Proactive Entanglement Routing in Quantum Networks

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Abstract

Efficiently establishing end-to-end entanglement in quantum networks is critical to achieve quantum communication. Quantum routing protocols must consider that quantum operations are inherently probabilistic and the entangled states degrade over time. The routing phase can be distinguished into proactive, reactive and hybrid routing. We investigate a proactive entanglement routing protocol where quantum nodes pre-establish local entanglement for rapid path selection. Using a discrete-time simulation on a grid network, we quantify the link entanglement rate of the adjacent repeaters nodes.

I. Introduction

The quantum internet envisions a global-scale infrastructure for distributing entanglement across distant users, forming the foundation for distributed quantum computing, advanced quantum sensing, and anonymous quantum communication [1]. Unlike classical networks, where data packets can be copied and forwarded, quantum networks face unique challenges including the no-cloning theorem [2]. In quantum communication, both entanglement generation and swapping succeed only with certain probabilities [3]. Quantum states can degrade over time with a process called decoherence.

Routing in quantum networks must therefore consider for time-varying resources and probabilistic success rates. In quantum entanglement routing, there are two broad approaches: reactive routing and proactive routing. A hybrid routing scheme can also be adopted, with the integration of above mentioned schemes. Reactive quantum routing establishes entanglement on-demand, but it suffers from high latency and low success rates because qubits decohere during the slow path setup [4]. While proactive routing pre-establishes and stores multiple entangled links, which increases the success probability of long-distance entanglement by providing more path options, but this requires more quantum memory. [5].

In this work, we present a discrete-time simulation framework for proactive entanglement routing in grid-based quantum networks. Through this framework, we evaluate the achievable entanglement rate between adjacent repeater nodes and examine how it varies with link length. Furthermore, by conducting comparative simulations, we determine the optimal atom cooling time that maximizes network performance.

The remainder of this paper is organized as follows. Section II describes the network model and the routing protocol. Section III presents the simulation results. Finally, Section IV concludes the paper.

II. Network Model and Routing

The quantum network is modeled as a graph $G = (V, E)$, where V represent quantum repeater nodes and E represent quantum channels.

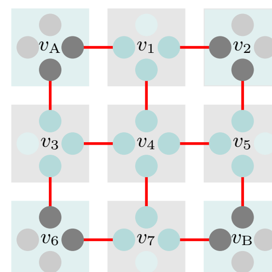

Fig. 1. A schematic of the square-grid (3×3 grid) topology, where the small squares denote the quantum repeaters with quantum memories. The red lines represent the channel linking the repeaters, where entanglement is established.

A. Node and Link Characteristics

1) **Nodes:** Each node $v_i \in V$ is equipped with a finite quantum memory of capacity M qubits. Two arbitrary nodes v_A, and v_B, are connected with entanglement channels as shown in Fig. 1.
2) **Links:** Each channel $e_{i,j} \in E$ is characterized by generation probability (P_gen), and decoherence time (T^coh).

B. Proactive Entanglement Routing

Proactive quantum routing protocols pre-establish entanglement paths based on link costs like expected throughput, making connections available before they're requested [6]. Unlike classical routing tables that store next-hop data, the routing tables used in Algorithm 1 list the locally-available entangled qubits at each node [5]. This system uses an efficient, hierarchical logic to proactively ensure end-to-end entanglement is always maintained between the set of neighbor nodes $N(v_i)$ for any given node v_i.

III. Simulation of Entanglement Rate

In this work, we simulate a quantum network composed of repeater nodes ($v_\mathrm{A}, v_1, \ldots, v_7, v_\mathrm{B}$) to model the link entanglement generation. The photon generation probability, and the detector efficiency are considered to calculate P_gen which also depends on the Bell-state measurement efficiency. Then, the overall success probability of a single entanglement attempt

Algorithm 1 Proactive Routing

Require: Initiating node $v_{\mathrm{A}} \in V$, target node $v_{\mathrm{B}} \in V$.
Ensure: End-to-end entanglement between v_{A} and v_{B}.

function ESTABLISHENTANGLEMENT($v_{\mathrm{A}}, v_{\mathrm{B}}$)
    ▷ Check for a direct, pre-established entangled link
    if $v_{\mathrm{B}} \in N(v_{\mathrm{A}})$ **then**
        Entanglement is already established.
        return success
    end if
    ▷ Check neighbors' routing tables for a 2-hop path
    for each neighbor $v_n \in N(v_{\mathrm{A}})$ **do**
        if $v_{\mathrm{B}} \in N(v_n)$ **then**
            Perform entanglement swapping at the intermediate node v_n. ▷ Connects the $v_{\mathrm{A}} \leftrightarrow v_n$ link and the $v_n \leftrightarrow v_{\mathrm{B}}$ link
            Entanglement is now established between v_{A} and v_{B}.
            return success
        end if
    end for
    return failure ▷ This case is highly improbable by design
end function

is calculated in terms of P_{gen}. Using this probability, the average total time required to achieve one successful link is determined, factoring in the time spent on the many expected failures. The analysis incorporates key system parameters, including photon loss which is modeled with attenuation length 22km, fiber speed 2×10^8ms, and a fixed memory coherence time of $T^{\text{coh}} = 10$ms.

The expected link entanglement rate $\mathrm{R}_{i,j}$ between adjacent nodes v_i and v_j is defined by

$$\mathrm{R}_{i,j}(T^{\text{coh}}) = \begin{cases} 0, & \text{if } T^{\text{coh}} < \tau_{i,j}, \\ \frac{1}{T_{i,j}}, & \text{otherwise,} \end{cases} \tag{1}$$

with $T_{i,j}$ denoting the entanglement generation time, and $\tau_{i,j}$ is the average time elapsed between the atom-photon entanglement generation [6]. $T_{i,j}$ is a function of atom cooling time τ_c, and the link distance $l_{i,j}$. Our primary analysis evaluates how different duty cycle durations for atom cooling time τ_c, impact this achievable entanglement rate. We simulate this by calculating the rates over link distances $l_{i,j}$ up to 200 km, accounting for the time cost of both successful and failed attempts, with the final rates being cut off by the channel's coherence time limit.

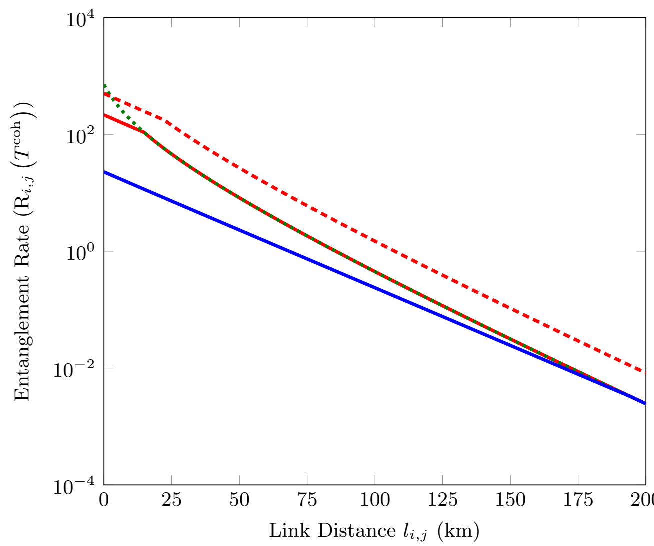

Fig. 2. Entanglement rate over a function of link distance. The red dashed line represents the entanglement rate between two nodes in free space with an atom cooling time τ_c= 100 μs. The dotted green, solid red, and blue lines correspond to simulated entanglement rates for atom cooling times τ_c= 10 μs, 100 μs, and 1 ms, respectively. The results illustrate how shorter atom cooling times enhance the achievable entanglement rate over varying link distances.

IV. Conclusions

In conclusion, we analyzed a proactive entanglement routing framework that pre-establishes high-fidelity quantum links to reduce latency and enhance network throughput. The link entanglement between two nodes was simulated to determine the optimal duration of atom cooling time of the referenced protocol. As shown in Fig. 2, the entanglement rate decreases exponentially with increasing link distance. Shorter atom cooling times yield significantly higher rates, particularly at shorter distances. It shows that optimizing atom cooling time is crucial for enhancing the overall efficiency of entanglement distribution in quantum networks.

Acknowledgment

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