recorded at high OSNR and BER of 10^{-3} obtained at an OSNR of 7 dB (0.1 nm noise bandwidth) for α=2.4 rad. As the phase deviation was reduced from this value, it was observed that the BER performance was degraded, both in terms of an increase in OSNR required to give a BER of 10^{-3} and the appearance of error floors at high OSNR.

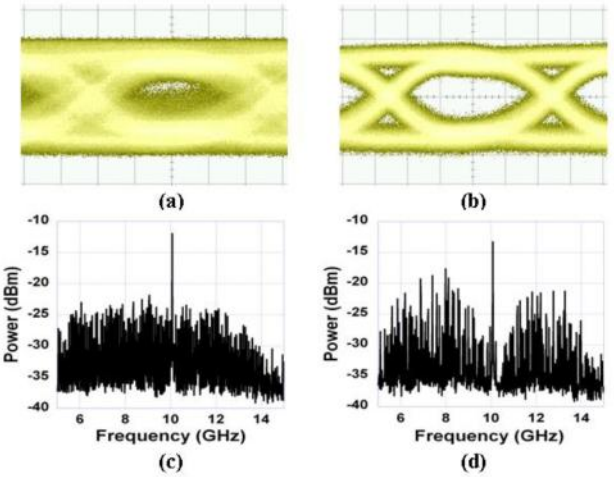

Fig. 2. Back-to-back received eye diagrams and RF spectra of the demodulated 10 Gb/s phase modulated signal when using a standard 2^7-1 PRBS (a,c) and the 8b10b encoded version of the same sequence (b,d).

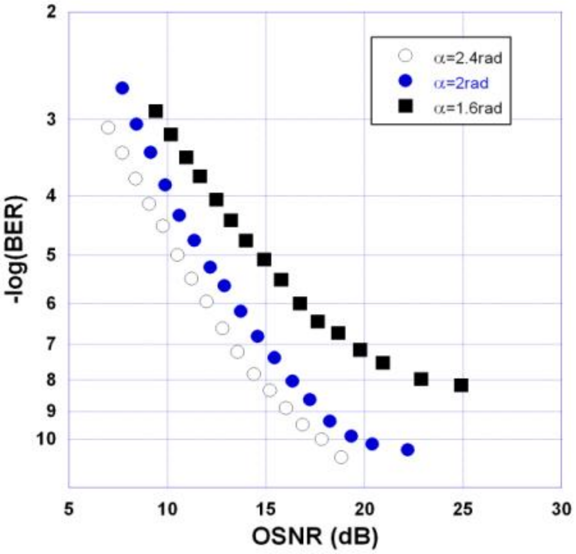

Fig. 3. Back-to-back BER for different values of peak-to-peak phase modulation deviation (α).

This is mainly due to the increase in power in the residual carrier (which carries no data) as the phase deviation is reduced, and the corresponding reduction in power of the data carrying part of the signal. For a phase deviation of 2.4 rad p-p, the power in the carrier is calculated to be 13% of the total power, resulting in an OSNR penalty of 0.6 dB compared to ideal binary PSK. As the phase deviation is reduced to 1.6 rad p-p, the power in the carrier increases to 49% of total power, and the theoretical OSNR penalty increases to 2.9 dB compared to ideal BPSK. Thus the majority of the change in OSNR at a BER of 10^{-3} observed experimentally can be attributed to this effect. In addition, the increased carrier power injected

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into the LO will increase the optical injection locking range, which determines the bandwidth over which phase fluctuations are tracked. While this should reduce the phase error due to the laser linewidths, it will also increase the data-to-phase crosstalk, contributing to increased penalty. The error floors at high OSNR similarly mainly reflect the reduction of eye amplitude as the carrier power is increased while the receiver noise remains constant.

4. Transmission experiment

We tested the system over two different transmission links. The first consisted of a 40 km uncompensated spool of SMF in the laboratory, in order to give an initial assessment of the impact of fibre propagation effects on the coherent receiver. The second link used part of the JANET Aurora dark-fibre research network, which links five UK universities. The section of the network used connected University College London to Chelmsford, Essex via three spans of SMF, with EDFAs at each of the intermediate nodes (Fig. 4). The SMF was looped back at Chelmsford to give a total length of 215 km. The link was compensated by dispersion compensating fibre modules with a total dispersion of -3700 ps/nm, split equally between pre- and post-compensation; there was no in-line dispersion compensation at the intermediate nodes. It is estimated that the residual dispersion at the operating wavelength was approximately 100 ps/nm (equivalent to less than 6 km of SMF). Since the dark-fibre network is provisioned for WDM operation, a CW “holding beam” was combined with the modulated signal in this single-channel experiment, and the relative power of the CW and modulated wavelengths adjusted to control the power in the signal channel to a level that prevented distortions due to non-linear effects.

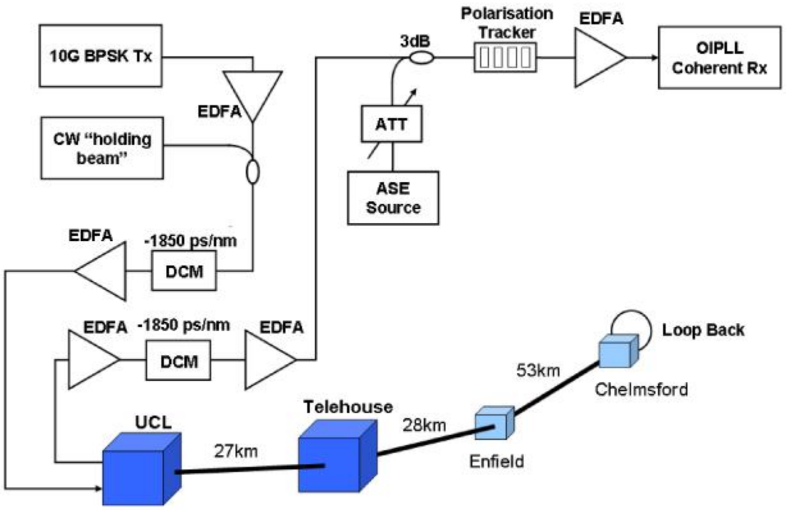

Fig. 4: Experimental arrangement for transmission over the JANET Aurora dark-fibre network.

Figure 5 shows the results of BER measurements on the 8b10b-encoded binary PSK signal after transmission over the two links. The bit rate (after encoding) was 10 Gb/s and the phase modulation deviation was 2.4 rad p-p. After transmission over the 40 km spool of uncompensated SMF, an OSNR penalty of less than 1 dB, compared to back-to-back operation, was observed at 10^{-3} BER, due to eye closure resulting from the effects of dispersion. Over the compensated installed network, however, there was almost no penalty at 10^{-3} BER compared to back-to-back. The penalty observed at lower BER ($<10^{-6}$) is because the eye amplitude is less than in the back-to-back case, resulting in lower receiver-noise-limited Q. This is due to incomplete filtering of the CW wavelength at the receiver, giving reduced signal power for a given receiver input power.

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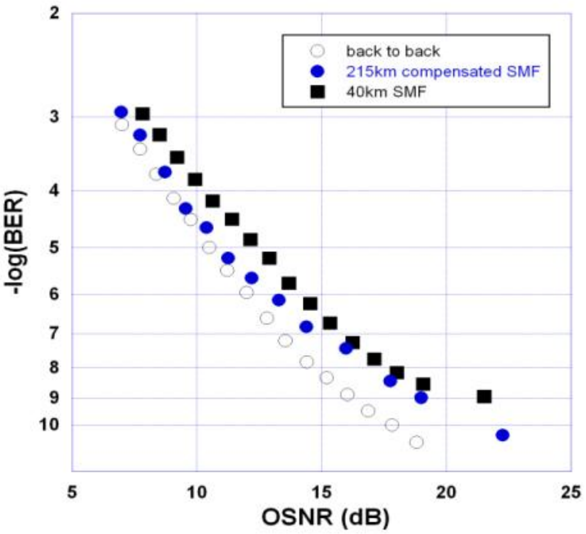

Fig. 5. BER of the phase-modulated 8b10b encoded signal at 10 Gb/s after transmission over standard single-mode fibre.

5. Conclusions

We have proposed 8b10b encoding as a simple and effective technique for suppressing data-to-phase crosstalk in PSK coherent homodyne optical receivers that employ wide-bandwidth, linear phase locking to a residual carrier for carrier recovery. The 8b10b encoding reduces the spectral content of the signal within the bandwidth of the phase lock loop, thereby reducing the data-to-phase crosstalk on the receiver LO. We have demonstrated the technique experimentally using a coherent homodyne receiver that uses a combination of optical injection locking and low-bandwidth electrical feedback to give a wide-bandwidth OPLL that enables low-error phase locking even for transmitter and LO lasers with a combined linewidth of several MHz. Under conditions where data-to-phase crosstalk prevented data demodulation of unencoded data with low BER (< 10^{-3}), the 8b10b encoding technique gave excellent back-to-back performance for binary PSK modulated data at an encoded data rate of 10 Gb/s: 10^{-3} BER was achieved at approximately 7 dB/0.1 nm OSNR, with BER less than 10^{-10} measured at an OSNR of 19 dB/0.1 nm. The practicality of the technique was confirmed by demonstrating penalty-free transmission over 215 km of dispersion-compensated, installed standard single-mode fibre.

Despite the approximately 1 dB power penalty associated with the coding overhead and the penalty resulting from the use of a residual carrier, the 8b10b encoding scheme enables synchronous demodulation of binary PSK with a simple implementation and with noise performance at BER=10^{-3} that is superior to IMDD or coherently detected OOK, and comparable to practical differential detected PSK using a balanced receiver [6]. Since the width of the spectral dip around the carrier resulting from the 8b10b encoding is proportional to the data rate, the scheme should give lower penalty operation at higher line rates (e.g. 40 Gb/s or higher). In addition, the proposed system could also be applicable to multi-level modulation formats (e.g. QPSK or QAM), and could in principle be extended to give polarisation-diverse operation by the addition of a suitable polarisation tracking scheme.

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