Idea I-2022-00162: Quantum receivers for efficient deep-space optical communications - Executive summary report

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I. Introduction

Development of deep-space optical communication systems (DOCS) poses a number of technical challenges as compared to conventional radio-frequency links. The higher energy of a single quantum (a photon) at the optical carrier frequency implies the need for dedicated modulation formats and receiver designs. The current technical standard for efficient DOCS is pulse position modulation (PPM) format (see Fig. 1) combined with direct detection (DD) [1, 2] which for photon-starved links is implemented as photon counting.

However, theoretical analyses indicate that this combination is not necessarily optimal, as in general it does not saturate the Gordon-Holevo capacity limit for an optical channel [3], which has been illustrated on Fig. 2. While in the case of downlink communication the selection of available modulation formats is fixed after the completion of the onboard transmitter and the launch of the mission, it is possible to continue development and upgrades of the ground receivers, in order to extend the duration of the communication windows and/or to enable operation in less favourable atmospheric conditions. In this project we aim to optimize the detection strategy of single-photon-level optical signal by analyzing and comparing the performance of various quantum receivers types. The receiver performance is characterized either in terms of average probability of symbol detection error or in terms of the mutual information per communication channel use (channel capacity) which assumes optimal classical (outer) error correction coding.

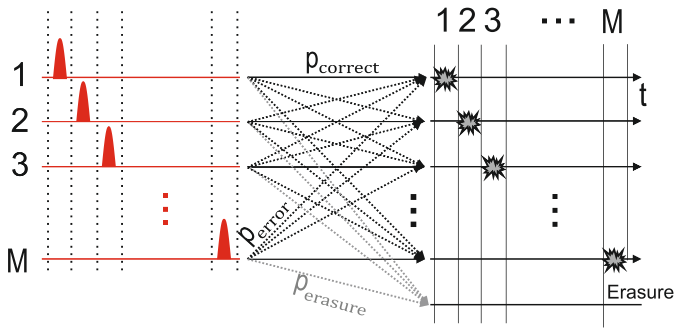

Figure 1: A technological standard for deep-space optical communications is pulse position modulation (PPM) format combined with direct detection. M-ary PPM format uses M equiprobable multislot symbols defined by the location of one pulse within a frame of M otherwise empty temporal slots. Thus one PPM frame can encode $\log_2(M)$ bits of information. For PPM signal the error occurs when the receiver observes a click event in a time slot which corresponded to empty bin. In turn erasure occurs when no clicks were observed over a time span of entire PPM frame.

II. Categorisation of quantum receivers

Current efforts related to the quantum receivers can be broadly classified into two categories. On the one hand theoretical communication limits are analysed using quantum optics and information theory formalism, where the optical signal is treated as a quantum state and the communication channel capacity is calculated using positive operator-valued measure (POVM) measurement matrices [4] and/or Holevo quantity [3]. On the other hand experimental proof-of-concept realizations of receivers are flourishing with a dominant contribution of displacement receivers [7] where the incoming signal is interfered with a local oscillator in order to statically or adaptively shift the incoming coherent state in a phase space, with a prominent example of conditional pulse nulling receiver. For the purpose of this study we have focused on the receivers which are capable of detecting PPM signals regardless of their technical realization difficulty. Some of them are overarching theoretical constructs requiring e.g. collective detection of signal time slots, while other employ a specific detection strategy with a well-defined technical implementation. The literature search resulted in the overall taxonomy of receivers presented in Fig.3 in a form of Venn diagram.

III. Optimal detection strategy

In general the selection of optimal detection strategy depends on the triple of optical link parameters (n_f, n_b, N), where n_f is the number of photons in optical pulse occupying the non-empty PPM slot, n_b is a background noise expressed in dark counts/detection slot/mode, while N is the number of registered time-frequency modes. The study revealed two noticeable trends which might be used as a rule of thumb in the selection of optimal detection strategy. First of all due to the finite conversion efficiency of the quantum pulse gating its use is warranted only for significant

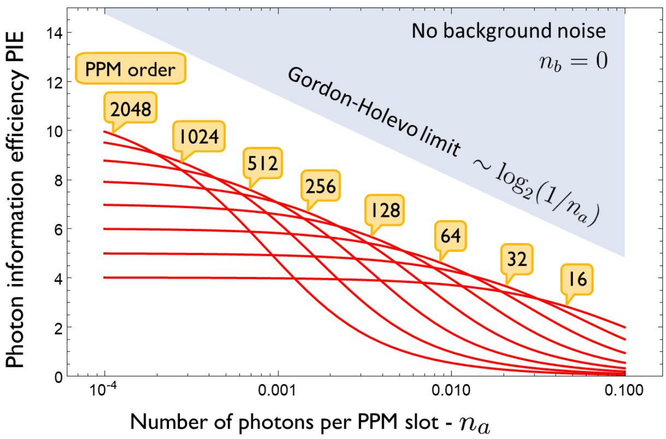

Figure 2: Gordon-Holevo limit on the photon information efficiency for a noiseless optical channel compared with the performance of pulse position modulation with varying order M.

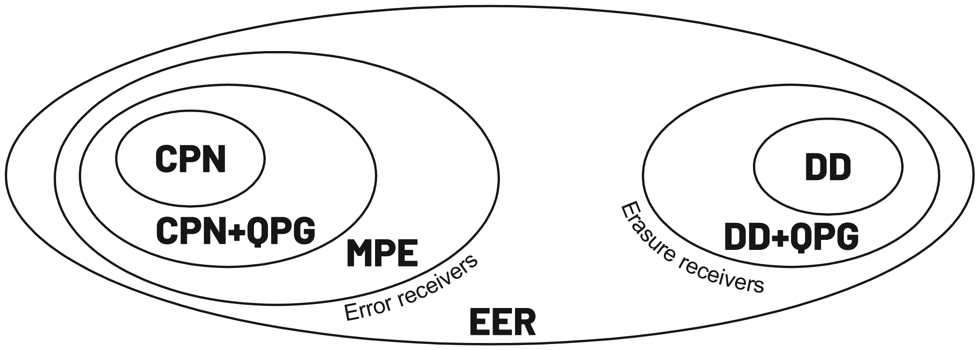

Figure 3: The categorisation of quantum receivers presented in a form of Venn diagram; EER, error-erasure receiver [4]; MPE, minimum-probability of error receiver; CPN, conditional pulse nulling receiver [5], DD, direct detection; QPG, quantum pulse gating [6]

background noise. Secondly the advantage of conditional pulse nulling over the direct detection is mostly pronounced for average number of photons in a frame $n_f \gg 1$. These two observations have been summarised in the Nolan chart presented in Fig. 4. The results obtained during the study clearly indicate the near-optimality of direct detection with sequential incoherent filtering in nighttime detection scenario ($n_f = 0.44$-1.43; $n_b = 5.5 \cdot 10^{-7}$), which corresponds to the left bottom corner of the Fig. 4. In the daytime scenario ($n_f = 0.44$-1.43; $n_b = 5.5 \cdot 10^{-4}$) the noise suppression provided by quantum pulse gating is very advantageous and might reduce the probability of error by almost 70%. The increase of the background noise resulting from daytime conditions can be interpreted as a shift along n_b axis in Fig. 4 which turns the optimal detection strategy from DD into DD+QPG.

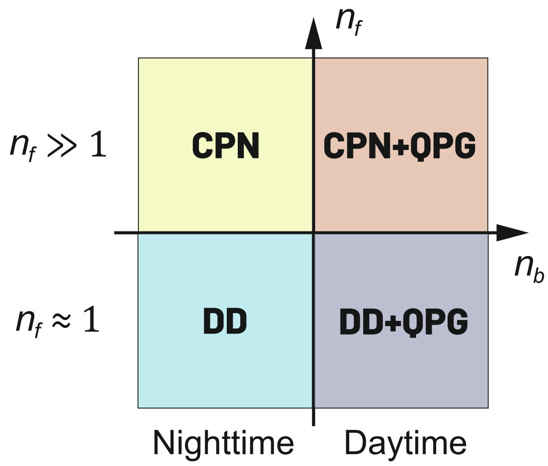

Figure 4: Rule of thumb for the selection of optimal detection strategy. The results obtained during the study clearly indicate the near-optimality of direct detection with sequential incoherent filtering in nighttime detection scenario, which corresponds to the left bottom corner of the chart. In the daytime scenario the noise suppression provided by quantum pulse gating is very advantageous and might reduce the probability of error by almost 70%. The increase of the background noise resulting from daytime conditions can be interpreted as a shift along n_b axis in the chart which turns the optimal detection strategy from DD into DD+QPG.

IV. Conditional pulse nulling vs. Direct detection

The natural figure of merit specifying the advantage provided by the conditional pulse nulling detector over the conventional direct detection is the probability of error P_{err}. In Fig. 5 we present the probability of error P_{err} for a perfect CPN receiver and compare it to the probability of error achievable using direct detection recevier. In Fig. 5(a) we present a data for noiseless scenario $n_b = 0$, while in Fig. 5(b) and Fig. 5(c) we present a data for realistic nighttime and daytime operation noise levels i.e. $n_b = 5.5 \cdot 10^{-7}$ counts/slot/mode and $n_b = 5.5 \cdot 10^{-4}$ counts/slot/mode respectively. The comparison is made for PPM orders varying from $M = 4$ to $M = 128$. In Fig. 5 we have assumed a constant number of modes $N = 100$ corresponding to a realistic spectral filtering bandwidth of 20 GHz and time slot duration of 5 ns. It is clearly visible that the reduction of error probability thanks to the CPN receiver is mostly pronounced in low background noise n_b and high average signal photon number n_f scenarios. In general the performance of both direct detection and conditional pulse nulling receiver is heavily affected by the background noise. This signifies the need for noise suppression techniques with a prominent example of quantum pulse gating.

V. Benefits of Quantum Pulse Gating

Quantum pulse gating applied to the received optical beam can in principle filter out the plurality of incoming time-frequency modes carrying background noise and preserve only a single mode

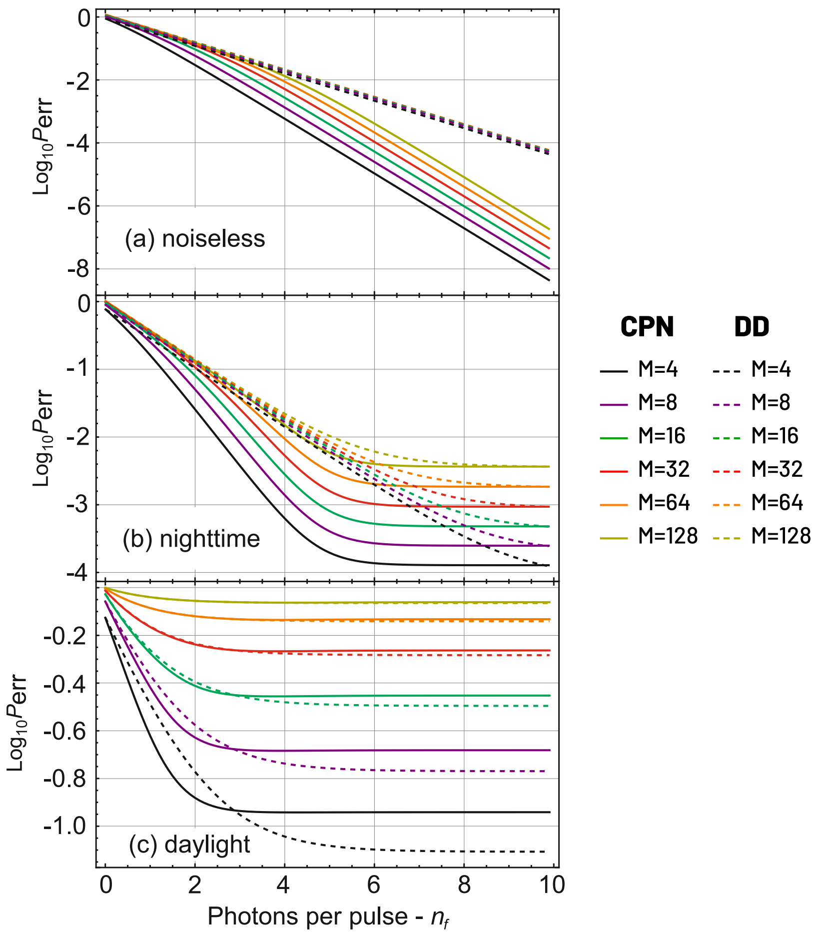

Figure 5: Theoretical probability of error in the CPN receiver (solid line) compared with the probability of error achievable with direct detection (dashed line). The comparison is made for PPM order varying from $M = 4$ to $M = 128$ and fixed number of modes $N = 100$. Three noise levels were taken into consideration: (a) $n_b = 0$ (noiseless scenario), (b) $n_b = 5.5 \cdot 10^{-7}$ counts/slot/mode (nighttime operation) and (c) $n_b = 5.5 \cdot 10^{-4}$ counts/slot/mode (daytime operation).

matched to the signal emitted by the optical transmitter onboard the satellite. This effectively reduces the number of detected modes from $N \approx 100$ to $N = 1$.

In Fig. 6 we present the theoretical probability of error P_{err} in direct detection receiver resulting from the utilization of QPG taking into account its finite conversion efficiency of 90%. We have assumed noise levels of: Fig. 6(a) $n_b = 5.5 \cdot 10^{-7}$ counts/slot/mode (nighttime operation) and Fig. 6(b) $n_b = 5.5 \cdot 10^{-4}$ counts/slot/mode (daytime operation). Interestingly for nighttime operation the reduction of error thanks to the noise suppression via QPG is similar to the increase of error due to the finite efficiency of QPG and consequential decrease of signal amplitude. In the daytime conditions the advantage of QPG is significant for the entire range of incoming signal power. This suggests that quantum pulse gating might become an enabling technology for the facilitation of optical ground station daytime operation.

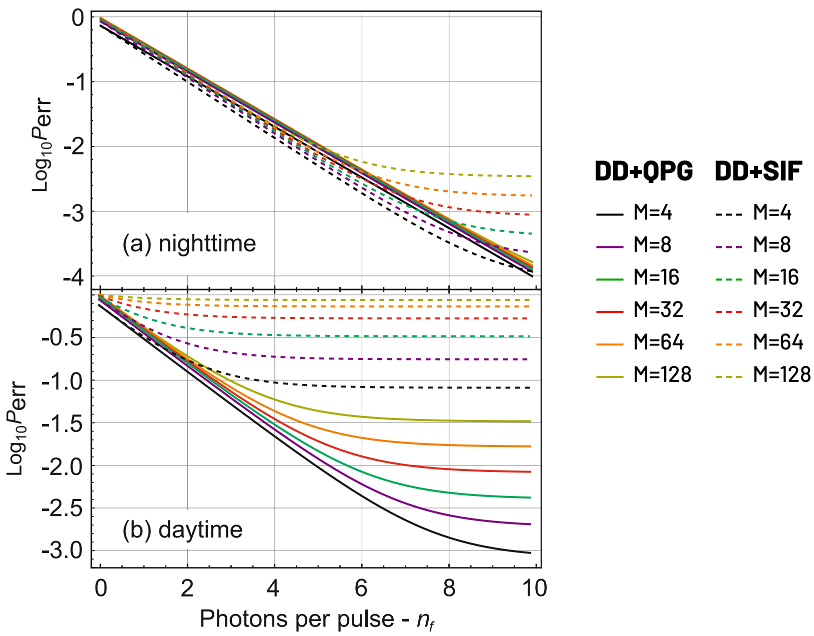

Figure 6: Theoretical probability of error P_{err} in the direct detection receiver with passive spectral filtering of incoming optical beam (dashed line) compared with the probability of error achievable with direct detection receiver with quantum pulse gating filtering (solid line). The comparison is made for PPM order varying from $M = 4$ to $M = 128$. Two noise levels were taken into consideration: (a) $n_b = 5.5{\cdot}10^{-7}$ counts/slot/mode (nighttime operation), (b) $n_b = 5.5{\cdot}10^{-4}$ counts/slot/mode (daytime operation). In the simulations we have assumed finite QPG conversion efficiency of 90%.

VI. Outlook

The implementation of CPN into realistic optical communication system will require a significant reduction of acceptable PPM frame duration from several microseconds used in proof of principle CPN experiments to several nanoseconds easily achievable in state-of the art optical transmitters. This in turns brings up the need for fast electronic systems capable of feeding the detection results of subsequent temporal slots into the symbol decoding tree. Another group of problems is related to maintaining the mode matching between incoming optical signal and local oscillator as well as keeping track of the correct displacement amplitude for the incoming signal vulnerable to transient intensity fluctuations resulting from atmospheric turbulences. Similarly the incorporation of quantum pulse into optical detection systems poses several technical difficulties. The hitherto demonstrated realisations of QPG usually rely on the ultrafast femtosecond laser which serves as a light source of a well-known properties providing temporally synchronized signal and pump beams. In realistic optical receiver the pump beam has to be matched to the modal characteristics of the onboard transmitter and temporally synchronized with incoming optical pulses in order to ensure genuinely single-mode output signal. The well-designed non-linear process aimed at the efficient conversion of incoming optical pulses into a single-mode output requires also a careful selection of signal, idler and pump beam wavelengths, the calculation of suitable phase-matching conditions as well as the selection of preferable non-linear medium.

References

[1] Zoran Sodnik et al. "Deep-space Optical Communication System (DOCS) for ESA's Space Weather mission to Lagrange orbit L5". In: *2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*. 2017, pp. 28–33. DOI: 10.1109/ICSOS.2017.8357207.

[2] Don M. Boroson et al. "Overview and results of the Lunar Laser Communication Demonstration". In: *Free-Space Laser Communication and Atmospheric Propagation XXVI*. Ed. by Hamid Hemmati and Don M. Boroson. Vol. 8971. International Society for Optics and Photonics. SPIE, 2014, 89710S. DOI: 10.1117/12.2045508. URL: https://doi.org/10.1117/12.2045508.

[3] Konrad Banaszek et al. "Quantum Limits in Optical Communications". In: *J. Lightwave Technol.* 38.10 (May 2020), pp. 2741–2754. URL: https://opg.optica.org/jlt/abstract.cfm?URI=jlt-38-10-2741.

[4] D. M. Boroson. "Toward optimum efficiency in a quantum receiver for coded ppm". In: 10562 (2017). Ed. by Bruno Cugny, Nikos Karafolas, and Zoran Sodnik, p. 105623M. DOI: 10.1117/12.2296040. URL: https://doi.org/10.1117/12.2296040.

[5] Jian Chen et al. "Optical codeword demodulation with error rates below the standard quantum limit using a conditional nulling receiver". In: *Nature Photonics* 6.6 (June 2012), pp. 374–379. ISSN: 1749-4893. DOI: 10.1038/nphoton.2012.113. URL: https://doi.org/10.1038/nphoton.2012.113.

[6] Andreas Eckstein, Benjamin Brecht, and Christine Silberhorn. "A quantum pulse gate based on spectrally engineered sum frequency generation". In: *Opt. Express* 19.15 (July 2011), pp. 13770–13778. DOI: 10.1364/OE.19.013770. URL: https://opg.optica.org/oe/abstract.cfm?URI=oe-19-15-13770.

[7] I. A. Burenkov, M. V. Jabir, and S. V. Polyakov. "Practical quantum-enhanced receivers for classical communication". In: *AVS Quantum Science* 3.2 (2021), p. 025301. DOI: 10.1116/5.0036959. eprint: https://doi.org/10.1116/5.0036959. URL: https://doi.org/10.1116/5.0036959.