

Optimized Entanglement Distribution among Quantum Memories

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Abstract: We evaluate entanglement distribution performance when an optimized quantum memory encoding method is used for two sources, the standard spontaneous parametric down conversion source and the zero added loss multiplexing source. Physical non-idealities are considered. © 2024 The Author(s)

1. Introduction

Quantum links for entanglement distribution constructed in the ‘midpoint source’ configuration [1, 2] require a high rate source of entangled photon pairs source that can be transmitted to the end users over the network. The most popular and widely studied source of photonic entanglement is the spontaneous parametric down conversion (SPDC) process [3, 4]. Alternative sources of entanglement have also been proposed for this task such as sources based on spontaneous four-wave mixing (SFWM), high-efficiency single photon emitters, as well as a heralded multiplexed cascaded photonic source design [5, 6]. Quantum memories can be used in conjunction with these sources to store entanglement transmitted over the channel, potentially improving the overall performance and efficiency of the protocol. In this article, we analyze the performance of the SPDC and the zero added loss frequency multiplexed (ZALM) sources in the presence of network imperfections with quantum memories. Our results show a true-to-performance comparison between the efficient deployment of SPDC and ZALM over these quantum links and might serve as important guidelines for future efforts in quantum internet development.

2. System Details

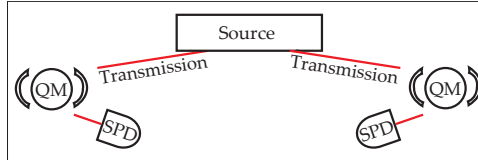


Fig. 1. Basic diagram of the general system under consideration, where entangled photon pairs are transmitted from a source, interact with quantum memories (QM), and are detected with single photon detectors (SPDs) heralding successful storage of the qubits

For our article, we consider photonic qubits in the dual rail encoding, where the logical states are $|\bar{0}\rangle \equiv |1, 0\rangle; |\bar{1}\rangle \equiv |0, 1\rangle$. The SPDC based source of entanglement which generates an entangled quantum state, given by, $|\psi\rangle = N_0 \left[\sqrt{p(0)} |0, 0; 0, 0\rangle + \sqrt{\frac{p(1)}{2}} (|1, 0; 0, 1\rangle + |0, 1; 1, 0\rangle) + \sqrt{\frac{p(2)}{3}} (|2, 0; 0, 2\rangle + |1, 1; 1, 1\rangle + |0, 2; 2, 0\rangle) \right]$ where N_0 is a normalization coefficient and $p(n) = (n+1)N_s^n / (N_s+1)^{n+2}$, N_s being the mean photon number. Here we truncate our state to two-photon pairs. Practical deployment of the SPDC source (for satellite or ground based quantum networks) is hindered by the vacuum and multi-photon pair terms that are produced in addition to the Bell state terms. The latter is the state component contributing to distributed entanglement; thus the vacuum and multi-photon pair terms hinder system performance. The ZALM source [5, 6] in its most discrete form produces a quantum state given by, $|\phi\rangle = N'_0 \left[\sqrt{\frac{p(1)}{2}} (|1, 0; 0, 1\rangle + (-1)^{m_1} |0, 1; 1, 0\rangle) + (-1)^{m_2} \sqrt{\frac{p(0)p(2)}{3}} (|0, 0; 1, 1\rangle + (-1)^{m_1} |1, 1; 0, 0\rangle) \right]$ where the exponents $m_1, m_2 \in \{0, 1\}$ depend on a heralding trigger and N'_0 is a normalization coefficient. Fundamentally, the

ZALM source is composed of two SPDC sources in conjunction with a linear optical Bell state measurement on the idler photons. This measurement heralds the creation of an entangled photon pair, removing the possibility of vacuum creation (assuming perfect noiseless detection). In the ideal case, each receiver site is also able to recognize erroneous two-photon terms, as these terms result in photons arriving only at one site and never at the other.

3. Results

We evaluate the performance of the described system (Fig. 1) by evaluating the final end-to-end quantum state ρ_{AB} and calculating the following metrics – (1) Fidelity of the final state with respect to the Bell state, $F = \frac{\langle \phi^- | \rho_{AB} | \phi^- \rangle}{\text{Tr}(\rho_{AB})}$, (2) a lower bound to the state’s distillable entanglement content via the hashing Bound, $I(\rho_{AB}) = \max[S(\rho_A) - S(\rho_{AB}), S(\rho_B) - S(\rho_{AB})]$ and (3) the distillable entanglement rate, $\mathcal{R}(\rho_{AB}) = I(\rho_{AB}) \times \text{Tr}(\rho_{AB})$, which is a lower bound to the maximal entanglement delivery rate of this system.

From Fig. 2, we observe that $\mathcal{R}(\rho_{AB})$ decreases as the loss (η) increases, scaling proportional to η^2 . For every value of the dark count probability, P_d , the ZALM source outperforms the SPDC source in distillable entanglement rate. The fidelity is informative as it describes how close our arriving state is to the actual Bell state. Our results show that ZALM is more robust than SPDC in the presence of loss, for each value of P_d SPDC quickly drops to a maximum fidelity of ~ 0.9 , before quickly dropping to an fidelity of 0.5, for a mean photon number of 0.2. On the other hand, ZALM maintains a fidelity at 1 before dropping to the fidelity of 0.5 for high loss, for a mean photon number of 10^{-6} . This transition occurs at a lower loss threshold for a larger value of P_d . The distillable entanglement is a measure of the entangled qubits that can be produced from the lower fidelity states. We have plotted the hashing bound, $I(\rho_{AB})$, which is the lower bound on the distillable entanglement. We see that for all values of P_d , ZALM outperforms SPDC in distillable entanglement for a given value of loss. Our work shows that in using quantum memories in a ‘midpoint source’ quantum link with physical non-idealities, the ZALM source outperforms a standard SPDC source and offers a better quality of end-party entanglement. In the presence of loss, the ZALM source distributes a higher fidelity state, in a more robust fashion - enabling high quality distributed entanglement with the accompanying benefit of higher distribution rate.

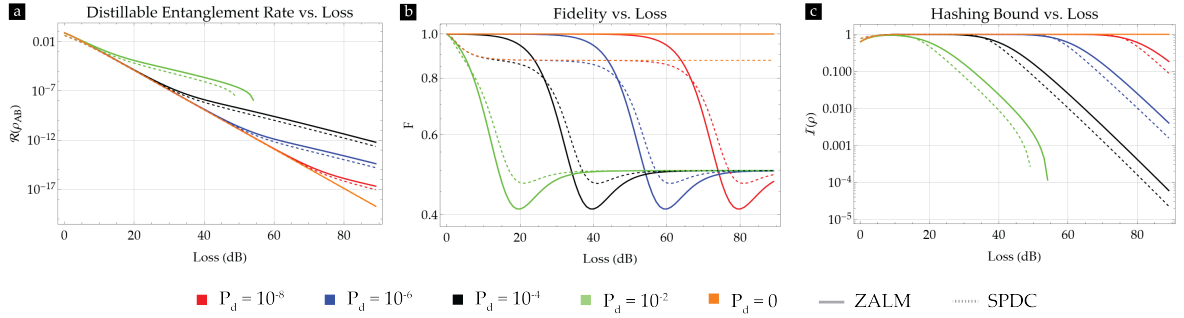


Fig. 2. Plots of system performance for three metrics versus system loss in dB, (a) distillable entanglement rate, (b) fidelity of the state with respect to the Bell state, (c) lower bound on the distillable entanglement, or in other words the Hashing Bound.

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