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 2¹⁵ – 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
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, $3.8 \times 10^{-3}$, 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 -41.5 dBm (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 $2 \times 10^{-2}$ 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 $3.8 \times 10^{-3}$ and $2.0 \times 10^{-2}$ 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 $3.8 \times 10^{-3}$. 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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