Research Portfolio: Quantum Computing Foundations

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Abstract

This portfolio summarizes a self-directed research project undertaken to build a robust software-based understanding of quantum computing, complementing my professional experience in cryogenic microwave engineering at ISRO. The work progresses systematically from the fundamentals of quantum circuits and entanglement to advanced topics directly relevant to experimental superconducting quantum computation: open quantum system dynamics and pulse-level control. Utilizing Qiskit and QuTiP, I implemented and analyzed key algorithms (Grover, Deutsch–Jozsa), simulated realistic noise channels (T_1, T_2, depolarizing), and designed DRAG pulses for leakage suppression. This portfolio demonstrates not only technical proficiency but also a deep conceptual understanding of the challenges in achieving quantum advantage, bridging the gap between theoretical concepts and practical hardware limitations.

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1 Introduction and Motivation

My professional work at ISRO involves the characterization of microwave components and low-noise amplifiers at cryogenic temperatures—a skillset directly applicable to the readout and control systems of superconducting quantum processors. To transition from supporting hardware to designing quantum experiments, I initiated this project to master the corresponding software stack and theoretical foundations.

The central theme of this research is to understand how abstract quantum algorithms manifest on realistic, noisy hardware and what techniques are required to mitigate errors. This portfolio is structured to reflect a bottom-up learning approach, culminating in projects that directly address the core challenges in current quantum computing research.

2 Project Summaries and Critical Analysis

2.1 Foundations of Quantum Circuits and Entanglement

Objectives: To establish a baseline understanding of quantum state manipulation, entanglement generation, and simulation workflows.

Implementation: Generated and measured Bell states using Qiskit's `qasm_simulator` and retrieved exact statevectors using the `statevector_simulator`.

Key Insight: The transition from probabilistic sampling of qubits to exact statevector analysis is crucial for debugging quantum algorithms. The Bell state simulations confirmed the perfect correlations expected from maximal entanglement, providing a control case for subsequent noise studies.

2.2 Modeling Noise and Decoherence

Objectives: To move beyond ideal simulations and model the environmental interactions that degrade quantum information.

Implementation:

- **Generic Noise:** Introduced depolarizing noise channels to Bell state circuits
- **Physical Noise:** Simulated a realistic superconducting qubit environment by combining thermal relaxation (T_1) and pure dephasing (T_2) errors with a depolarizing component

Key Insight and Analysis: The simulations quantitatively showed how T_1 processes drive the state towards $|0\rangle$, while T_2 processes destroy phase coherence without affecting energy populations. For entanglement—a phase-sensitive property—dephasing error was observed to be more destructive than relaxation error at equivalent rates. This underscores the importance of characterizing both T_1 and T_2 times in hardware and the need for error mitigation strategies tailored to specific algorithmic requirements.

2.3 Quantum Algorithm Implementation

Objectives: To demonstrate quantum advantage on tractable problems and understand oracle design.

Implementation:

- **Grover's Algorithm (2-qubit):** Implemented the search algorithm, confirming the characteristic amplitude amplification
- **Deutsch–Jozsa Algorithm (n=3):** Verified the algorithm's deterministic advantage by correctly identifying constant and balanced functions with a single query

Key Insight: While these algorithms are well-understood theoretically, their implementation provides practical experience with amplitude manipulation and the role of oracles. The Deutsch–Jozsa algorithm serves as a perfect, verifiable demonstration of a quantum advantage that is impossible classically, even for a small number of qubits.

2.4 Advanced Topics: Open Systems and Pulse Control

Objectives: To engage with cutting-edge research topics in quantum control and error suppression.

Implementation:

- **Open Quantum Systems (QuTiP):** Modeled a driven transmon qubit using the Lindblad master equation. Simulated its non-unitary evolution under the effects of relaxation and dephasing, visualizing the blurring of the Bloch vector and the decay of state fidelity over time
- **DRAG Pulse Design (Qiskit Pulse):** Designed and simulated Derivative Removal by Adiabatic Gate (DRAG) pulses to suppress the leakage population from the $|1\rangle$ state to the $|2\rangle$ state during a gate operation, a critical error in weakly anharmonic superconducting qubits like transmons

Key Insight and Analysis: This represents the most significant contribution of this portfolio. The Lindblad simulation moves beyond the gate-level noise models of Qiskit Aer, providing a more physical, continuous-time picture of decoherence. The DRAG project directly connects to my hardware background; the pulse's performance is highly sensitive to the qubit's anharmonicity (α), mirroring the calibration challenges faced in real labs. Successfully reducing leakage in simulation is a first step towards understanding the complex pulse-shaping techniques required for high-fidelity gates on actual hardware.

3 Conclusion and Future Directions

This portfolio has provided me with a comprehensive software foundation to complement my hands-on experience with cryogenic systems. I have progressed from executing textbook algorithms to modeling the complex physical interactions that define the current challenges in quantum computing.

My future research goals, which I aim to pursue at ETH Zurich, are directly informed by this work:

1. **Advanced Error Mitigation:** Exploring techniques like Probabilistic Error Cancellation (PEC) and Zero-Noise Extrapolation (ZNE) applied to multi-qubit circuits
2. **Machine Learning for Calibration:** Investigating the use of ML algorithms to optimize pulse parameters (like DRAG β) and automate the tuning of quantum devices
3. **Experimental Collaboration:** Applying this combined hardware–software understanding to characterize novel qubit designs and improve multi-qubit gate fidelities in an experimental setting

My unique perspective, straddling the domains of cryogenic engineering and quantum information science, positions me to contribute meaningfully to the experimental quantum computing efforts at ETH Zurich.

4 Technical Appendices

- **Software and Skills:** Qiskit (Terra, Aer, Pulse), QuTiP, Python (NumPy, SciPy, Matplotlib), OpenQASM
- **Hardware Relevance:** This software work is informed by professional experience with cryogenic systems (4 K), VNA S-parameter analysis, and low-noise amplifier characterization at ISRO
- **Repository Guide:** The complete, reproducible code for all projects is available in the accompanying GitHub repository: `https://github.com/asmeeta-quantum/ETH_Qiskit_Workspace`