FY24 Strategic University Research Partnership (SURP)

Robust Neural Network Decoders for Quantum Error Correction Systems

Principal Investigator: Dariush Divsalar (332)**; Co-Investigators:** Matthew Thill (332), Samuel Dolinar (332), Michael Cheng (333), Bane Vasic (University of Arizona), Michele Pacenti (University of Arizona), Dimitrios Chytas (University of Arizona)

Objectives: Quantum Error Correction (QEC) introduces unique challenges compared to classical error correction. The presence of short cycles in the Tanner graph, arising from the commutation constraint, significantly impacts the overall effectiveness of error correction in the system. Additionally, error degeneracy hinders the success of classical iterative decoders. Furthermore, the unreliable syndromes resulting from noisy measurement circuits, coupled with the limited decoherence time of qubits, necessitate the development of low-latency systems.
To tackle these challenges comprehensively, our research will focus on multiple fronts. Firstly, we will delve deeper into the integration of Deep Neural Networks (DNN) techniques and explore error-prone structures within Quantum Low Density Parity Check (QLDPC) codes. This endeavor aims to devise new decoding algorithms capable of reducing decoding error probabilities by a minimum of two orders of magnitude. Secondly, we will study novel decoding algorithms that strike a balance between low complexity and high performance, leveraging error degeneracy to achieve optimal results.

Background: Quantum computing has demonstrated the potential to surpass classical computing algorithms when executed on quantum machines. As a result, there is considerable interest in the development of quantum systems, as they offer the ability to solve problems that classical systems are unable to tackle effectively. Quantum computers leverage quantum mechanics phenomena like Entanglement and Superposition to store, process, and transmit information using Quantum Bits (Qubits). However, a significant challenge lies in the inherent susceptibility of Qubits to errors, necessitating the design of fault-tolerant quantum systems.

Approach and Results: Quantum low-density parity check (QLDPC) codes are an important class of quantum error correction (QEC) since they offer finite multiplicative overhead [1], finite asymptotic rates with non-zero fault-tolerant thresholds [2], and support low-complexity iterative decoding. In addition to unavoidable cycles and trapping sets, QLDPC codes are highly degenerate, i.e., their minimum distance is higher than the weight of their stabilizers [3], [4]. This requires new decoding algorithms that account for degenerate errors which have no equivalent counterpart in classical error correction. Our research focuses on developing innovative approaches to enhance error rates and reduce decoding complexity, both in classical and quantum error correction. We developed a message-passing decoding algorithm, that incorporates asymmetric rules to variable nodes contained in trapping sets [A]. In this way, message-passing algorithms can exploit the degeneracy of quantum codes. Performance results demonstrated that our approach outperforms other message-passing algorithms in the literature. Regarding the improvement of the error floor performance of QLDPC codes under low-latency requirements, in [D] we have proposed a low-complexity bit flipping approach that takes advantage of the correlation of X/Z errors. By exploiting the correlations, we observed orders of magnitude improvement for different codes we simulated at the same latency. In [B], we have developed a low-complexity decoding approach which is applicable to surface codes and attains competitive results to state-of-the-art decoders such as MWPM and UF by exploiting the structure of topological codes. Our proposed technique obtains a decoding threshold of 7.5% for the 2D toric code and 7% for the rotated planar code over the BSC. In [C], we employ RNNs targeting the decoding of QLDPC codes. Leveraging the quasi-cyclic property of Lifted-Product codes, our RNN-based decoding techniques enhance error rates by decoding quantum-trapping sets. The RNN decoder offers advantages such as reduced training set size and network parameters, facilitating potential hardware implementation. Further works on QLDPC codes, include the development of a collective bit-flipping decoding approach which can improve error-floor performance of QLDPC codes by orders of magnitude compared to more complex iterative decoders while also requiring a short number of iterations. Further research toward QEC includes our suggestion of a distributed quantum computing (DQC) approach where medium-sized quantum processors share high-fidelity entangled states for operations.

Significance/Benefits to JPL and NASA: Quantum communications and quantum computing is an area directly called out in JPL's strategic implementation plan. This task developed high-performance, low-complexity, fault-tolerant decoding algorithms for quantum communications systems, and quantum computers thus enhancing NASA and JPL's capabilities to support future communications systems based on quantum technologies. A near-term example is a joint effort by NASA/NIST/NRO to develop technologies for a national quantum communications and networking strategy and mission, currently being evaluated for inclusion as a mandated 6-year quantum space program within NASA. Another example is "NASA SCaN Quantum Communications Technologies (SIP)" that might need the proposed technology.

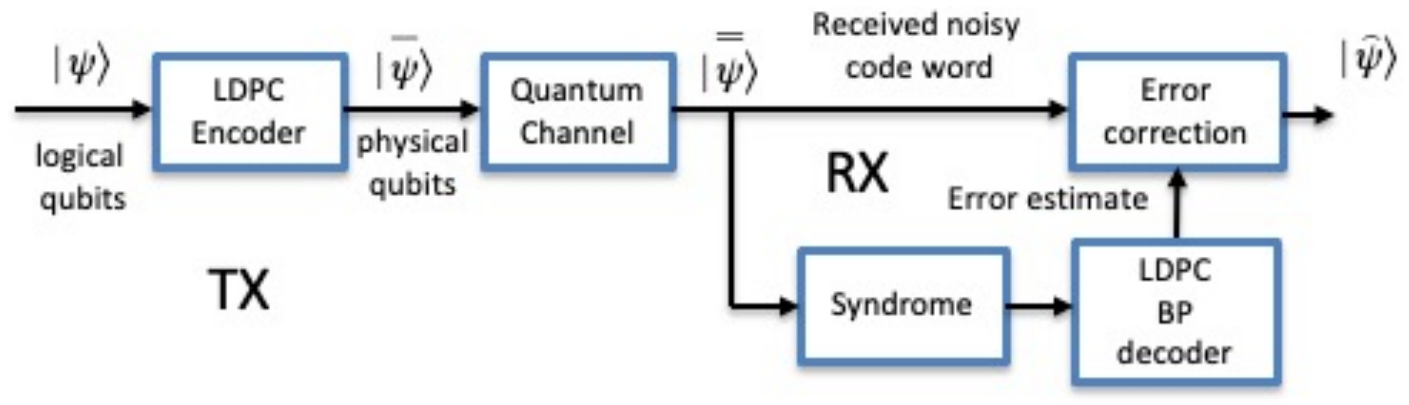

Fig. 1: QLDPC encoder, Quantum channel, quantum decoder. LDPC BP decoder can be replaced with Neural Network BP decoder in Figure 2.

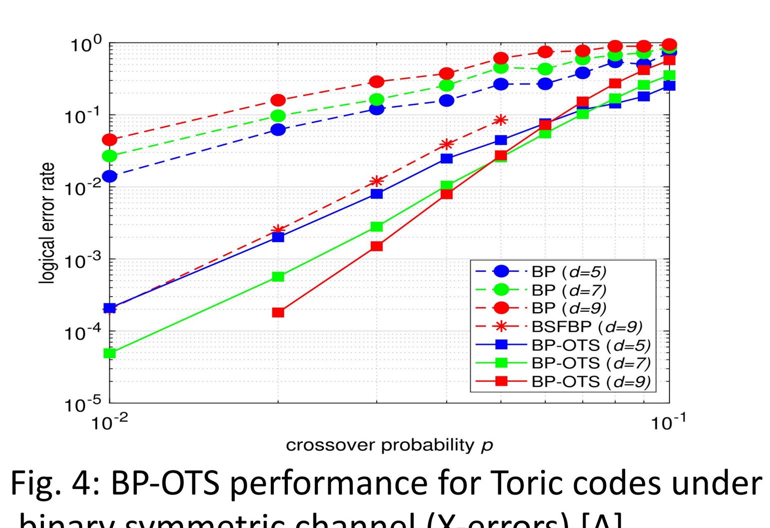

Fig. 4: BP-OTS performance for Toric codes under binary symmetric channel (X-errors) [A]

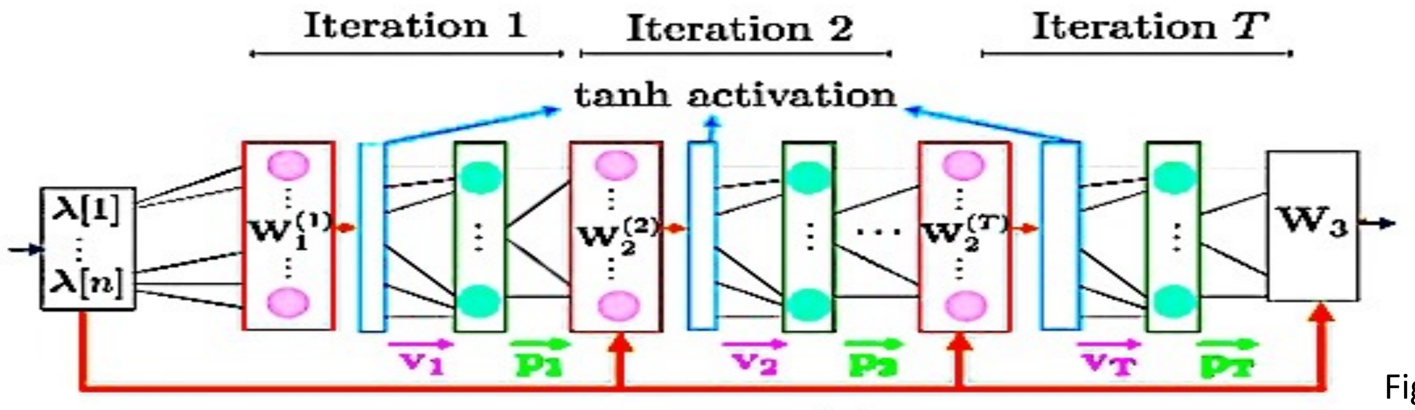

Fig. 2: Neural Network BP decoder

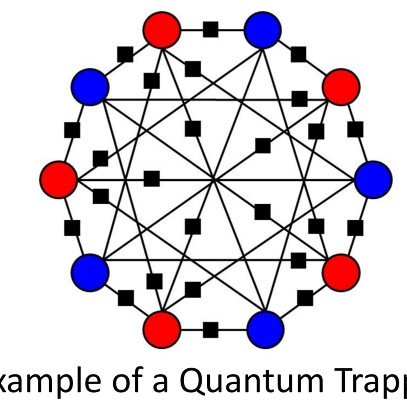

Fig. 3: Example of a Quantum Trapping Set

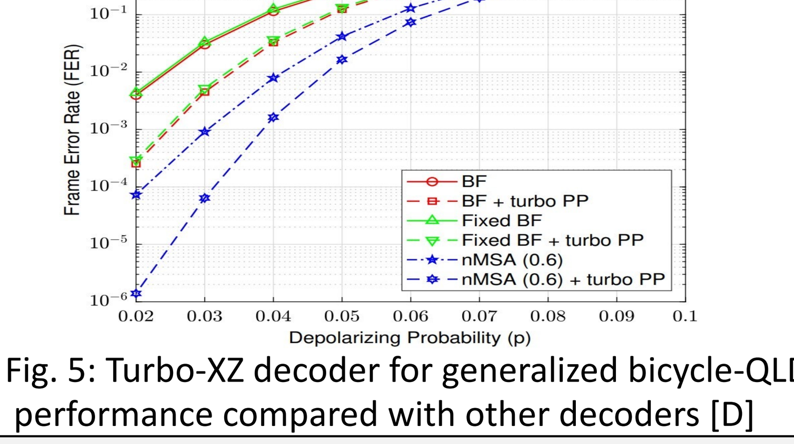

Fig. 5: Turbo-XZ decoder for generalized bicycle-QLDPC code performance compared with other decoders [D]

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

RPD-041 Clearance Number: CL#24-5314

Publications:

A. D. Chytas, M. Pacenti, N. Raveendran, M. F. Flanagan and B. Vasić, "Enhanced Message-Passing-Decoding of Degenerate Quantum-Codes Utilizing Trapping-Set Dynamics," IEEE Communications Letters, 2024.

B. M. Pacenti, M. F. Flanagan, D. Chytas, and B. Vasić, "Progressive-Proximity Bit-Flipping-Decoding Surface-Codes," IEEE Transactions on Communications, 2024.

C. A. K. Pradhan, N. Raveendran, N. Rengaswamy, X. Xiao, and B. Vasić, "Learning to decode trapping-sets in QLDPC codes," ISTC-2023.

D. N. Raveendran, E. Boutillon, and B. Vasić, "Low-latency flipping-decoders for improving error floor performance in quantum LDPC codes," ISTC-2023.

E. B. Vasić, N. Raveendran, A. K. Pradhan, and D. Divsalar, Low-latency-decoding of hypergraph-product-codes, ITA-Workshop-2024.

PI/Task Mgr. Dariush Divsalar **Contact Information:** dariush.divsalar@jpl.nasa.gov