Practical Resource Optimization of Quantum-Enabled Communication Channels

M V Jabir[1], F R Annafianto,[1], I A Burenkov[2,3], A Battou[1], and S V Polyakov[2,4]

[1] *Advanced Network Division , National Institue of Standards and Technology, Gaithersburg MD, USA*
[2] *Quantum Measurement Division , National Institue of Standards and Technology, Gaithersburg MD, USA*
[3] *JQI, Joint Quantum Institute, University of Maryland and National Institute of Standards and Technology, College Park MD, USA*
[4] *Department of Physics, University of Maryland, College Park MD, USA*
Contact Email: jabir.marakkarakathvadakkepurayil@nist.gov

Optical communication plays a pivotal role in establishing the global Internet. Long-distance optical links are using nearly all the capacity enabled by today's technology. The exponential growth of the data transfer over the Internet has no sign of slowing down. Thus telecommunication is headed to the so-called "capacity crunch". To avert the exponential growth of physical resources - bandwidth and energy - required to support this demand, it is imperative to look for new enabling technologies, such as quantum measurements. The maximum channel capacity is limited by the fundamental properties of the measurement, and all classical measurements employed in telecommunication are bounded by the shot-noise limit (SNL). A quantum-enabled measurement has a much lower energy requirement for reliable communication constrained by the lower bound - the Helstrom Bound (HB). Most practical quantum receivers demonstrated to date are based on legacy phase-shift keying (PSK). We have shown that the time-resolved quantum receiver with the specially developed modulation scheme known as coherent frequency shift keying (CFSK) practically maximizes the advantage of quantum measurement. Experimentally, this new receiver has the highest energy efficiency (the lowest error probability at a given energy per symbol) to date [**?**] However, CFSK uses a larger bandwidth than PSK. Here the goal is to find an optimal encoding that would optimize the combined resource use: both bandwidth and energy at the same time.

In this work, we introduce a novel modulation scheme, the hybrid frequency phase shift keying (HF-PSK). The alphabet length $M{=}M_f \times M_{ph}$, where M_f is the number of frequencies and M_{ph} is the number of different phases used at each frequency. Our new modulation can be seen as a generalization of the PSK and CFSK schemes because for $M_f = 1$, it becomes the PSK, and for $M_{ph} = 1$ it becomes the CFSK. We experimentally investigate the combined resource efficiency of HFPSK, PSK, and CFSK for $M{=}4$, 8, and 16 with our time-resolved quantum receiver testbed. The combined resource efficiency (CRE) is defined as the product of energy efficiency (EE, bits/photon) and spectral efficiency (SE, bits/s/Hz). We find that HFPSK offers the best CRE experimentally and theoretically. Also, our observed experimental CRE (CRE_{exp}) surpasses the shot noise limited CRE (CRE_{SNL}) for nearly all encoding schemes that we considered.

In conclusion, this contribution presents a systematic experimental and theoretical study of the quantum measurement advantage and its practical use for quantum-enabled classical communication.