Quantum and Classical Communications in Shared Optical Fibers: Teleportation and Beyond

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Abstract: We discuss recent experimental progress in quantum teleportation systems operating in the same fibers as high-rate classical communications. We evaluate methods for optimizing teleportation fidelity in the presence of spontaneous Raman scattering noise.

1. Introduction

Realizing many proposed applications in quantum networking requires the distribution of high-fidelity single photon and entangled photon quantum states between distant quantum nodes as well as joint measurements between independent photons such as Bell state measurements (BSMs). With these capabilities, one can perform operations such as quantum state teleportation and entanglement swapping, amongst others. Significant progress in quantum teleportation systems over deployed optical fiber networks have been made in recent years [1]. However, these were implemented on quantum dedicated fibers. In general, a significant challenge for scaling fiber-based quantum networks is the fact that the optical fiber infrastructure is also used for classical telecommunications and networking, meaning it is highly desirable for both quantum and classical networks to simultaneously operate in the same fibers as opposed to the economically expensive alternative of having completely independent fiber infrastructures. Further, classical light-based signals can be used to improve quantum network functionalities, such as time synchronization of photon detection or distant pulsed quantum sources [2]. Similarly, having both quantum and classical signals operating in the same fiber would make full use of the available fiber between the nodes.

To ensure that both quantum and classical signals can share a single fiber, wavelength division multiplexing (WDM) can be employed via allocating quantum and classical signals to different wavelength channels. However, the relatively higher powers of classical signals will unavoidably generate noise photons into neighboring wavelength channels, the main process being spontaneous Raman scattering (SpRS). Without careful engineering of the physical system, classical powers need to be attenuated (thus reducing the classical data capacity) to prevent significant degradation of quantum fidelity. Such integration has been studied in a variety of scenarios, such as single photon transmission [3], entanglement distribution [4], and BSMs between single photons [5]. However, quantum state teleportation, entanglement teleportation (entanglement swapping), and many other more advanced multi-photon quantum applications remain understudied in terms of the design considerations needed for deploying these systems alongside classical networks.

Recently, we demonstrated a quantum state teleportation system with polarization encoded qubits and two spontaneous parametric down conversion sources operating over a 10.5-km fiber link simultaneously carrying a 400-Gbps C-band (1547.32 nm) classical communications signal [6]. We utilized WDM technology to multiplex and demultiplex quantum/classical signals to allow single photon and entangled photon transmissions to a Bell state measurement node near the midpoint of the link whilst the classical signal by-passed via WDMs to transmit the entire fiber length (Fig. 1(a)). To mitigate the effects of SpRS noise, we built an O-band ($\sim$1300 nm) teleportation system to place quantum signals in the low gain and anti-Stokes suppressed regions of the Raman noise spectrum relative to the C-band signal [4]. Further, we employed narrowband spectral filtering ($\sim$8 GHz) of the photons to reject SpRS photons and erase distinguishability in order for Hong-Ou-Mandel (HOM) interference to occur at the BSM node. Figure 1(b) shows a measured HOM interference fringe while 11 dBm of 1547.32-nm power was transmitted over the link, where we obtained a visibility of $V_{\mathrm{HOM}} = 71.2 \pm 2.1\%$. Figure 1(c) shows the fidelity $F = \langle \psi_A | \rho_B | \psi_A \rangle$ of Bob's measured density matrix ρ_B to Alice's ideal qubit $|\psi_A\rangle$ determined via quantum state tomography for various initial states. We obtained an average teleportation fidelity for an arbitrary qubit of

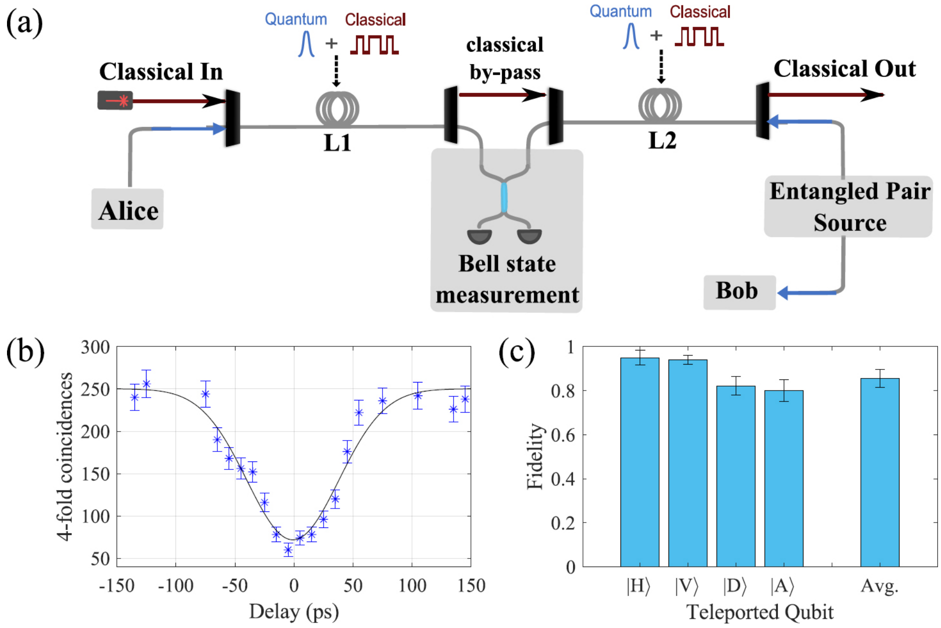

Fig. 1. (a) Conceptual diagram of a quantum teleportation system operating over a fiber link carrying a classical communications signal. (b) Four-fold coincidence Hong-Ou-Mandel interference fringe (per 150 s) and (c) teleportation fidelity for various teleported qubits over a 10.5-km fiber simultaneously carrying a 400-Gbps C-band signal for $L_1 = 5.4$ km and $L_2 = 5.1$ km [6].

$F_{avg} = 85.6 \pm 4.0\%$, well above the non-classical limit of $F = 66.7\%$. We found that utilizing our WDM design and SpRS noise mitigation methods, the quantum and classical systems had negligible impact on the operation of each other. From further analysis, we predict C-band powers >20 dBm could be tolerated with our system design.

2. Outlook

As a proof-of-principle demonstration, these results provide a significant step towards improving the scalability of the next generation of quantum network technology. However, many outstanding questions still remain. In general systems, the rate of SpRS noise highly depends on the allocation of quantum and classical wavelengths and the optimal choice will be widely system dependent. Further, the SpRS rates will increase as a function of fiber length in our system design, whilst the quantum signal rates will decrease, thus reducing the signal-to-noise ratio. This is particularly important for photonic sources based on spontaneous parametric processes, which, absent of any background noise, have the highest entanglement fidelity and HOM interference visibility at low photon-pair generation rates due to the degrading effect of multi-pair emission at higher rates. Increased SpRS noise and higher transmission losses over longer fibers will require finding optimal pair generation rates that balance both increased background noise and multi-pair emission. We will discuss these issues and our further progress in experimentally evaluating the design considerations at the conference.

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