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Abstract:

Quantum networks are expected to play a major role in the future of quantum technologies. They allow quantum information to be shared between distant parties and serve as the foundation for long-distance quantum communication, shared quantum computing, and distributed quantum sensing. In recent years, small-scale experimental demonstrations have shown progress in these domains. However, large-scale demonstrations on real hardware is still a major challenge as unlike classical communication, quantum signals are fragile—they cannot be copied or amplified, due to the quantum no-cloning theorem. As a result, building, scaling, and maintaining quantum networks becomes significantly more challenging due to noise, signal loss, gate imperfections, and control limitations.

A key requirement for utilizing quantum networks as devices that outperforms classical ones, is generating multiparty entanglement, but unlike many-body systems, the way entanglement is created and manipulated is fundamentally different. In many-body systems, entanglement arises naturally from interactions described by a global Hamiltonian. In contrast, quantum networks do not have built-in mechanisms. Entanglement must be created on purpose, distributed across distant nodes, and preserved over time—even in the presence of decoherence, gate errors, and limited hardware performance. Quantum repeater protocols try to solve this by dividing long-distance channels into smaller segments and connecting them in stages. However, in practice, these methods are highly sensitive to errors and noise at every node, which limits their performance on near-term devices. Moreover, most existing models of quantum networks assume ideal conditions such as uniform noise, perfect link quality, and homogeneous network structure, which often remain far from realistic scenarios that observed in experimental setups. Numerical tools such as tensor networks and exact diagonalization, which are meant for closed systems with local interactions, cannot be applied directly for distributed quantum networks due to long-range entanglement, measurements, and lack of traditional symmetries.

This project proposes a new and realistic approach to these challenges. We will develop a hybrid framework that combines theory and simulation to study quantum networks under practical conditions. A key feature of our approach is that noise is not treated as a side effect—it is built directly into the simulation models. We include realistic noise sources, such as non-Markovian and correlated errors, based on experimental data. To design scalable quantum network architectures, we follow a two-fold approach. First, we use tensor network methods—originally developed for many-body systems—to represent how entanglement builds up and spreads across distributed nodes, even in the presence of noise. Second, we analyze the non-stabilizer features of the network, which gives us clues about where classical simulation is still possible. Together, these tools help us understand both the quantum advantage and the limits of classical simulability in large-scale network design.

Finally, we will develop entanglement certification techniques without full state tomography so that fewer measurements, suitable for current noisy devices, are necessary. We will test all protocols on both real and simulated hardware to validate and benchmark performance under different noisy conditions. In short, this project aims to build a realistic, noise-aware framework for quantum networks. It offers practical tools both for theorists and experimentalists and supports progress towards development of scalable, and reliable quantum architecture, contributing to scientific understanding and future quantum infrastructure in India.