

Energy-Bandwidth optimization of quantum-enabled communication channels

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Abstract: We introduce new modulation schemes and experimentally verify that they enhance the accuracy of practical quantum measurements and significantly optimize the combined use of energy and bandwidth for long communication alphabets. © 2021 The Author(s)

Bandwidth and energy are two fundamental resources needed to exchange digital information. Information is encoded in a finite set of physical states known as symbols. Encoding schemes differ in their use of parameters, such as frequency, phase and/or amplitude of coherent states, to encode data(bits). The number of states used for data encoding or the alphabet length (M) may also vary. The encoding scheme and the alphabet length are selected to optimize data transfer for given resources in the communication channel. However, there is a classical limit on this optimization which determines the maximum channel capacity of underlying system. Classical optical measurements are bounded by the shot noise limit (SNL). The SNL sets the minimum energy of an input state required such that the classical receiver discriminates states with the desired error probability. Terabits of data are communicated through global networks, hence using nearly all the available capacity of current optical interconnects the underlying system is approaching the so called "capacity crunch" [1]. To hinder the exponential growth of physical resources required to support this expansion, it is imperative to look for new enabling technologies, such as quantum measurement. A quantum-enabled receiver has a much lower energy requirement for reliable communication - the Helstrom Bound. Most practical quantum receivers demonstrated to date are based on a legacy classical modulation (such as Phase shift keying (PSK) where information is encoded in phase). Recently, the time resolved quantum receiver with the specially developed modulation scheme known as coherent frequency shift keying (CFSK) was demonstrated. This receiver has shown to have the highest energy efficiency (the lowest error probability at a given energy per symbol) to date [2]. However, CFSK uses a larger bandwidth than PSK. Here the goal is to find an optimal encoding that would optimize the combined resource use (i.e. both bandwidth and energy at the same time). Here we introduce a hybrid frequency phase shift keying (HFPSK) with alphabet length $M=M_f \times M_{ph}$, where M_f is the number of frequencies used and M_{ph} is the number of different phases used at each frequency. We experimentally investigate the resource efficiency of HFPSK, PSK, and CFSK using the time resolved quantum receiver.

The experimental setup follows the diagram in Fig. 1. A laser at 633 nm is sent to a 1:99 beam splitter and then reflected and transmitted beams are sent to a signal preparation module and an LO preparation module, respectively. Signal and LO preparation modules, shown as grey boxes, are comprised of the double-pass acousto-optic modulator (AOM). The quantum receiver is comprised of an LO preparation module, a 99:1 beamsplitter, a single photon detector (SPD) and a field programmable gate array (FPGA). Encoding methods and feedback algorithms are changed by reprogramming the FPGA and no change in the physical layout is needed. The frequency shifts and dimensionless detuning parameter are set to the value of $\Delta\omega = 2\pi \times 7629$ rad/s and $\Delta\omega T = \pi/2$ for all modulation schemes. To discriminate the input signal state, an arbitrarily chosen initial hypothesis h_0 is sent to the beam splitter. The displaced input signal is sent to the SPD. Every time a photon is detected, an electronic pulse is sent to the FPGA. The k -th pulse gets registered at time t_k , as shown in the inset of Fig. 1. The FPGA computes Bayesian probabilities, updates the most likely hypothesis h_k , and switches the LO to the next hypothesis. h_k is computed based on the previous hypothesis h_{k-1} and the photon detection time t_k . The LO change is represented in Fig. 1 by the filling color of the LO pulse $h_0, h_1, h_2 \dots h_f$, where f is the number of single photon detection during each measurement. At the end of the pulse, the current most likely hypothesis h_f represents our best knowledge about the input state. If h_f matches the signal, a discrimination is considered successful, otherwise an error is registered. The average number of energy per bit (in photons per bit) is obtained for a desired probability of error.

To demonstrate the trade-off in the resource use, we plot the energy consumption (EC) vs. spectral efficiency (SE) for a fixed symbol error rate (SER). Energy consumption is defined as an average number of photons ($\langle n \rangle$) per bit required for reliable communication, whereas spectral efficiency is defined as number of bits communicate over a unit bandwidth, Hz in 1 s. The SE is defined by the encoding scheme; the EC is measured in the experiment

