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Reduced OSNR Penalty for Frequency Drift Tolerant Coherent Packet Switched Systems Using Doubly Differential Decoding

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Abstract: In this paper we will demonstrate the improved BER performance of doubly differential phase shift keying in a coherent optical packet switching scenario while still retaining the benefits of high frequency offset tolerance.

OCIS codes: (060.1660) Coherent communications; (060.4259) Networks, packet-switched; (060.4265) Networks, wavelength routing.

1. Introduction

The non-linear Shannon capacity limit is being reached [1] while the demand for increased throughput in the optical internet is increasing. An alternative way of increasing throughput is to use optical packet switching (OPS) in order to maximize utilization of the available spectral resources. OPS also has the added benefit of reducing the number of optical/ electronic/ optical conversions required in the routing processes [2]. In addition, the use of coherent transmission in such OPS networks will allow for high spectral efficiency.

Since OPS networks typically use fast switching tunable lasers at the transmitter and/ or local oscillator (LO), the switching tunable laser will exhibit a frequency transient at the start of a packet resulting in a large, time-varying frequency offset (FO) between the transmitter and the LO at the coherent receiver. If this transient is not compensated there can potentially be a large waiting time (10's of nanoseconds) before data can be successfully received [2], resulting in reduced network throughput. This transient FO problem needs to be overcome to optimize network efficiency; hence, a FO compensation algorithm which can deal with large frequency transients is required. It was shown in [3] that doubly differential decoding can result in a greatly reduced waiting time after a tunable laser switches wavelengths compared with single differential decoding. However, doubly differential decoding can result in required optical signal to noise ratios (OSNR) penalties of 4.77dB in theory for QPSK formatted data [4]. In this paper we will demonstrate a digital signal processing (DSP) scheme which can greatly reduce this OSNR penalty thus enabling doubly differential decoding to be deployed in switching environments to enhance network efficiency.

2. Theory

Doubly differential quadrature phase shift keying (DDQPSK) has been explored in recent years in simulation [5] and experiment [4]. A key feature of doubly differential decoding is its ability to tolerate very high FOs as demonstrated in [4]. This large FO tolerance was exploited in [3] in the case of an OPS scenario where doubly differential binary phase shift keying was shown to be able to decode coherent optical packets with much shorter waiting times after the switching event of a tunable laser, than single differential binary phase shift keying. It was also stated in [3] that this large FO tolerance would allow for relaxed precision requirements of the tunable lasers' wavelengths. However, it is also known that doubly differential decoding suffers a large optical signal to noise ratio (OSNR) penalty, theoretically 4.77dB [4], resulting from adding noise terms together in the decoding process. One method to decrease this penalty has been suggested in [5] by replacing the second simple differential stage of the receiver by a Multi-Symbol Decision-Feedback Carrier Phase Estimation (MS-DF-CPE) method which feeds back previous decisions in order to improve the performance of the second differential stage.

In this paper we suggest a new approach where m^{th} power FO compensation (where m is the number of phase states, e.g m=4 for QPSK) [6] and m^{th} power phase estimation [6] are performed first, a hard decision is subsequently made on the QPSK constellation, and then after this hard-decision the constellation is differentially decoded twice as shown in Fig. 1 (c). By performing the doubly differential operation after the hard decision, the (1/m/Tsample) FO ambiguity introduced by the m^{th} power FO compensation [7] can be removed, with Tsample being equal to the symbol period in this paper. After this the bits are mapped from phases to bits using Gray coding.

The decoding methods used for (a) m^{th} power single differential quadrature phase shift keying (SDQPSK), (b) simple DDQPSK and (c) m^{th} power DDQPSK are shown in Fig. 1 below. Note that for m^{th} power DDQPSK the FO compensation has a slight variation where it tracks FOs as they drift over a (Symbol Rate)/(2m) boundary by unwrapping the estimated differential phase in the FO compensation scheme similar to what was suggested in [7]. It has been found in experiments that this method tends to produce twice as many errors as SDQPSK with less than 1dB penalty at a bit error rate (BER) of 10^{-3}.

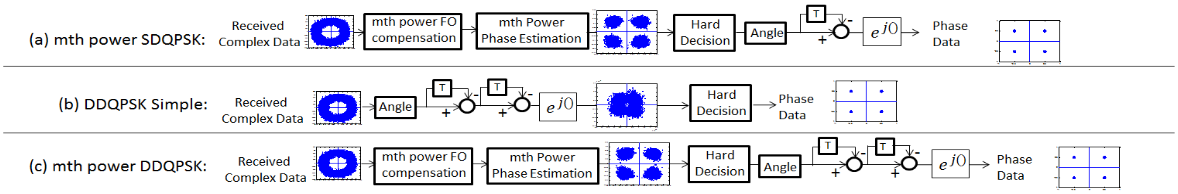

Fig. 1. Processing used for (a) m^{th} power SDQPSK, (b) simple DDQPSK and (c) m^{th} power DDQPSK decoding

3. Experimental Setup

Shown in Fig. 2 below is the experimental setup for demonstrating the performance of our proposed scheme. At the transmitter is a sampled-grating distributed Bragg reflector (SG-DBR) laser which is switched between two wavelengths (1541.4nm and 1547.5nm) by a (pre-emphasis free) square wave voltage source applied to one mirror section of the SG-DBR device. The switching laser stays on each wavelength for 500ns. A polarization controller (PC) alters the polarization of the transmitted carrier to optimize it for modulation with the IQ modulator. The modulator is driven by electrically amplified data signals from a pattern generator with two level signals (one PRBS7 and its delayed inverted form) so that 10GBd QPSK data can be transmitted. This is followed by a variable optical attenuator (VOA), then an erbium doped fiber amplifier (EDFA) which feeds into a 50/50 coupler. At the other input to the 50/50 coupler we introduce amplified spontaneous emission (ASE) noise from a high power EDFA, with the power being varied by a computer controlled VOA, and a 5nm filter was used to keep the spectral profile of the noise as flat as possible. One output from the coupler was fed into another VOA which was followed by an optical spectrum analyzer (OSA) used to automatically measure the OSNR of the signal. The other output from the coupler was fed into a 2nm filter to remove ASE noise. This was followed by a PC to optimize the polarization of the signal input to the polarization-diverse coherent receiver. The LO was a low linewidth tunable laser source which was passed through a polarization controller before being fed into the LO input of the polarization diverse coherent receiver.

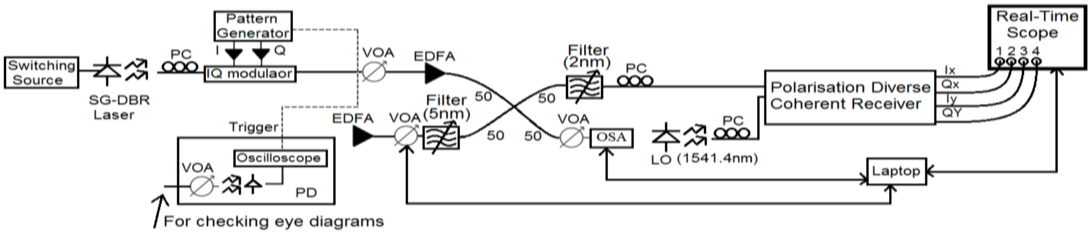

Fig. 2. Experimental setup to compare performance of m^{th} power SDQPSK, simple DDQPSK, and m^{th} power DDQPSK, in terms of BER versus OSNR

In order to measure BER vs. OSNR, the signal power was determined to be the power of the transmitting laser in its static state measured at its peak by the OSA. During the experiments the level of loaded ASE noise was varied by a computer controller VOA. The level of noise was measured by the OSA with 0.1nm resolution and was used in conjunction with the static signal power level to calculate the OSNR (this has been compared with static transmitter measurements which give similar BER versus OSNR measurements). The QPSK beat signals were captured by a 12.5GHz analogue bandwidth real time scope which had a sampling rate of 50Gsamples/s. A photodiode (PD) and oscilloscope were used to monitor the optical eye of the QPSK signals to ensure the DC bias points of the IQ modulator were correct. There were 11 averaging points used in the m^{th} power FO estimation algorithm and 11 points used in the m^{th} power phase estimation algorithm (note this does not affect waiting time). The steady-state FO (i.e. the FO which is reached at the end of the packet) was changed for different measurements in order to show the tolerance of m^{th} power DDQPSK to large FOs. However, even in the 0GHz steady-state FO case the transient FO measured has a range greater than 3GHz at the start of the switch. For the switching data, the bits used in the BER calculation were only for parts of the packet where the amplitude of the packet was greater than 70% of the average amplitude of the packet (this essentially resulted in 98% utilization of the 500ns burst time). Note that more than $1.8*10^5$ bits were used for each BER measurement so that BERs of $1*10^{-3}$ could be measured reasonably.

4. Results

Shown in Fig. 3 below is the BER versus OSNR for different steady-state FOs and different blanking times (waiting time before the data decoding starts after 70% amplitude is reached) after switching the transmitting laser for (a) m^{th} power SDQPSK, (b) simple DDQPSK and (c) m^{th} power DDQPSK. It can be seen in figure 3(a) that SDQPSK only works well for the 0GHz steady state FO, and only after a blanking time of 30ns, requiring an OSNR of 15.5dB for a BER of $1*10^{-3}$. SDQPSK performance is severely degraded with a blanking time of 0ns due to the large transient FO after the switch (error floor around 10^{-2}), and is even worse when there is 3GHz steady-state FO (error floor above 10^{-1}). It can be seen in figure 3(b) that simple DDQPSK can operate at both steady-state FOs and has similar performance with both blanking times, but it is unable to reach BERs less than $1*10^{-3}$ even at OSNR values greater than 21dB. However, m^{th} power DDQPSK can achieve BERs less than $1*10^{-3}$ for both steady-state FOs and achieves similar performance for both blanking times. The penalty for using m^{th} power DDQPSK compared with SDQPSK at 0GHz steady-state FO is less than 1dB and this is the case using either blanking time. Also, m^{th} power DDQPSK is able to reach BERs less than $1*10^{-3}$ for a 3GHz steady-state FO with either blanking time. The high OSNR required at 3GHz steady-state FO is most likely due to the limited bandwidth of the real time scope. Hence, m^{th} power DDQPSK has been demonstrated to have large FO tolerance, almost the same OSNR performance as m^{th} power SDQPSK and the ability to transmit data even with transient FOs (as is the case when the blanking time is set to 0ns), which shows that it is a suitable modulation format for achieving optimum throughput in coherent optical packet-switched networks.

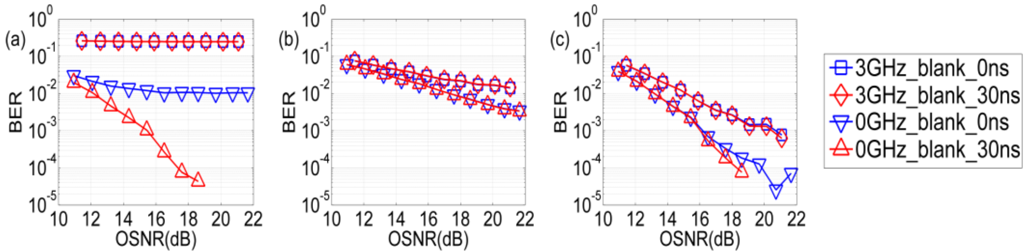

Fig. 3. Plots of BER versus OSNR for (a) m^{th} power SDQPSK, (b) simple DDQPSK and (c) m^{th} power DDQPSK for different blanking times and different steady-state FOs for the switching experiment.

5. Conclusion

It has been demonstrated that m^{th} power DDQPSK can overcome the OSNR penalty limitations of simple DDQPSK (less than 1dB penalty with respect to m^{th} power SDQPSK), while still retaining tolerance to high FO (shown here to be up to 30% of the symbol rate). The technique can successfully operate in a packet switched environment as it can recover data signals immediately after the switching event of a tunable laser (less than 5ns). Hence, m^{th} power DDQPSK is a suitable and realistic modulation format for coherent optical packet switched systems.

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