One photon per bit communication for free-space optical links

Ravikiran Kakarla [(1)], Jochen Schröder [(2)], Peter A Andrekson [(2)]

[(1)] Optoelectronic research centre, University of Southampton, Southampton, UK.

[(2)] Photonics laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg, Sweden. peter.andrekson@chalmers.se

Abstract W*e demonstrate a free-space transmission experiment showing bit-error-free, "black-box" sensitivity of 1 photon-per-information-bit (PPB) at a net information rate of 10.5 Gb/s. The system uses a simple modulation format (QPSK) transmitter and near noiseless phase sensitive pre-amplified coherent receiver.*

Introduction

Increased data output of satellite born sensors operated by agencies like NASA, ESA and JAXA imposes greater demands on the communication systems to operate at higher data rates and to reach farther distances into space [1]. Improving the receiver sensitivity is considered the most important method to improve data throughput with few received photons possible. Pulse position modulation (PPM) is widely considered in space communications as it can reach capacity at low signal-to-noise ratio (SNRs) [2], but with significant loss of spectral efficiency. Photon counting receivers are often used to receive PPM symbols enabling sensitivities of few photons per bit. A key drawback is the need to be cooled to 2-4 K and their inability to detect photons at rates of multiple Gb/s [7-9].

Future space communication systems such as inter-satellite links and satellite to ground are expected to operate at speeds of several 10s of Gb/s and beyond. Space communication has therefore looking to adopt advanced modulation formats with optically pre-amplified coherent detection in combination with advanced FEC are a promising solution to improve both data rates and receiver sensitivity. One impressive result using single-quadrature (SQ) homodyne detection receiver without pre-amplifier resulted in a sensitivity of 1.5 PPB at 156 Mb/s [3], where the data rate was limited by the optical PLL bandwidth. Demonstrations with EDFA pre-amplified coherent receivers resulted in sensitives as low as 2.1 PPB at 10 Gb/s [4]–[6].

The capacity for a pre-amplified dual-quadrature coherent homodyne receiver is [7].

$$C_{\text{preamp}} = B\log_2\left(1+\frac{2S}{F_n h\nu B}\right)$$

By rewriting it, $C_{\text{preamp}} = B\log_2\left(1+2n_s/F_N\right)$ where where F_n is the noise figure (NF) of the pre-amplifier, S is the signal power, h is Planck's constant, ν is the frequency of the optical carrier wave, and the bandwidth B is the inverse of the symbol period.

n_s is the number of photons per transmitted symbol. For an erbium-doped fiber amplifier (EDFA), $C_{EDFA} = B\log_2\left(1+2n_s\right)$ [7].

PSAs have a theoretical NF of 0 dB, amplifying the signal's both quadratures without excess noise [8]. A two mode PSA, due to the coherent addition of input waves and incoherent addition of noise by four-wave mixing, the output SNR of each wave is 3 dB better than the input, corresponding to a NF of -3 dB. However, the overall NF of the PSA is still 0 dB when accounting for both the required input waves with the same information [9].

The capacity of the PSA is $C_{PSA} = B/2\log_2\left(1+4n_s\right)$ where the factor B/2 is due to the loss of spectral efficiency as signal and idler are carrying the same information.

PSA provides the same capacity as that of ideal shot noise limited receiver, and also same lowest sensitivity, which is 0.35 PPB. The advantage of PSA receiver being not limited by detector quantum efficiency and can operate at any high data rates.

On the other hand, a simple QPSK(BPSK) can perform better than higher order modulation formats in power efficiency, used in this experiment.

Experiment

Fig. 1 shows a conceptual diagram of a free-space optical transmission link with a PSA pre-amplifier in the receiver. At the transmitter, the binary data was FEC-encoded using a code from the digital video broadcasting standard (DVB-S2), consisting of a concatenation of a ½-rate LDPC and an high-rate (0.6%) BCH code. The data was then modulated onto the signal wave by QPSK modulation at a symbol rate of 10.52 Gbaud, resulting in a net information rate of 10.52 Gbps. The signal was then combined with a continuous-wave pump in a "copier stage" to generate a conjugate idler wave, containing the same information as the signal, by using

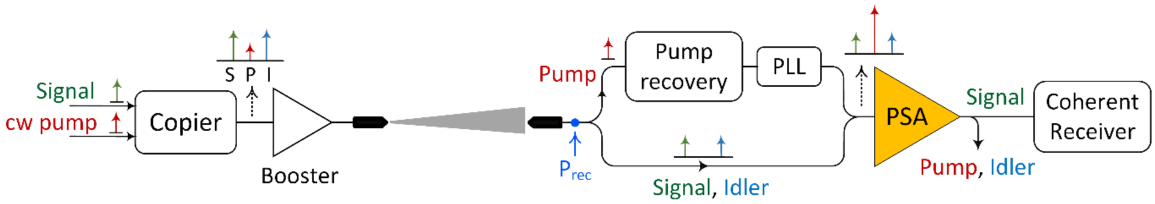

Fig. 1. Conceptual diagram of a free-space communication link with a PSA pre-amplified coherent receiver; S-Signal; P-pump; I-Idler; PLL, Phase-locked-loop; PSA, Phase sensitive amplifier.

four-wave mixing (FWM) in a nonlinear optical fiber. All three waves, signal, idler and pump are then launched into the free-space channel; in our case a short 1m free-space link implemented in the laboratory followed by an optical attenuator to emulate the beam diffraction-induced loss in a real link. The received power (P_{rec}) is defined as the total power of signal, idler and pump after the receiver lens as depicted in Fig. 1 thus represents the "black-box" receiver sensitivity. The launch power is determined by the final booster amplifier is equally important as the receiver sensitivity in an actual free-space link. It is therefore essential that signal and idler power are approximately equal, and the pump power corresponds to only a small fraction of the total launch power. In our case the pump power was substantially smaller than the combined signal and idler power resulting in a nearly negligible power budget penalty. At the receiver, the pump was separated from the signal and idler and recovered using optical injection locking [10]. We were able to recover a stable high power (approximately 1 W) pump wave at input power levels as low as -72 dBm, which is at least 12 dB smaller than the received signal power level.
An optical phase-locked loop (PLL) after pump recovery maintained a constant relative phase between the three waves for maximum phase sensitive gain. The signal, idler and recovered pump were then combined inside a HNLF for phase sensitively amplification of the signal. After the PSA, the signal was filtered and detected using a standard coherent receiver and a real-time oscilloscope for subsequent off-line signal processing and FEC decoding.
The bit error rate (BER) of the received signal was measured to evaluate the performance of the PSA pre-amplified receiver and was also compared with an EDFA pre-amplified receiver as shown in Fig 2. The power scales include total input power, i.e. signal, idler, and pump waves for PSA, and only signal power for the EDFA. The power budget penalty caused by the presence of the pump wave in the PSA (~12 dB below the combined power of signal and idler) was at most 0.26 dB. The pre-FEC BER in Fig. 2 show that the PSA perform 2.5 dB better than the EDFA based receiver, which is attributed to difference in noise figures of the amplifiers, measured to be 1.2 dB for the PSA and 3.7 dB for the EDFA, respectively.

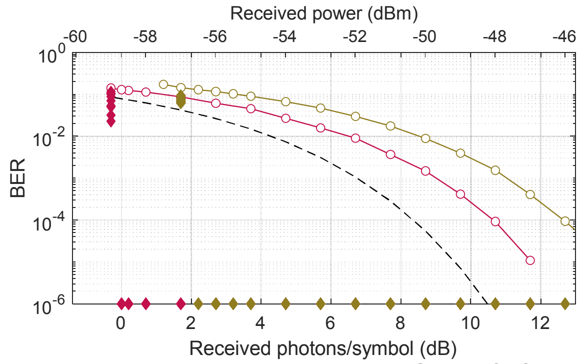

Fig. 2. Experimental results with 10.52 Gbaud QPSK data, EDFA pre-FEC (brown line with open circles); EDFA post-FEC (brown solid diamond markers); PSA pre-FEC (red line with open circles as measured points); PSA post-FEC (red diamond markers). The dashed line shows the theoretical estimate for QPSK data for a PSA with 0 dB NF.

The post-FEC BER was determined after FEC decoding and is also shown in Fig. 2. A coding gain of 11.8 dB was obtained at a BER=10^{-5} for both the EDFA and PSA pre-amplified receivers. The results show that error-free (below BER = 10^{-6}) transmission can be achieved with a received power of 1 photon/symbol or 1 photon/information bit (PPB) (including FEC overhead) with a PSA pre-amplifier and is the best "black-box" sensitivity reported to date. This result is more than 3 dB better than the previously best reported sensitivity of 2.1 PPB at similar data rate and FEC [4]. In our EDFA case, error-free performance was achieved at 1.7 PPB. We estimated the possible sensitivity of our specific system with an ideal FEC using generalized mutual information (GMI) to be 0.85 PPB. These results are shown in our publication [11].
Fig. 3. depicts the trade-off between spectral efficiency and sensitivity for receivers used in free-space communications along with experimental sensitivity records using these techniques. PPM is plotted as the envelope of all m-ary PPM (green line) showing the best achievable sensitivity for given spectral efficiency. A specific example format, 64-PPM is also plotted, as this is frequently used in space communications. Although PPM formats provide the best possible sensitivity at very low spectral efficiencies, they require large receiver bandwidth to achieve high information rates,

which is very challenging with photon counting receivers.

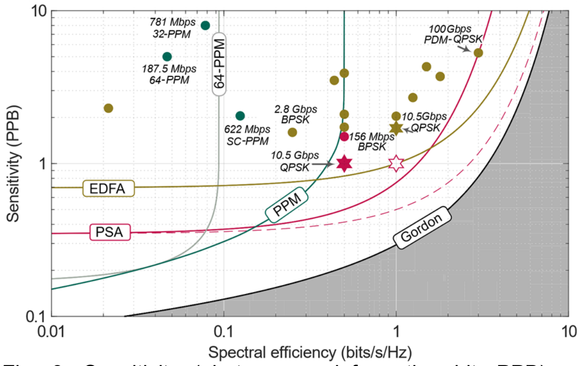

Fig. 3. Sensitivity (photons per information bit, PPB) versus spectral efficiency (bits/s/Hz) with different implementations. Theoretical curves are indicated by lines, while experimental data are indicated with symbols. Experimental sensitivity records of photon counting receivers (green markers); Record sensitivities of advanced modulation formats with pre-amplified coherent receivers (brown markers), single quadrature detector (red marker); Experimental data was extracted from the references [3]–[6], [12]–[16]; The PSA result presented here is denoted by a red star (Red filled, and unfilled) and the EDFA result is represented by brown star

Coherent receivers with PSA pre-amplifiers do not only have 3 dB sensitivity advantage over EDFA pre-amplifier-based receivers at low spectral efficiency but are also much more spectrally efficient than PPM formats. PSAs pre-amplified coherent receivers are amplifying both quadratures of the signal and reach the best sensitivity among all receivers over spectral efficiencies ranging from 0.16 b/s/Hz to 1.6 b/s/Hz. Considering state-of-the-art signal bandwidths of 60 GHz, this corresponds (in the ideal case) to data rates between 9.6 and 96 Gbit/s which is extremely relevant for future space communication systems.
The theoretical lines of PSA and EDFA crossover as EDFAs provide better sensitivity at high spectral efficiencies (>1.6 b/s/Hz) compared to PSAs as PSA require to transmit signal and idler thus twice the bandwidth. However, for single channel systems, as employed in space communications, receiver bandwidth utilization is more important than optical spectral efficiency due to the unrestricted channel bandwidth and limited receiver bandwidth. In this case the loss of spectral efficiency due to the idler can be ignored as at the same symbol rate the receiver bandwidth of PSA and EDFA pre-amplified receiver are the same. The PSA curve then shifts towards the right by 3 dB as indicated by the red dashed line in Fig. 3. The result if we also ignore the loss in optical spectral efficiency in the experiment is indicated by the white star. We conclude by noting that a "black-box" record sensitivity of 1 PPB was demonstrated at 10.5 Gbps using a simple, spectrally efficient modulation format, enabled by the PSA and by ultra-low power injection locking based pump recovery. The fundamental advantages enable reach extension, increase of information rate and/or reduction of size of the involved optics and we believe that these results represent a significant contribution in the field of space communication and LIDAR applications such as Earth monitoring.

Acknowledgements

We thank A. Mecozzi, C. Antonelli, A. Lorences-Riesgo, K. Kikuchi, M. Mazur and M. Karlsson for discussions. Sumitomo Electric and OFS Denmark are acknowledged for providing optical fibers used in the experiments. This work was supported by the Swedish Research Council (grantVR-2015-00535) and European Research Council (project ERC-2018-PoC 813236).

References

[1] D. Cornwell, "Space-Based Laser Communications Break Threshold," *Opt. Photonics News*, vol. 27, no. 5, p. 24, May 2016.

[2] S. Butman, J. Katz, and J. Lesh, *IEEE Trans. Commun.*, vol. 30, no. 5, pp. 1262–1264, May 1982.

[3] M. L. Stevens, D. O. Caplan, B. S. Robinson, D. M. Boroson, and A. L. Kachelmyer, *Opt. Express*, vol. 16, no. 14, p. 10412, Jul. 2008.

[4] T. M. Yarnall *et al.*, in *Optical Fiber Communication Conference*, 2013, pp. 1–3.

[5] X. Liu, T. H. Wood, R. W. Tkach, and S. Chandrasekhar, *Opt. Fiber Commun. Conf.*, vol. 1, no. c, pp. 1–3, 2011.

[6] D. Lavery *et al.*, in *Optical Fiber Communication Conference*, 2012, pp. 1–3.

[7] K. Kikuchi and S. Tsukamoto, *J. Light. Technol.*, vol. 26, no. 13, pp. 1817–1822, 2008.

[8] C. M. Caves, *Phys. Rev. D*, vol. 26, no. 8, pp. 1817–1839, 1982.

[9] Z. Tong *et al.*, *Nat. Photonics*, vol. 5, no. 7, pp. 430–436, 2011.

[10] R. Kakarla, J. Schröder, and P. A. Andrekson, *Opt. Lett.*, vol. 43, no. 23, p. 5769, Dec. 2018.

[11] R. Kakarla, J. Schröder, and P. A. Andrekson, *Light Sci. Appl.*, vol. 9, no. 1, p. 153, Dec. 2020.

[12] M. E. Grein *et al.*, in *Conference on Lasers and Electro-Optics*, 2008, pp. 1–2.

[13] M. E. Grein *et al.*, in *Advanced Photon Counting Techniques IX*, 2015, vol. 9492, p. 949208.

[14] B. S. Robinson *et al.*, *Opt. Lett.*, vol. 31, no. 4, p. 444, Feb. 2006.

[15] X. Liu, S. Chandrasekhar, T. H. Wood, R. W. Tkach, E. C. Burrows, and P. J. Winzer, in *European Conference and Exposition on Optical Communications*, 2011, pp. 1–3.

[16] D. J. Geisler, V. Chandar, T. M. Yarnall, M. L. Stevens, and S. A. Hamilton, in *Conference on Lasers and Electro-Optics*, 2015, pp. 9–10.