National Aeronautics and Space Administration

FY23 Strategic University Research Partnership (SURP)

# Robust Neural Network Decoders for Quantum Error Correction Systems

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**Objectives**: 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 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. Quantum Error Correction (QEC) applies well-established classical error correction techniques to quantum systems, aiming to mitigate errors introduced by quantum measurements, gates, and channels.

**Approach and Results**: To address the challenges of error correction in QLDPC codes, we employ RNNs [A]. Leveraging the quasi-cyclic property of Lifted-Product codes, our RNN-based decoding techniques reduce 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. Another challenge in QEC is taking into account the implementation complexity when designing a decoder, given the throughput constraints that it must meet for effectively achieve fault-tolerance; in this optics, we developed the Quaternary-Binary Message-Passing decoder (QB-MPD), and we are collaborating with top-tier researchers in hardware implementation, to develop decoding algorithms able to meet the throughput requirements. Part of our work also involved classical error correction. We further our investigation on low complexity decoding algorithms which exploit stochastic gradient descent. We generalized our previous work on Adaptive Diversity Gradient-Descent Bit Flipping (AD-GDBF), introducing the generalized AD-GDBF (gAD-GDBF). This decoder improves decoding performance and reduces complexity, as it's a variant of the well-known Bit-Flipping decoder; moreover, it's suitable for being employed on Additive White Gaussian Noise (AWGN) channels, and with irregular codes.

**Significance/Benefits to JPL and NASA**: Quantum communications is an area directly called out in JPL's strategic implementation plan. This task will develop high-performance, low-complexity, fault-tolerant decoding algorithms for quantum communications systems, thus enhancing JPL's capabilities to support future communications systems based on quantum technologies, such as secure satellite communications. 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.

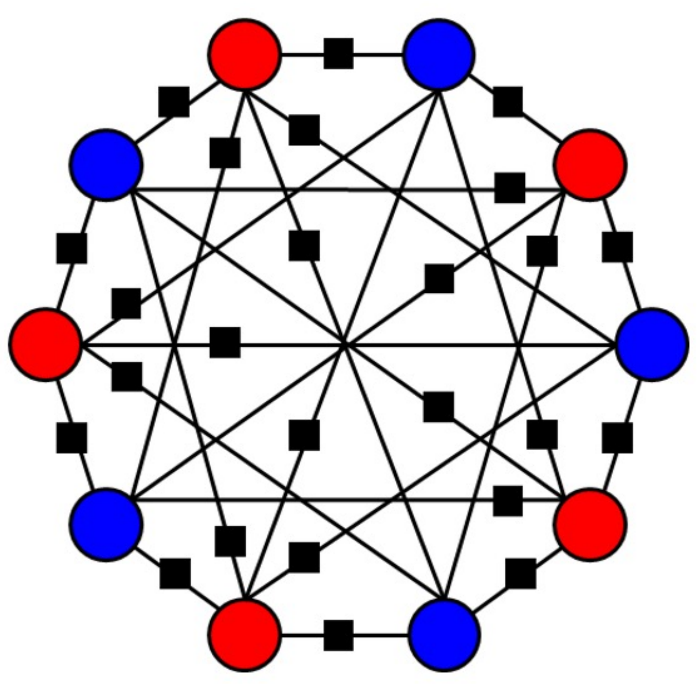

**Figure 1** Example of a Quantum Trapping Set

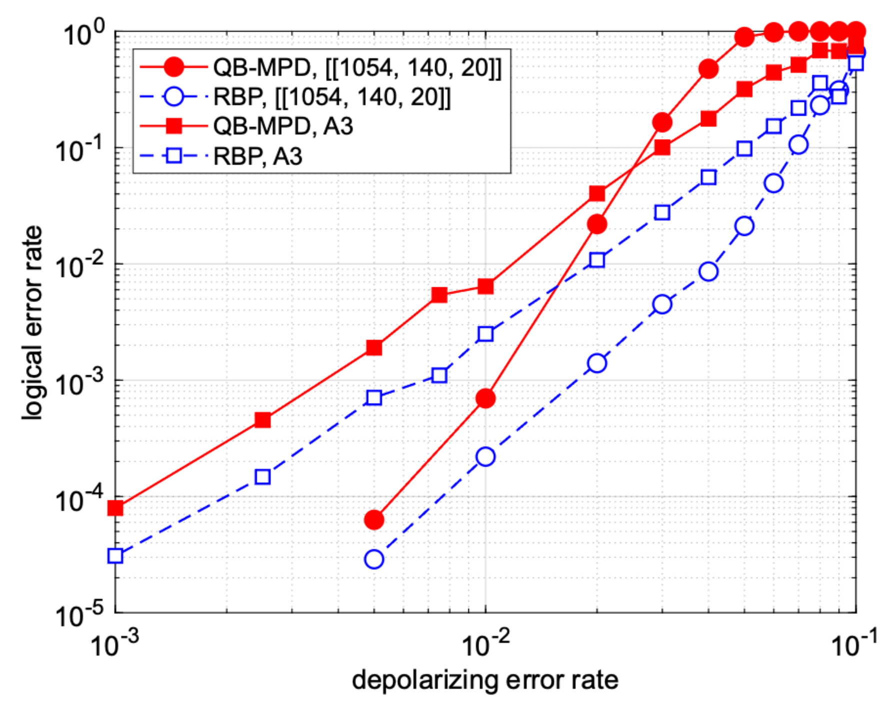


**Figure 2** QB-MPD decoder performance; for low depolarizing error rate, approaches Refined Belief Propagation.

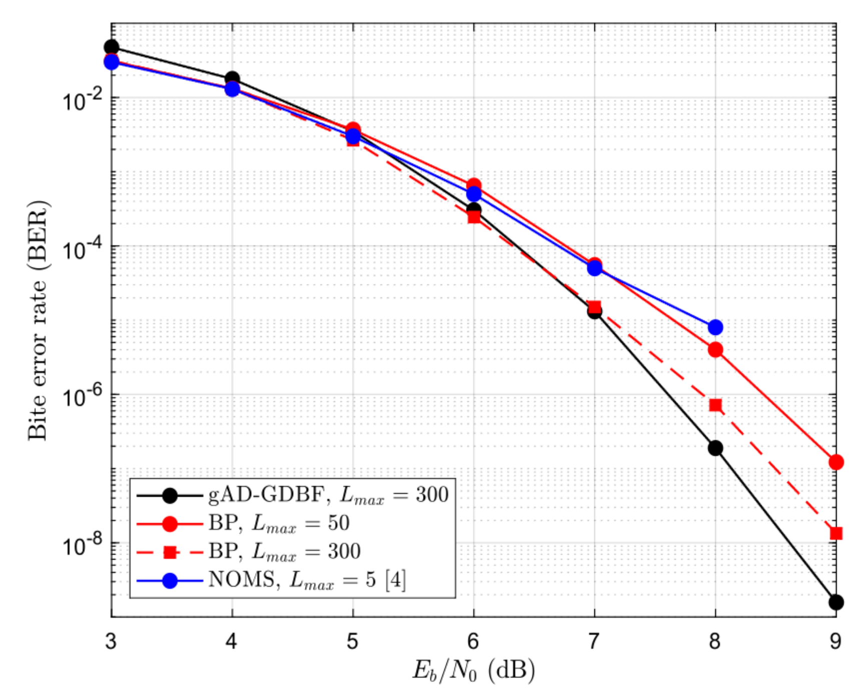


**Figure 3** gAD-GDBF performance compared with other decoders (Belief Propagation and Normalized Min-Sum)

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## Publications:

A. Asit Kumar Pradhan, Nithin Raveendran, Narayanan Rengaswamy, Xin Xiao, and Bane Vasić, "Learning to Decode Trapping Sets in QLDPC Codes", the *2023 IEEE International Symposium on Topics in Coding (ISTC)*, Brest, France, 2023.
B. Ten more publications and 7 invited talks by University of Arizona co-investigators during FY 2023 on quantum error correction (QEC) including neural network decoders for QEC codes. The list is included in the Final report

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