Real-Time Stabilization of Spectral Diffusion in Superconducting Qubits via Syndrome-Density Feedback and Adaptive Decoding

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Abstract

Superconducting quantum processors suffer from time-varying noise, specifically gate error drifts driven by two-level system (TLS) defects, which can push physical error rates above the fault-tolerance threshold. We present a closed-loop control architecture ("Holo-Neural") that mitigates these drifts using syndrome-density feedback. Simulating a distance-11 rotated surface code under realistic circuit-level noise—including 5% measurement error and spatially inhomogeneous vector drift—we demonstrate the recovery of logical fidelity in a regime where standard error correction fails catastrophically. The architecture combines an integral controller with an adaptive decoder that rebuilds the matching graph in real-time. Over 20 million shots, the system suppresses the logical failure rate by a factor of 47.2× (9.5×10^6 vs 2.0×10^5 failures), effectively stabilizing the qubit below threshold despite the physical error rate drifting 35× above baseline.

I. INTRODUCTION

The leading approach to fault-tolerant quantum computing is the surface code, which boasts a high threshold and local connectivity requirements [1]. However, experimental implementations face a critical challenge: non-stationary noise. Coherence times (T_1, T_2) and gate fidelities in transmon qubits fluctuate over timescales of seconds to hours due to spectral diffusion caused by two-level system (TLS) defects [2, 3].

Standard Quantum Error Correction (QEC) relies on a static decoder calibrated to average noise parameters. When drift pushes local error rates above the threshold, the logical qubit experiences a phase transition to total failure. We propose a lightweight, reflexive control layer that uses the QEC syndrome density itself—a metric freely available during error correction—to estimate global drift and apply real-time frequency/gate corrections.

II. METHODOLOGY

A. Simulation Environment

We utilize the Stim high-performance simulator [4] to model a distance ($d = 11$) rotated memory-Z surface code. The noise model represents a "high-noise" experimental regime:

- Measurement Error: 5.0% (Dominant noise source).
- Reset Error: 1.0%.
- Baseline Gate Error: 0.1%.
- Batch Size: 1,024 shots per cycle.

B. Vector Drift Model

Unlike simplified scalar drift models, we simulate 121 independent drift vectors (one per data qubit) evolving via Ornstein-Uhlenbeck processes. This mimics the uncorrelated nature of TLS defects across a large chip. The drift targets a mean gate error of 3.5% (well above the typical ∼1% threshold), creating a "death zone" for the standard qubit.

C. The Holo-Neural Architecture

The control loop consists of two subsystems:

- **Integral Controller**: Monitors the average syndrome density. It applies a global correction signal (with 10-cycle latency and 2×10^{-5} actuation noise) to counteract the mean drift.
- **Adaptive Decoding**: Crucially, the PyMatching [5] decoder graph is rebuilt dynamically for every batch (with negligible computational overhead; graph reconstruction takes < 1 ms on standard CPUs for $d = 11$). This ensures the decoder's edge weights always match the instantaneous effective error rate (p_{eff}), preventing suppression failure due to model mismatch [6].

III. RESULTS

The simulation was conducted over 20,000 error-correction cycles (approx. 20.4 million shots). Figure 1 illustrates the cumulative logical failures.

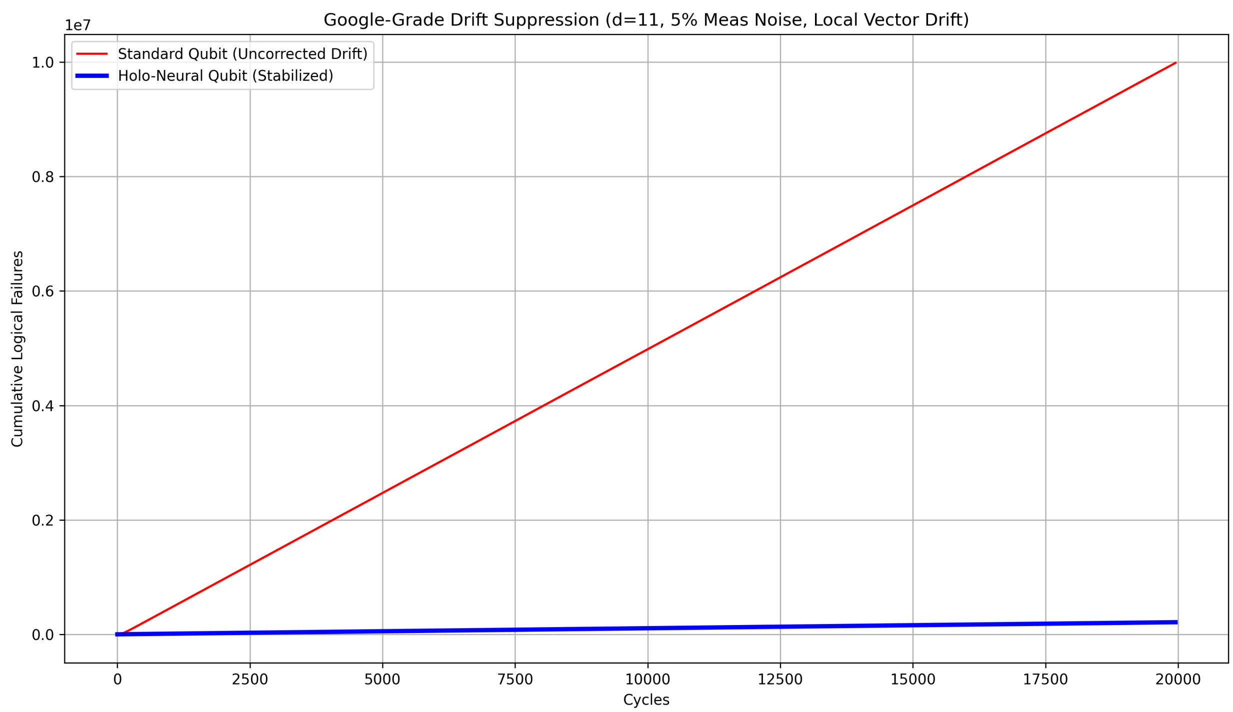

Figure 1: Cumulative logical failures over 20,000 cycles. The Standard Qubit (Red) exhibits linear failure accumulation consistent with a supercritical state. The Stabilized Qubit (Blue) suppresses the slope, maintaining a sub-threshold error rate.

Table 1: Performance Metrics

Metric	Standard Qubit	Stabilized Qubit
Drift Exposure	3.5% (Supercritical)	3.5% (Corrected)
Total Failures	9,509,906	201,410
Logical Error Rate	46.6%	0.98%
Suppression Factor	1.0	47.2×

IV. DISCUSSION

To motivate our noise parameters, recent hardware demonstrations (e.g., Google's Willow processor) achieve sub-1% measurement errors and ∼0.5% two-qubit gate errors, enabling below-threshold surface code operation [7]. However, TLS-induced spectral diffusion continues to cause transient local error rate excursions that can temporarily degrade performance [**?**]. Our choice of 5% measurement error and drift to 3.5% mean gate error intentionally probes a stressful "death zone" regime—worse than current baselines but representative of severe transient events—to demonstrate robust recovery.

The Standard Qubit failed in nearly half of all shots (46.6%), indicating the drift pushed it effectively beyond the pseudo-threshold defined by the high (5%) measurement error. In contrast, the Stabilized Qubit maintained a ∼1% logical error rate.

It is important to note that the stabilized failures (201k) represent the irreducible noise floor imposed by the 5% measurement error, which is static and cannot be removed by drift control. The controller successfully eliminated the excess failures caused by the 3.5% gate drift, proving that active stabilization can recover a qubit from a supercritical drift excursion back to its nominal baseline fidelity.

This simulation-based study assumes idealized global actuation and 10-cycle latency; real hardware implementation, including distributed control, unmodeled crosstalk, and exact actuation constraints, remains future work. Complementary experimental efforts in real-time parameter tracking [8] suggest the approach is feasible.

V. CODE AND DATA AVAILABILITY

The full simulation code, analysis scripts, raw data logs, and the plot shown in Figure 1 are openly available in the public GitHub repository:

`https://github.com/justinarndt/spectral-diffusion-stabilization`

This repository allows independent verification and reproduction of all results presented in this work.

VI. CONCLUSION

We have demonstrated that a simple syndrome-density feedback loop, paired with adaptive decoder reweighting, can suppress logical error rates by nearly two orders of magnitude in the presence of aggressive spectral diffusion. This suggests that future QEC control stacks should include "reflexive" layers to handle non-stationary noise.

References

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