Fast Wavelength Switching Transceivers for Bandwidth on Demand Based Coherent Optical Networks

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Abstract *The recent progress in fast wavelength switching transceivers for bandwidth on demand coherent optical networks is outlined and several techniques employed to mitigate the effects of tuneable laser FM noise are presented.*

Introduction

Agile optical networking has long been proposed as a network paradigm, employed to efficiently allocate bandwidth on demand in order to maximise throughput, while simultaneously minimising cost. The scope of the 'agile' optical network has evolved from early optical burst or packet switched networks [1], to the introduction of reconfigurable optical add/drop multiplexers [2] and to the current variant; coherent optical burst switching [3,4] or bandwidth on demand based software defined networking (SDN) [5].

Tuneable coherent transceivers will play an integral role within SDNs as they provide full C-band wavelength provisioning, bandwidth allocation with sub-wavelength granularity and nanosecond reconfiguration times. In addition to this, digital coherent reception provides numerous advantages such as frequency selectivity, high receiver sensitivity and the ability to compensate transmission impairments such as chromatic dispersion and polarisation mode dispersion.

Dynamic wavelength provisioning at the transmitter and frequency selectivity for burst acquisition at the receiver, are both achieved using monolithically integrated semiconductor tuneable lasers [6,7]. While the tuneable laser is a key enabling technology for fast wavelength switching coherent transceivers, the large Lorentzian phase noise and low frequency $1/f$ noise associated with these devices poses a significant challenge.

This paper will review the recent progress in fast wavelength switching coherent transceivers and outline several techniques employed to digitally compensate the various components that comprise the frequency modulation (FM) noise of a semiconductor tuneable laser.

Fast Wavelength Switching Transceiver

The basic configurations of the transmitter and receiver subsystems within a fast wavelength switching coherent transceiver are illustrated in Fig. 1. The transmitter (Fig. 1(a)) consists of a widely tuneable semiconductor laser, which should typically exhibit a switching time of <100ns, high frequency stability and low phase noise. By rapidly varying the switching voltages applied to the laser tuning sections, finite optical bursts can be generated at any wavelength channel on the ITU grid. Each burst is subsequently modulated using a dual polarisation IQ modulator.

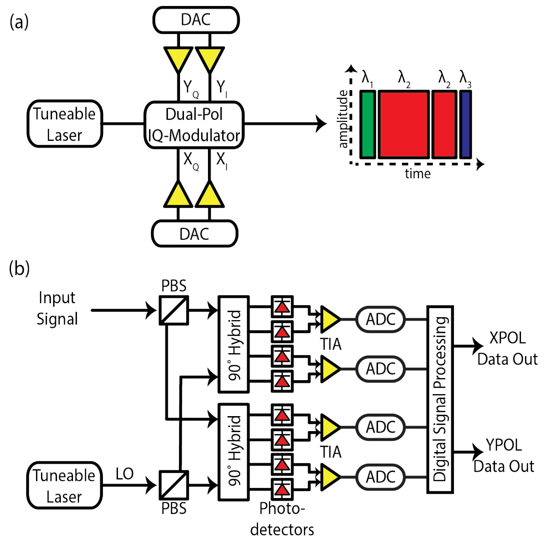

Fig. 1: (a) Fast wavelength switching burst mode transmitter and (b) dynamic burst mode coherent receiver.

In a SDN, the desired modulation format and symbol rate are applied to the modulator using four independent digital to analogue convertors (DACs). The launch power of each optical burst is controlled using the semiconductor optical amplifier that is integrated with the tuneable laser. At the receiver (Fig. 1(b)), a second tuneable laser is used as a local oscillator (LO) and the frequency is tuned to coincide with the incoming burst of interest. The coherently received bursts are digitised using analogue to digital convertors (ADCs), after which the required digital signal processing

(DSP) is carried out.

There have been many combinations of this transmitter-receiver pair reported in the literature. Simsarian et al. reported the first experimental demonstration of an optical burst switched coherent receiver[3], which utilised a fixed wavelength transmitter and a tuneable receiver that employed a 16-section external cavity laser (ECL) as a LO. This work was extended by replacing the ECL with a commercially available digital supermode distributed Bragg reflector (DS-DBR) tuneable laser[7] and improved training symbols were used to aid packet alignment and frequency offset (FO) recovery[8].

Conversely, a burst mode transmitter combined with a fixed frequency receiver has also been demonstrated[9,10]. Training symbols were used to assist in the initialisation of the constant modulus algorithm (CMA) based equaliser, which was implemented in real-time. The initialisation avoided the singularity issue associated with the CMA equaliser and also reduced the convergence time, which is crucial for optical burst switched networks.

We have previously demonstrated coherent burst mode transmission and reception for various modulation formats, such as QPSK[11], 16QAM[12] and OFDM[13]. Commercially available DS-DBR tuneable lasers were used at both the transmitter and as a LO within the coherent receiver. Regardless of the modulation format or the symbol rate, severe performance penalties were incurred if the FM noise associated with the semiconductor tuneable laser was not adequately compensated.

Tuneable Laser FM Noise

Conventional tunable lasers, such as the ECL, exhibit a phase noise dominated by the Schawlow-Townes-Henry linewidth. However, widely tunable semiconductor lasers, such as the DS-DBR laser, SG-DBR laser or the Y-branch DBR laser, employ a combination of passive tuning sections and the free carrier plasma effect to rapidly change wavelength. The absence of gain clamping in the passive sections results in large $1/f$ noise and also contributes to higher Lorentzian phase noise.

The white component of the laser FM noise spectrum represents the Lorentzian phase noise and is fundamentally determined by the cavity length of the gain section, the linewidth enhancement factor and the output power. The low frequency $1/f$ noise is dominated by the electrical noise of the laser driving signals, the tuning efficiency of each passive section and the optimum biasing point within each supermode boundary[14].

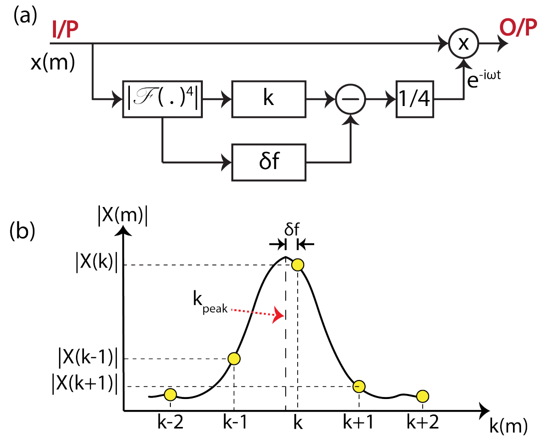

Fig. 2: (a) Block based frequency offset estimation and (b) schematic of approximate-fit algorithm to find frequency offset correction factor.

Large laser FM noise severely degrades the BER performance of coherent OBS networks that utilise phase sensitive higher order modulation formats. In particular, large frequency noise leads to errors in the $\pi/2$ phase unwrapping within the carrier and phase estimation algorithm in the receiver DSP, which results in cycle slips and catastrophic bit errors.

FM Noise Mitigation Techniques

The low frequency $1/f$ noise of passively tuned semiconductor lasers can be compensated through a number of techniques such as signal pre-emphasis of the laser drive signals[15] or a digital block based frequency offset estimation algorithm[4]. Signal pre-emphasis reduces the switching time of the tuneable laser and also relaxes the requirements of the digital frequency offset estimator in the receiver DSP, however it is challenging to optimise the pre-emphasis for every switching combination, which would also potentially differ from laser to laser.

Fig. 2(a) illustrates the block based FO estimator. In a parallelised implementation of the receiver DSP[16], the sampled serial data is rearranged into blocks with a length proportional to the inverse of the ASIC clock speed. The power spectral density (PSD) of each block is initially obtained by taking the Fourier transform of the complex data. The index (k) of the PSD peak, X(k), corresponds to the frequency offset. However, as a finite number of samples are used to compute the discrete Fourier transform, the resolution of the estimate is limited. Therefore a correction factor (Δf) is obtained using an approximate-fit technique[17] before the FO is compensated, as seen in

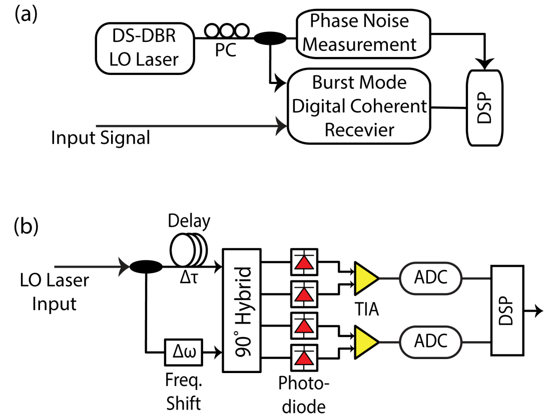

Fig. 3: (a) Fast wavelength switching digital coherent receiver and (b) digital coherence enhancement measurement scheme.

Fig. 2(b). This technique can be used in conjunction with differential symbol decoding to overcome the problem of cycle slips[4]. Differential symbol decoding incurs a small OSNR penalty of ∼0.5dB, however it becomes non-trivial for square QAM formats higher than 16QAM.

Digital coherence enhancement is an alternative receiver based technique, that can be used to compensate the Lorentzian and non-Lorentzian distributed phase noise of a fast wavelength switching coherent transceiver and thus enables the use of higher order M-QAM modulation formats. This technique consists of an optical measurement of differential phase, followed by DSP to calculate the phase noise of the LO laser and is illustrated in Fig. 3. The output of the fast wavelength switching LO laser is split into two paths. One path passes directly into the LO port of the burst mode coherent receiver, while the second enters a low speed coherent receiver (Fig. 2(b)) for phase noise estimation. This technique completely compensates the tuneable laser FM noise[12], however it is important to note that this scheme only corrects the phase noise of the LO laser. A similarly performing compensation scheme would also be required in the transmitter if a fast wavelength switching laser is used to generate the optical bursts[18].

Although a combination of signal pre-emphasis, optimised training symbols, DSP techniques or coherence enhancement may make coherent optical burst switching possible for a wide variety of modulation formats, it is the OFDM format that provides the most promising platform for OBS. OFDM employs specific training symbols to achieve synchronisation and this can be exploited for burst detection and channel estimation[19]. Although OFDM is inherently sensitive to phase and frequency noise, a DC pilot tone can be used to compensate the combined FM noise of both the transmitter and receiver lasers[13]. Finally, the use of the OFDM cyclic prefix to accommodate chromatic dispersion alleviates the necessity for rapid channel dispersion estimation, which is required to accommodate the variable path history that occurs in OBS networks.

Therefore, fast wavelength switching DP-OFDM coherent transceivers with DC pilot tone based FM noise compensation may provide the greatest potential for future bandwidth on demand based software defined networks.

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