Hybrid Quantum Networks for High-Fidelity Entanglement Distribution

Lee, Yuan; Bersin, Eric; Dahlberg, Axel; Wehner, Stephanie; Englund, DIrk

Publication date
2020

Document Version
Final published version

Published in
2020 Conference on Lasers and Electro-Optics, CLEO 2020 - Proceedings

Citation (APA)
Lee, Y., Bersin, E., Dahlberg, A., Wehner, S., & Englund, DI. (2020). Hybrid Quantum Networks for High-Fidelity Entanglement Distribution. In *2020 Conference on Lasers and Electro-Optics, CLEO 2020 - Proceedings* Article 9193484 (Conference Proceedings - Lasers and Electro-Optics Society Annual Meeting-LEOS; Vol. 2020-May). IEEE.

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Hybrid Quantum Networks for High-Fidelity Entanglement Distribution

Yuan Lee[1], **Eric Bersin**[1], **Axel Dahlberg**[2,3], **Stephanie Wehner**[2,3], **Dirk Englund**[1]
[1] *Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge MA 02139, USA*
[2] *QuTech, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*
[3] *Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*
leeyuan@mit.edu

Abstract: We present an architecture for multiplexed quantum repeaters using local connectivity to improve fidelity in entanglement distribution. Simulations indicate our scheme achieves rates comparable to competing schemes, with fidelity improvements that increase with repeater size.

1. Introduction

Quantum communication and distributed quantum computing require quantum entanglement to be shared between distant parties. One of the challenges involved in establishing entanglement between distant qubits is that of photon loss in the connection between the qubits, severely limiting the rate of entanglement generation. Therefore, quantum repeaters have been proposed that can potentially achieve better performance than the direct connection alone. Networks of quantum repeaters can then distribute entanglement between many clients.

We consider emission-based entanglement protocols for quantum repeater networks of solid-state qubits connected by photonic links (Figure 1a). These protocols involving photon-mediated entanglement [1, 2] require detector stations between repeater nodes. We abstract these physical links into connections that can be used to distribute entanglement [3]. These connections can be multiplexed, for example temporally, spectrally or spatially.

Current proposals for creating quantum repeaters typically consider a single optical access point per repeater qubit register. In this paper, we show that exploiting high local connectivity between qubits at repeater nodes allows for higher fidelity entanglement for equivalent qubit number.

2. Hybrid Repeater Scheme

Consider a repeater that connects two client nodes, Alice and Bob. Typical repeater protocols establish entanglement with Alice first, before attempting entanglement with Bob (Figure 1b). The repeater must thus hold its Alice-entangled register for the time it takes to establish entanglement with Bob. Our proposed scheme allows both Alice and Bob to attempt entanglement with the repeater simultaneously. The repeater then uses local, low-loss connections to link Alice's and Bob's entangled qubits (Figure 1c), thereby establishing entanglement across the channel. This "hybrid" scheme, using both distant lossy channels and local low-loss channels, thus only has to hold any entangled register for the difference in time to establish entanglement on either side of the repeater, reducing the amount of time any Alice- or Bob-entangled register has to idle before it is consumed. These entangled registers then have less time to decohere, improving the fidelity of the entangled pair distributed to Alice and Bob.

Increasing the repeater size (i.e. the number of repeater registers) allows us to exploit the multiplexed modes in a single connection. For a fair comparison of repeater schemes, we compare repeaters of the same total number of qubits. All repeater registers make exactly 1 entanglement attempt with a client node in a single clock cycle. The clock rate is limited by the round-trip time of flight between a detector station and the connected repeater node.

The hybrid repeater matches Alice-entangled registers with Bob-entangled registers as they are generated. We consume entangled repeater registers using Bell state measurements that teleport repeater qubits onto client qubits. For simplicity, Alice- and Bob-entangled registers are consumed in their order of generation.

3. Simulation Results

We simulate both the traditional and hybrid repeater schemes using NetSquid [netsquid.org], which is a discrete event simulator for quantum networks. For the ease of illustration, we use the Barrett-Kok protocol for entanglement generation over distant links with link efficiency $\eta = 0.9$ and local links with perfect transmission. However, our conclusions also hold for other entanglement protocols, and for links with more realistic link efficiencies.

Figure 1d shows the entanglement rate for the hybrid and traditional schemes. The hybrid rate is slightly lower than, but still comparable to, the traditional rate. We attribute the lowered hybrid rate to the time needed to match Alice- to Bob-entangled registers. The ratio of hybrid to traditional rates tends to 1 as the repeater size increases.

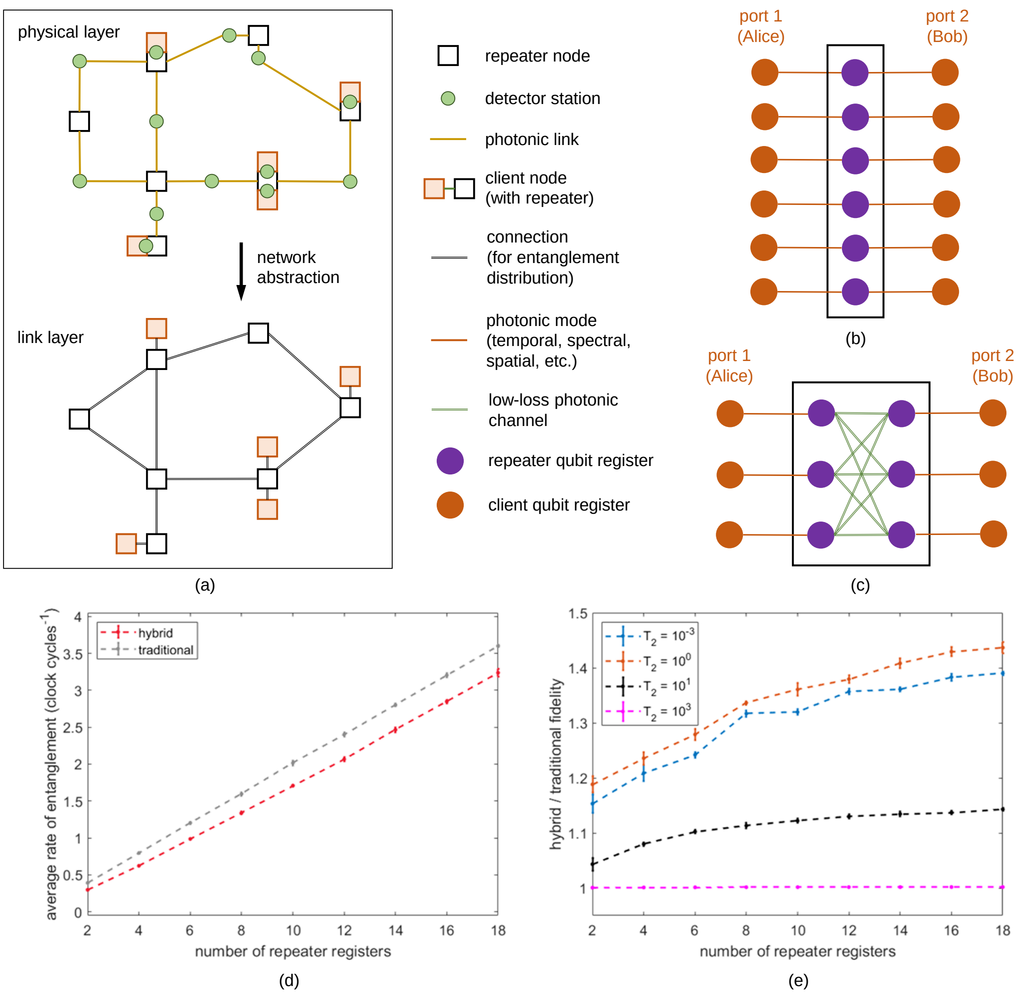

Fig. 1. Example of emission-based quantum repeater networks. (a) Illustration of a quantum repeater network, both with physical links (top) and abstract connections (bottom). (b) Abstract representation of a traditional repeater scheme. (c) Abstract representation of the proposed hybrid scheme, which uses local low-loss connections to rapidly generate entanglement between repeater registers. Local entanglement can then be used to link up Alice-entangled and Bob-entangled registers. (d) Simulated entanglement generation rates for traditional and hybrid repeater schemes. Error bars are the standard errors of the mean from 5 independent trials. (e) Simulated ratio of hybrid to traditional fidelities $F_{\text{hyb.}}/F_{\text{trad.}}$ under various qubit coherence times T_2. (T_2 is in units of clock cycles.)

Figure 1e shows the ratio of hybrid to traditional entanglement fidelities. As predicted, the hybrid scheme has a dramatic improvement in fidelities over the traditional scheme, especially when the coherence times of the registers are low. Data from a wider range of repeater sizes than shown in Figure 1e indicate that the improvement in fidelity ($F_{\text{hyb.}}/F_{\text{trad.}} - 1$) scales approximately with the cube root of the repeater size.

A hybrid repeater can be realized using recent advances in integrated photonics, such as the fast on-chip switching of many optical modes. Under realistic qubit coherence times, the hybrid repeater scheme can provide significantly improved entanglement fidelities at entanglement rates comparable to traditional repeater schemes.

References

1. S.D. Barrett and P. Kok, “Efficient high-fidelity quantum computation using matter qubits and linear optics.” *Physical Review A* **71**, 060310 (2005).
2. F. Rozpedek, R. Yehia, *et al.*, “Near-term quantum-repeater experiments with nitrogen-vacancy centers: Overcoming the limitations of direct transmission.” *Physical Review A* **99**, 052330 (2019).
3. A. Dahlberg, M. Skrzypczyk, *et al.*, “A Link Layer Protocol for Quantum Networks.” In *ACM SIGCOMM 2019 Conference (SIGCOMM’19), August 19-23, 2019, Beijing, China.*