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Abstract: We present efficient multi-flow entanglement routing in Quantum Tree Network (QTN) with sublinear overhead, congestion-free operations, and error correction, outperforming conventional mesh networks.

1. Introduction

Quantum networks (QNs) have emerged as a promising solution for transmitting quantum states over long distances, enabling various applications in quantum information science and technology . These networks distribute entanglement between remote quantum systems, allowing for communication, resource sharing, blind quantum computing, and distributed sensing [1]. The efficient distribution of entanglement, known as entanglement routing, is a central research goal in QNs.

In a QN, entanglement is distributed to two dedicated end nodes by generating short-distance entanglement and performing entanglement swapping over the path connecting them. Intermediate nodes in the network perform various tasks, including heralded entanglement generation [2], storing quantum states until a success signal is received, selecting entangled qubits, and recovering fidelities using purification or quantum error correction [3]. Quantum networks operated as above are close to the circuit-switched network, where the channel usage of one party blocks the use by others.

Current and near-future quantum networks are memory-limited and pose congestion challenges in circuit-switched networks, where the number of entanglement routing paths exceeds the available qubits in a router. To address this, we aim to develop scalable quantum networks that support simultaneous multi-flow entanglement routing. Scalable networks should meet three conditions: (1) enable error-corrected entanglement flow proportional to the number of users, (2) operate without congestion, and (3) require sublinear quantum memories per end node.

In this work, we propose a quantum tree network (QTN) that satisfies these conditions and overcomes the limitations of conventional mesh networks. The QTN architecture allows for optimal entanglement routing without the need for time-consuming multipath-finding algorithms [4].

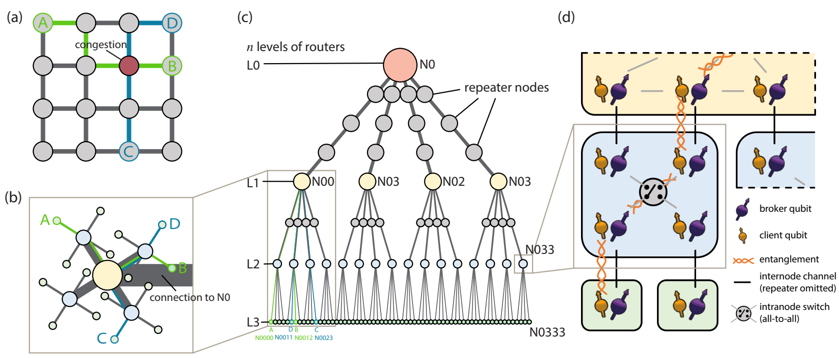

Fig. 1. (a) Quantum mesh network with congested nodes highlighted in red. (b) Architectural view of QTN with node size and edge width representing allocated qubits. (c) k-ary quantum tree network ($k = 4$) with labeled layers and repeater chains for inter-layer connections. (d) Quantum router architecture utilizing broker-client qubits for robust and scalable entanglement distribution. All-to-all intranode connectivity is assumed.

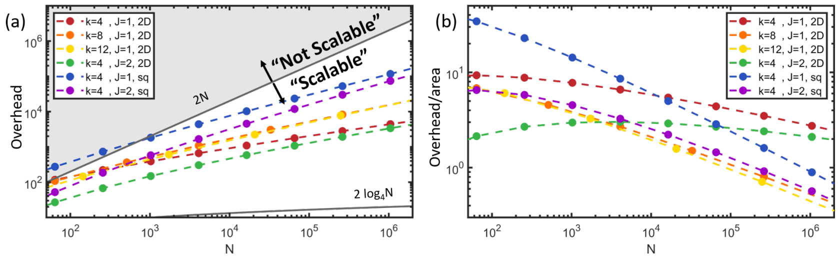

Fig. 2. (a) The resource overhead of quantum tree networks (QTNs) for user numbers. $J = 1$ QTNs with $k = 4, 8$, and 12 deployed on a 2D surface exhibit lower overheads (red, orange, and yellow markers), while $J = 2$ encoded QTN shows a faster scaling but smaller overheads (green markers). Deploying QTNs with square-lattice end nodes (blue and purple markers) leads to faster scaling and larger overhead. (b) The resource overheads are presented in terms of qubits per user per elementary link length squared. Larger k QTNs (orange and yellow) scale better with N compared to smaller k QTNs (red), and square lattice QTNs (blue and purple) scale better than surface-covering QTNs (red and green). Small k, surface-covering QTNs are more suitable for dense networks with aggregated users, while large k, square lattice QTNs are preferable for sparse networks.

2. Architecture and overhead

The QTN architecture is based on a hierarchical tree structure, where end nodes are the leaves of a tree (Fig. 1). The communication between end nodes is facilitated through routers located at internal nodes of the tree. This hierarchical arrangement allows for efficient and scalable entanglement routing in quantum networks. A key advantage of the QTN architecture is its scalability. The overhead, defined as the qubit-per-node ratio, scales sublinearly with the number of end nodes. Specifically, the overhead scaling for any k-ary tree is given by $\mathcal{O}\left(N^{\log_k a_k} \cdot \log_k N\right)$, where N represents the number of end nodes and a_k denotes the growth rate of channel length as we move from the leaves to the root node.

We examine the resource overhead of a deployed quantum tree network (QTN). The resource overheads for different QTN configurations are plotted in Figure 2. QTNs with larger k values and square lattice configurations exhibit better scaling with N. Surface-covering QTNs with smaller k values are more suitable for dense networks, while square lattice QTNs with larger k values are better for sparse networks. The exponent J in the analysis represents the encoding rate, which influences the resource scaling for error correction. The resource overhead of the error-corrected QTNs can be expressed as $\sim \mathcal{O}(N^{\log_k a_k} \cdot (\log_k N)^J)$. The specific value of J depends on the error correction code used. For example, for the linear-scaling CSS codes, $J = 1$, and for the 2D surface code, $J = 2$.

Note: An expanded version of the manuscript is available on ArXiv [5].

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