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Realizing High Sensitivity at 40 Gbit/s and 100 Gbit/s

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Abstract: We experimentally investigate modulation formats for realizing high data rate and high power sensitivity using coherent reception with low noise-figure optical preamplification. 40 Gbit/s PS-QPSK exhibits a sensitivity of 4.3 photons/bit while 100 Gbit/s PDM-QPSK exhibits a sensitivity of 5.3 photons/bit at 3.8×10^{-3} BER.

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1. Introduction

Receiver sensitivity is a parameter crucial to determining the capacity of an optical communications network. The absolute optical power sensitivity of a receiver is fundamentally restricted by the shot noise limit, and there are several techniques which can be employed in order to approach this limit, including coherent detection and forward error correcting codes (FEC). Another recent approach has been to utilize advanced modulation formats with intrinsic sensitivity gains. One such format, pulse position modulation (PPM), allows arbitrary sensitivity improvements at the expense of spectral efficiency. While recent efforts have demonstrated that some of this spectral efficiency can be recouped [1], such formats have not yet been shown to offer data rates beyond a few Gbit/s.

More recently still, it has been experimentally demonstrated that a reasonably high sensitivity can be achieved using the advanced modulation format polarization-division-multiplexed quadrature phase shift keying (PDM-QPSK) and that an even better sensitivity can be obtained using the four-dimensional modulation format, polarization-switched QPSK (PS-QPSK) [2]. The spectral efficiency limit of PS-QPSK is 3 bit/s/Hz, while for PDM-QPSK it is 4 bit/s/Hz, making these formats attractive candidates for high capacity networks.

With this requirement of high spectral efficiency, what more can be done to improve receiver sensitivity? One further way of approaching the shot noise limit is to preamplify the receiver using a high gain optical amplifier with a low noise figure. In this work, we use a dual-stage erbium doped fiber amplifier (EDFA) offering a gain of 45 dB with a measured noise figure at 1550 nm of 3.25 dB. To demonstrate the effectiveness of this approach for high data rates, we generate, transmit, and detect a 42.9 Gbit/s PS-QPSK signal. To demonstrate the effectiveness of this approach for higher capacity networks, we also investigate receiver sensitivity using 112 Gbit/s PDM-QPSK.

Note that, in this work, we have assumed the use of hard-decision FEC with an overhead of 7% (or 12% including Ethernet overhead for 100 Gbit/s), and a target bit error rate (BER) of 3.8×10^{-3}, however this work is equally applicable to the use of alternative FEC structures.

2. Experimental Configuration

The experimental receiver sensitivity investigations undertaken in this work required the generation of two distinct modulation formats; PS-QPSK at 14.3 GBd, shown in Fig. 1(a), and PDM-QPSK at 28 GBd, shown in Fig. 1(b). Both of these formats are based upon generation of a QPSK signal, which was achieved by modulating CW light from an external cavity laser (ECL) (100 kHz linewidth) at 1554 nm using a triple Mach-Zehnder (IQ) modulator. The modulator was driven, at a data rate commensurate with the required symbol rate, using two decorrelated pseudo random binary sequences (PRBS) of length $2^{15} - 1$.

For PS-QPSK generation Fig. 1(a), the QPSK signal entered a polarization-switching stage which involved, initially, equally splitting the signal into two branches. Each branch contained a Mach Zehnder modulator (MZM), one

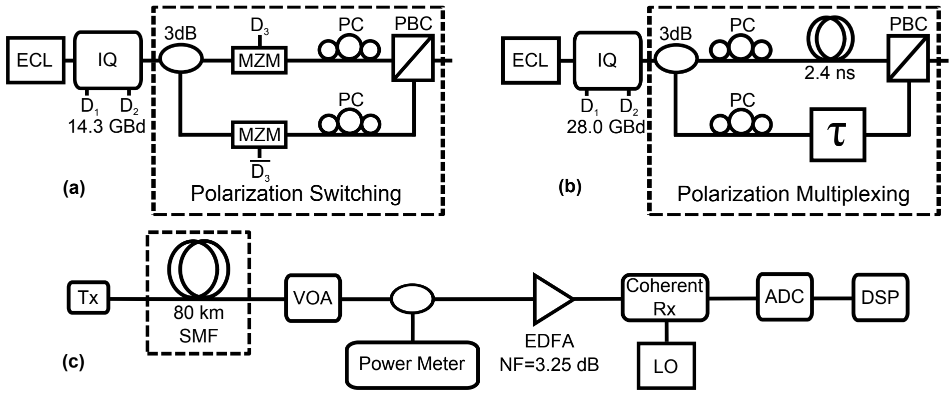

Fig. 1. The 42.9 Gbit/s PS-QPSK transmitter is shown in (a) while the 112 Gbit/s PDM-QPSK transmitter is shown in (b). Shown in (c) is the experimental configuration for investigating the sensitivity of a digital coherent receiver. A low noise figure EDFA was employed to further improve receiver sensitivity. When transmission was considered, the signal was passed through an 80 km SMF spool before entering the coherent receiver.

of which was driven with a third PRBS sequence while the other was driven with the inverse sequence. Driving the modulators symbol-synchronously effectively extinguished one arm when the other was in the transmit state. Polarization controllers (PC) were used to set orthogonal polarizations in each arm before recombination using a polarization beam combiner (PBC). Using this technique, the third bit of information was encoded on the state of polarization of the signal.

In the case of PDM-QPSK Fig. 1(b), polarization multiplexing was emulated using a similar method to the polarization switching stage. Here, after the splitting, a passive fiber delay line was used to decorrelate the two polarizations. Again, a PC in each branch and a PBC were used to set orthogonal polarization states.

Where transmission was considered, an 80 km spool of standard single mode fiber (SMF) was placed between transmitter and receiver, with a variable optical attenuator (VOA) used to decrease the received optical power to the desired level. Without transmission, the VOA was used in isolation. The signal then entered a two stage, high gain EDFA with a noise figure of 3.25 dB at the wavelength of interest, before entering a coherent receiver. The local oscillator laser (LO) used was, again, an ECL, with comparable properties to the signal laser.

An array of analogue-to-digital converters (ADC) were used to transfer the signal into the digital domain where the waveforms were processed offline. The digital signal processing (DSP) techniques used for PS-QPSK are described in [3], with the equalizer described in detail in [4]. For PDM-QPSK, we used the DSP detailed in [5]. In the case of transmission, we used the dispersion compensating filter, also described in [5], for both formats, assuming an average chromatic dispersion of 16.3 ps/nm/km.

3. Experimental Results and Discussion

It is clear from Fig. 2(a) that the use of a low noise figure preamplifier has enabled sensitivities close to the theoretical limits, even at these high data rates. At the BER of interest, 3.8×10^{-3}, the sensitivity penalty for both formats is just 1.4 dB, while the penalty with respect to the theoretical limit assuming a 3.25 dB noise figure preamplifier is only 1.1 dB. Therefore, the sensitivity for PS-QPSK is -46.5 dBm (4.3 photons/bit) while for PDM-QPSK it is -41.5dBm (5.3 photons/bit).

In this work, we have assumed the use of a hard-decision FEC code however, to enable comparison with other work in this area, we consider the impact of soft-decision codes. Allowing for a larger coding overhead of 25%, there exist codes which can correct a 2×10^{-2} BER to below 10^{-15} [7]. Assuming these parameters, the sensitivities of the formats are 3.4 photons/bit for PDM-QPSK, while PS-QPSK would achieve a sensitivity of 3.1 photons/bit. Of course, the net data rate is reduced if these codes are assumed, however, there is no fundamental reason why this sensitivity could not be achieved at higher symbol rates.

Shown in Fig. 2(b), are the receiver sensitivity results for both formats after 80 km transmission. Crucially from a network design perspective, there is no measured penalty in transmission for 42.9 Gbit/s PS-QPSK, while for

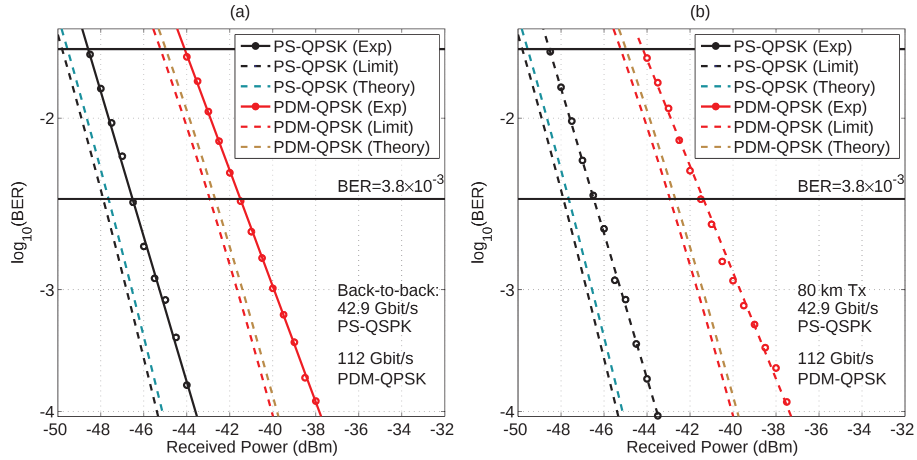

Fig. 2. Receiver sensitivity of 40 Gbit/s PS-QPSK and 100 Gbit/s PDM-QPSK. The solid black lines highlight the 3.8×10^{-3} and 2.0×10^{-2} FEC limits. Shown in (a) are the back-to-back sensitivities, while in (b) transmission over 80 km SMF is considered. The shot noise limit (Limit) and the theoretical limit using a 3.25 dB noise figure preamplifier (Theory) are shown as derived from the formula in [6].

112 Gbit/s PDM-QPSK we note that the transmission penalty is less than 0.1 dB.

4. Conclusions

We experimentally investigated, and verified in transmission over 80 km, the impact of a low noise preamplifier on the sensitivity of a digital coherent receiver. We found that, with a 3.25 dB noise figure EDFA, the receiver sensitivity was within 1.4 dB of the shot noise limit for both PDM-QPSK (5.3 photons/bit) and PS-QPSK (4.3 photons/bit) at a BER of 3.8×10^{-3}. We note that if a soft decision code were to be used, the sensitivity of PDM-QPSK would have been 3.4 photons/bit, while PS-QPSK would achieve 3.1 photons/bit; albeit with a reduction in net data rate.

5. Acknowledgements

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