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**Publication date**
2023

**Document Version**
Final published version

**Published in**
2023 Conference on Lasers and Electro-Optics, CLEO 2023

**Citation (APA)**
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# Distributed entanglement and teleportation on a quantum network

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**Abstract:** We report on the realization of a multi-node quantum network. Using the network, we have demonstrated three protocols; generation of a entangled state shared by all nodes, entanglement swapping and quantum teleportation between non-neighboring nodes.

## 1. Introduction

A future quantum internet can unlock fundamentally new technologies by sharing entangled states and quantum information across the nodes of the network. In the past decade, many buildings blocks of such a network have been demonstrated. In particular, the heralded distribution of entanglement between two physically separated nodes and quantum teleportation has been achieved on various platforms, however connecting multiple nodes into a multi-node quantum network remained an open challenge. Here, we present the experimental realization of a multi-node quantum network. The research presented in this abstract is based on References [1,2].

## 2. Multi-node quantum network

Our network consists of three nodes, Alice, Bob and Charlie, see Figure 1. Each node contains a diamond chip, hosting a nitrogen-vacancy center that acts as a communication qubit to generate remote entanglement with neighboring nodes. Additionally, Bob and Charlie have access to a memory qubit in the form of a carbon-13 nuclear spin. To generate entanglement between neighboring nodes, we make use of the single-photon entanglement protocol [3,4]. The experiments on the network are enabled by three technological improvements [1].

To meet the phase stability requirement of the single photon protocol, we have developed a scalable phase-stabilization scheme. The combination of homodyne and heterodyne phase detection allows us to stabilize the optical phase with a high bandwidth and prevents reflected excitation light to leak into the detectors during entanglement generation.

To distribute entangled states across multiple nodes, generated entangled states must be stored in the memory qubits while new entanglement links are created. To mitigate dephasing of the memory qubit due to operations using the communication qubit, we operate the middle node Bob at a high magnetic field (B = 189 mT) and observe that the performance of the memory qubit is mostly limited by the intrinsic dephasing $T_2^*$. As a result, we can do $\approx$1800 entanglement attempts, before the memory qubit has completely dephased.

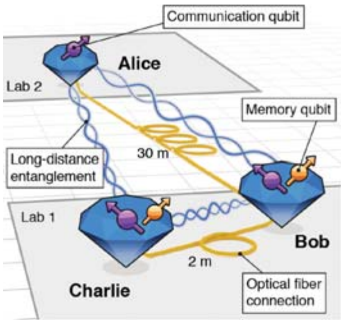

Fig. 1: The multi-node quantum network consists of three nodes, Alice, Bob and Charlie. Each node consists of a communication qubit (purple spin). Additionally, Bob and Charlie have access to a memory qubit (orange spin).

We implement an asynchronous bidirectional serial communication scheme between microcontrollers at the nodes, enabling both the required timing synchronization of the nodes and the exchange of feed-forward information for the quantum network protocols.

With these technologies, we are able to perform two canonical network protocols: the distribution of genuine multipartite entanglement and entanglement swapping to two non–nearest neighbor nodes. For both protocols two entangled are established, Alice-Bob and Bob-Charlie. To generate a multipartite entangled Greenberger-Horne-Zeilinger (GHZ) state, Bob entangles his two qubits locally upon success of the second link within a preset number of attempts, and measures the state of his communication qubit. Depending on the result, Charlie performs a feed-forward operation to construct the GHZ state. The resulting state has a fidelity of $F = 0.538(18)$ with respect to the ideal GHZ state at a heralding rate of 1/(90 s), the state fidelity above 0.5 certifies the presence of genuine multipartite entanglement distributed across the three nodes. To execute entanglement swapping, Bob performs a

Bell-state measurement once the two entangled links are ready. Again, depending on the results, Charlie performs a feed-forward operation to obtain the entangled state with Alice. The fidelity of the Alice-Charlie entangled state is $F = 0.551(13)$, with respect to the maximally entangled state, with a heralded rate of 1/(40 s).

## 3. Quantum teleportation across the network

Quantum teleportation is the central routine for reliably sending qubits across lossy network links. Because the quantum information is not transmitted by a physical carrier, the protocol is insensitive to loss in the connecting photonic channels and on intermediate nodes [5]. To realize the quantum teleportation between the end nodes Alice and Bob in our network, we incorporate a set of innovations [2].

We improve the nearest-neighbor entanglement fidelity by implementing a tailored heralding scheme. By monitoring the detection path of the phonon-side band, which are not used for entanglement generation, we can flag erroneous events where both qubits emitted a photon or when one qubit emitted two photons.

We extend the memory coherence by performing a decoupling pulse on the memory qubit after successful generation of the second entangled link and rephase the qubit for the same amount of time it took to herald to entangled state. In this way, the memory qubit coherence increases to ≈5300.

Lastly, we introduce a basis-alternating repetitive readout for the memory qubit. The key point of this readout strategy is to alternatingly map the computational basis states of the memory qubit to the communication qubit state, optically readout the communication qubit and reject the outcome when the results of the different mappings are inconsistent.

Supported by these additional innovations, we are able to perform the quantum teleportation protocol. We use to entanglement swapping protocol to generate the Alice-Charlie entangled state (the teleporter). Once the state is heralded, Charlie stores the state on his memory qubit and uses the communication qubit to encode the state to be teleported. Consequently, he performs a Bell-state measurement on his two qubits and communicates the result to Alice. Depending on the outcomes, Alice performs a feed-forward operation and reconstructs the teleported state. For an arbitrary state, the fidelity of the teleported state is $F = 0.702(11)$ at an experimental rate of 1/(117 s). This value exceeds the classical bound of 2/3 by more than three standard deviations, thereby proving the quantum nature of the protocol.

## 4. Outlook

The multi-node quantum network and its capabilities open the door to exploring advanced multi-node network protocols and can serve as a testbed for higher-level quantum network control layers. To scale up the network, quantum frequency conversion of the photon emitted by the NV to the telecom band will allow for quantum network tests over metropolitan distances.

## 5. Acknowledgments

We acknowledge financial support from the EU Flagship on Quantum Technologies through the project Quantum Internet Alliance (EU Horizon 2020, grant agreement no. 820445); from the European Research Council (ERC) through an ERC Starting Grant (S.W.); through an ERC Consolidator Grant (grant agreement no. 772627 to R.H.); from the Netherlands Organisation for Scientific Research (NWO) through a VICI grant (project no. 680-47-624) and the Zwaartekracht program Quantum Software Consortium (project no. 024.003.037/3368). M.P. acknowledges support from the Marie Skłodowska-Curie Actions - Nanoscale solid-state spin systems in emerging quantum technologies - Spin-NANO, grant agreement no. 676108. S.B. acknowledges support from an Erwin-Schrödinger fellowship (QuantNet, no. J 4229-N27) of the Austrian National Science Foundation (FWF).

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