How to Generate Long-distance Entanglement in a Homogeneous Repeater Chain

Daily Supervisor: Soubhadra Maiti (s.maiti-1@tudelft.nl)
Project Supervisor: Prof. Dr. Stephanie Wehner

Introduction

Entanglement is a uniquely quantum phenomenon that enables revolutionary applications not achievable with classical systems. Quantum networks leverage entanglement and superposition to enable cutting-edge tasks such as distributed quantum computing, secure communication, and advanced sensing [1].

A major challenge in realizing quantum networks is generating high-quality entanglement between distant nodes. Quantum repeaters facilitate long-distance entanglement distribution through a process called entanglement swapping. Adding more quantum repeaters in a network also comes with additional challenges and detrimental effects on the quality of entanglement. Previous studies have investigated entanglement generation in a repeater chain, particularly using ion trap quantum processors [2], providing estimates of entangling rates at long distances. In this project, we aim to perform a detailed simulation of a quantum repeater chain for optimal architecture and assess hardware requirements for maximizing entanglement quality over long-range distances.

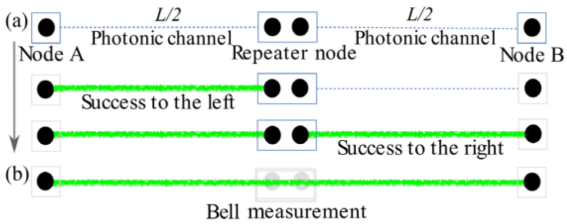

Figure 1: Quantum repeater concept [2]. (a) Repeater nodes attempt entanglement generation (green lines) within each elementary link between its qubits (black spheres) and qubits in each neighboring node separately. Whichever link succeeds first is stored in memory until the other link succeeds. (b) A Bell state measurement in the repeater node establishes entanglement over a larger distance (Node A and B in picture).

Research Objectives

This project aims to investigate the performance and optimization of quantum repeater chains to enhance entanglement distribution over long distances. The key objectives are:

(1) Set up simulation for entanglement generation over a 500 km repeater chain. Obtain the rate and fidelity for a given number of repeaters.

(2) Use optimistic parameters for ion traps from Quantum Internet Alliance (QIA) [3] SGA Phase II to determine the optimal number of repeaters for the 500 km chain. How does it vary with the total distance?

On completion of the concrete goals mentioned above, and depending on the project timeline, we will look into the additional research questions as our stretch goals:

(a) Assess the advantage of this homogeneous repeater chain over a heterogeneous architecture as envisioned in the QIA prototype network [3]. This includes evaluating the maximum achievable performance with current ion-trap systems and identifying necessary hardware improvements for high-fidelity entanglement in teleportation and quantum key distribution.

(b) Investigate with simulation the impact of different entanglement generation schemes (e.g., single-click vs. double-click) and resource constraints on the repeater chain's performance.

In this project, you will be using *NetSquid* [4], a Python-based simulator developed by our research group, and simulations on a supercomputer. The focus will be on ion trap systems, utilizing both current and optimistic parameters provided by the Quantum Internet Alliance (QIA) [3], a pan-European initiative aiming to realize a prototype quantum network by 2029. The study will contribute to the broader effort of developing scalable quantum communication infrastructure.

Project Goals

By the end of this project, the following deliverables and learning outcomes are expected:

Deliverables

- A comparative analysis of repeater chain performance, highlighting trade-offs and optimal configurations.
- Detailed hardware requirements for achieving high-fidelity entanglement at practical rates.
- Document findings in the form of a BEP thesis and potentially a journal paper.

Learning Outcomes

- Basic understanding of ion traps as a quantum computing platform and various entanglement generation schemes (e.g., double-click and single-click).
- Learn to work with pre-existing code.
- Run simulations on a supercomputer.

Requirements

The ideal candidate should have:

- Basic knowledge of quantum mechanics (e.g., superposition and entanglement).
- Familiarity with Python programming.
- Experience with Git (preferred but not mandatory).

References

1. H. J. Kimble, (2008). The quantum internet. Nature, 453(7198), 1023–1030.
2. V. Krutyanskiy et al., "Telecom-Wavelength Quantum Repeater Node Based on a Trapped-Ion Processor," *Phys. Rev. Lett.*, vol. 130, p. 213601, May 2023.
3. Quantum Internet Alliance: Building a global quantum internet made in Europe, https://quantuminternetalliance.org/.
4. NetSquid: The Network Simulator for Quantum Information using Discrete Events, https://netsquid.org/.