Bx Thesis Proposal Form

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Section 1: To be completed by student

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Second Reader:* TODO ** Please provide this information if already available.*
Thesis Title: Parallel window decoding with BP+LSD inner decoders for CSS qLCPC codes
Thesis Proposal:* ** Roughly 2-3 pages describing the proposed project.*

Fault tolerant quantum computing promises a means to solve problems that classical computers can not in a reasonable period of time [4]. It has several important applications including cryptography, optimization problems, drug discovery, simulations, and more. However, solving problems in these areas requires scalable quantum devices that do not exist today. Major bottlenecks preventing such devices include lack of real-time decoding and large qubit overhead. Current common infrastructures for quantum computers use offline decoders and surface codes. The data backlog due offline decoders results in computation running exponentially slower [2]. Additionally, implementing surface codes requires a large qubit/space overhead. As a result, current quantum computers will struggle to scale.

Parallel window decoding has been proposed as a solution to address the decoding backlog by processing decoding windows independently and simultaneously [2]. Additionally, Quantum Low-Density Parity-Check (qLDPC) codes offer a path to reduce space overhead by enabling the encoding of multiple logical qubits per set of physical qubits [5], unlike surface codes. Belief-Propagation plus Localized Statistics Decoding (BP+LSD) further enhances the CSS subclass of qLDPC codes by allowing efficient, parallel decoding of sub-graphs associated with decoding regions [6]. This thesis implements parallel window decoding with BP+LSD inner decoders for CSS qLDPC codes and investigates its performance to address the decoding and space overhead challenges in current quantum devices. By benchmarking decoding time and accuracy against current sequential BP+OSD decoding for qLDPC codes, this work aims to evaluate whether parallel window decoding is a viable approach for scalable, real-time fault-tolerant quantum computing.

Quantum error correction aims to correct errors in quantum circuits by processing syndromes generating my error correcting circuits. Decoders are responsible for processing syndromes to detect whether an error has occurred. Without real-time decoding, quantum error correction required for fault tolerance runs too slow. The data backlog problem occurs when the rate of processing of syndrome bits is slower than the rate of generating the syndromes. When decoding can not keep up with the high throughput of syndromes generated from error correction circuits [1], the quantum computer runs exponentially slower [2]. As a result, scalable and universal quantum computation is not feasible due to this data backlogging [2].

Current work in parallel window decoding has shown that it is possible to have slow decode speeds while avoiding a backlog [2]. Parallel window decoding schemes are implemented by dividing decoding windows into alternating layers. In the first layer, syndromes in commit regions are decoded in parallel and their solutions are committed [2]. In the second layer, syndromes in commit regions and artificial defects generated from the previous layer are decoded and committed in parallel [2]. The decoding within the windows is performed by the inner decoder and the choice of what the inner decoder is and the global decoder is has an impact on the ability to perform real-time decoding. The parallel window decoding comes without any decrease in logical fidelity [2] and the ability to solve the backlog problem even for large throughput. This gives hope to a scalable fault-tolerant quantum computation.

In addition to the need for real-time decoding, the large qubit overhead of devices hinders their scalability. Due to the prevalence of the surface code in current infrastructure, there is a large qubit overhead that devices have to incur for the familiar decoding and universal gate sets that come with the code. Surface codes of distance d require d^2 physical qubits to encode one logical qubit. Furthermore, surface codes encode a single logical qubit per block [5]. With the demand for more logical qubits for more involved problems to be solved by quantum computers, the space overhead cost of implementing surface codes is a limiting factor for the scalability of current devices.

Quantum Low-Density Parity-Check (qLDPC) codes are a promising solution to the space overhead bottleneck. Because qLDPC codes can encode multiple logical qubits per block, they have a much higher encoding rate compared to surface codes [5]. As a result, there have been results showing that qLDPC codes can result in a constant space overhead [5]. This is an important step in the creation of a scalable fault-tolerant quantum computer as a constant space overhead allows for quantum computers with more logical qubits than with surface codes given the same number of physical qubits.

The widely used decoder for qLDPC codes is the Belief-Propagation plus Ordered Statistics Decoding (BP+OSD). Belief propagation (BP) is an error correction method used in classical computing that converges on the most likely cause of the error given the syndromes. However, in quantum computing, because of quantum degeneracy (different physical errors resulting in the same logical error), BP does not always converge [6]. In these cases when BP does not converge, the Ordered Statistics Decoding finds the most likely error that caused the syndrome by inverting a full-rank submatrix of the parity check matrix [6]. Even though BP+OSD performs well on qLDPC codes, the OSD stage of the decoder has a large runtime overhead [6] making it an unlikely candidate for an inner decoder in a parallel window decoder.

Localized Statistics Decoding (LSD) is a proposed replacement for the OSD stage of the BP+OSD decoder in the CSS subclass of qLDPC codes. LSD similar to OSD finds the most likely error that led to the syndrome by inverting a full-rank submatrix of the parity check matrix [6]. However, instead of performing this calculation after finding the full-rank submatrix as in OSD, LSD applies matrix inversion independently and concurrently for the individual sub-graphs associated with these decoding regions [6]. Benchmarking of BP+LSD shows that it has a similar performance to BP+OSD [6]. LSD's support for parallelism and its on-par performance with OSD makes it a candidate for the inner decoder of parallel window decoding scheme for CSS qLDPC codes.

This thesis will explore parallel window decoding with a BP+LSD inner decoder for different CSS qLDPC codes to test whether it is a valid choice for a fault-tolerant quantum computing infrastructure. It will implement a parallel window BP+LSD decoder and benchmark its decoding times and accuracy against a sequential BP+OSD decoder for different CSS qLDPC codes. Success will be assessed by analyzing the speed improvements and the impact on decoding accuracy, aiming for significant decode speed gains without significant accuracy loss.

Sources

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Section 2: To be completed by thesis advisor and program director

Thesis Advisor:	TODO
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Program Director:	TODO
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