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Multiplexed entanglement generation over quantum networks using multi-qubit nodes

Suzanne B. van Dam,[1,2] Peter C. Humphreys,[1,2] Filip Rozpędek,[1] Stephanie Wehner,[1] and Ronald Hanson[1,2]

[1] *QuTech, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands*

[2] *Kavli Institute of Nanoscience, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands*

Quantum networks distributed over distances greater than a few kilometers will be limited by the time required for information to propagate between nodes. We analyze protocols that are able to circumvent this bottleneck by employing multi-qubit nodes and multiplexing. For each protocol, we investigate the key network parameters that determine its performance. We model achievable entangling rates based on the anticipated near-term performance of nitrogen-vacancy centres and other promising network platforms. This analysis allows us to compare the potential of the proposed multiplexed protocols in different regimes. Moreover, by identifying the gains that may be achieved by improving particular network parameters, our analysis suggests the most promising avenues for research and development of prototype quantum networks.

Recent progress in the generation, manipulation, and storage of distant entangled quantum states has opened up an avenue to the construction of a quantum network over metropolitan-scale distances in the near future [1, 2]. One of the key challenges in realizing such quantum networks will be to overcome the communications bottleneck induced by the long distances separating nodes. This occurs because probabilistic protocols require two-way communication and, for such distances, the entanglement generation rate becomes limited by the time required for quantum and classical signals to propagate.

It is unlikely that quantum networks will attain sufficient levels of complexity in the near future to support the transmission of complex multi-photon entangled states necessary to overcome this bottleneck through error correction [3, 4]. This motivates the development of alternative methods to circumvent this limited communication rate, of which the most promising near-term approach is through multiplexing entanglement generation [5–10].

Previous proposals have developed multiplexed entanglement-generation protocols for networks based on atomic-ensemble quantum memories and linear optics [6, 9, 11] and for networks in which each node consists of many optically accessible qubits that can be temporally, spectrally or spatially multiplexed [5, 7, 8, 10]. However, these proposals are not effective for promising multi-qubit hybrid network node architectures [12], in which one (or a few) optically accessible communication qubits in each node provide a communication bus to interface with multiple local memory qubits. Several platforms have demonstrated the key elements of such a system, including nitrogen-vacancy (NV) centres in diamond [13, 14], trapped ions [2], and quantum dots [14, 15].

Here we focus on the scenario of efficiently generating heralded remote entanglement between two hybrid multi-qubit nodes separated by tens of kilometers in a quantum network. We propose two strategies for multiplexing entanglement generation using multi-qubit architectures, identifying the scaling of the entangling rates with the distance between nodes. We compare these strategies to an alternative protocol based on the distribution of entangled photon-pairs [16], modelling all three protocols analytically and with Monte Carlo simulations. This allows us to identify optimal protocols for different regimes of distance and node performance.

In order to be able to effectively assess the potential of these network protocols, it is vital to incorporate the known and anticipated limitations of potential platforms from the start. In this paper we therefore use network parameters representing the expected near-term performance of NV centre nodes. These centres are promising nodes for such a network, combining a robust and long-lived ^{13}C nuclear-spin quantum register [17, 18] with a photonic interface. Our conclusions are nonetheless broadly applicable to other platforms with comparable system performances, particularly trapped ions [2].

Our analysis highlights the potential of multiplexed distillation-based schemes to provide high rates of remote entanglement generation and the most favourable scaling with respect to losses. For such schemes, we have identified the swap gate time between the communication and the memory qubits as the key parameter in constraining the achievable entanglement generation rate, as this limits the number of quantum memories that can be used. This highlights the importance of developing methods to increase this storage rate while ensuring that memories remain robust to decoherence.

We find that the protocol based on distribution of entangled photon-pairs has a different dependence on the system parameters, with its performance only weakly constrained by the memory storage time. However, its increased sensitivity to losses hinders its performance over long distances. In addition, there is considerable uncertainty in the projected performance of entangled-pair sources in the near-term, particularly with regard to the source brightness. Until brightnesses on the order of 0.1 per attempt can be achieved, our analysis suggests that these schemes will not perform as effectively as the multiplexed distillation-based protocols.

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