CAREER: Scalable Computing Architectures for Quantum LDPC Codes

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A. Project Summary

Motivation: Quantum computing, networking and sensing possess the potential to impact society in profound ways that are not possible with existing classical technologies. Recent years have seen several demonstrations of small working quantum systems but these devices have severe limitations due to noise and decoherence. While some quantum algorithms can tolerate such noise to some extent, the real challenge is *scalability* to system sizes large enough to provide the massive gains promised in theory. It is widely acknowledged that quantum error correction (QEC) is essential for scalable and reliable quantum technologies. Currently, the leading approach with an associated blueprint is through topological quantum low-density parity-check (QLDPC) codes such as the surface code. However, these codes have parameters $[\![n, O(1), O(\sqrt{n})]\!]$ so that they only encode a fixed number of logical qubits and can only correct errors up to square root of the code size. While their nearest-neighbor connectivity is attractive from a hardware standpoint, especially for superconducting qubits, their suboptimal parameters imply a very large resource overhead with growing size. A recent breakthrough showed that QLDPC codes with optimal parameters, i.e., $[\![n, O(n), O(n)]\!]$, can be constructed, but these require many long-range connections that are challenging to build in hardware.

In this project, we propose to investigate a *distributed* implementation of QLDPC codes while drawing comparisons with a monolithic architecture. Such an approach has been briefly explored for the surface code in the past, but we argue that it is more suited for these optimal QLDPC codes. This would entail executing non-local logical operations and syndrome measurements via shared high-fidelity entangled resource states and classical communications between the nodes. While the monolithic approach requires engineering highly non-local connections, a distributed architecture only necessitates the offline production of entangled states between non-local nodes, which is likely more manageable.

Key words: Quantum error correction; logical operations; non-local measurements; Greenberger-Horne-Zeilinger (GHZ) states; entanglement distillation; quantum low-density parity-check (QLDPC) codes; iterative decoding

Intellectual Merit: We will investigate both fundamental and applied (systems-level) aspects of a distributed architecture for optimal QLDPC codes. The involved technical challenges also connect well with the quantum networking work of the PI for the NSF-ERC Center for Quantum Networks. Specifically, quantum repeaters form the cornerstone of scalable quantum networks and the task of distilling high-fidelity entangled resource states is one of the key responsibilities of the repeater. This project will create new synergies between quantum computing and networking through tasks such as QEC-based entanglement distillation protocols. The intellectual contributions of this project include: (1) a fundamental understanding of the challenges associated with performing logical operations and error correction in a distributed setting; (2) protocols to distill (potentially encoded) entangled states that enable these distributed operations on the QLDPC codes under investigation; (3) a study of the classical communication overhead and latency incurred by this architecture; (4) coding strategies that enforce local algebraic structure at nodes while maintaining global graph sparsity to facilitate fault-tolerant gates and efficient decoding; (5) careful comparisons between this approach and the standard monolithic architecture for fault-tolerant quantum computing. Besides, the project will also investigate connections to measurement-based quantum computing that can be leveraged in the proposed setting.

Broader Impacts: The proposed project will have a long-term impact on society by solving fundamental problems related to scalability of quantum technologies. However, during the course of the project, we will develop educational opportunities related to the project that targets the growing need of preparing a diverse quantum-ready workforce. Specifically, we will develop a graduate level course on quantum error correction with an emphasis on projects rather than exams, to be taught at The University of Arizona. This will be integrated with the existing Master's program in the College of Optical Sciences with an emphasis in Quantum Information Science and Engineering (QISE) as well as the proposed Master's program in the Department of Electrical and Computer Engineering with a focus in QISE. For students and teachers at Pima Community College and high schools in Tucson, we will develop tutorials and summer research activities that teach the fundamentals of error correction both in classical applications, such as data storage and wireless communications, as well in quantum technologies. The PI has co-taught a 3.5-hour tutorial on Classical and Quantum Error Correction in the 2023 Winter School of the NSF-ERC Center for Quantum Networks, which will be adapted and improved for the above outreach activities. These materials and teaching experiences will be used to develop a self-contained monograph or textbook on this topic, which is a pressing need in the community.