Systematic Diagnosis of Noise in SC Qubits

Focus: Prioritized noise categories & diagnostic methodologies

(Single- and Two-Qubit Systems)

Noise Categories & Prioritization

1. **SPAM Errors**
    - State prep & readout errors
2. **Intrinsic Decoherence**
    - T_1 (energy relaxation)
    - T_2 (dephasing via 1/f, etc.)
3. **Control & Gate Errors**
    - Pulse calibration imperfections (single- and two-qubit)
4. **Leakage Errors**
    - Transitions out of the computational subspace
5. **Crosstalk & Correlated Noise**
    - Inter-qubit interference & common-mode noise

SPAM Errors (Highest Priority)

- **Objective:** Ensure accurate initialization & measurement.
- **Diagnosis:**
  - Build confusion matrices from repeated $|0\rangle/|1\rangle$ preparations.
  - Use active reset / heralding techniques.
- **Key Methods:**
  - Fast, non-destructive readout
  - Measurement-based reset

References: Krantz et al. (2019); Ristè et al. (2012)

Intrinsic Decoherence

T_1 and T_2 Measurements

- **T_1 (Relaxation):**
  - Inversion Recovery experiments.
- **T_2 (Dephasing):**
  - Ramsey & Echo sequences.

Noise Spectroscopy

- **Technique:**
  - Use CPMG / decoupling sequences to extract noise PSD.

References: Krantz et al. (2019); Müller et al. (2019)

Control & Gate Errors

Single-Qubit Gates

- **Diagnostics:**
  - Rabi, Ramsey experiments for pulse calibration.
  - DRAG pulse shaping to cancel leakage & AC Stark shifts.
- **Benchmarking:**
  - Randomized Benchmarking (RB) / Gate Set Tomography (GST).

Two-Qubit Gates

- **Spectroscopy:**
  - Chevron plots to extract coupling strengths.
- **Diagnostics & Benchmarking:**

Leakage Errors

- **Issue:**
  - Undesired excitations to $|2\rangle$ or higher.
- **Diagnosis:**
  - Modified readout to distinguish $|2\rangle$.
  - Leakage randomized benchmarking.
- **Mitigation:**
  - Pulse shaping (DRAG, adiabatic pulses).
  - Optional active reset of leaked states.

References: Chen et al. (2016); Motzoi et al. (2009)

Crosstalk & Correlated Noise

- **Key Sources:**
  - Control line interference, residual ZZ coupling.
  - Global environmental events (e.g., cosmic rays).
- **Diagnosis:**
  - Measure crosstalk matrix (single-qubit pulses vs. neighbors).
  - Simultaneous RB & GST on multi-qubit systems.
  - Cross-correlation analysis over time.
- **Mitigation:**
  - Active compensation via pre-distortion.
  - Architectural isolation & tailored decoupling (e.g., CA-DD).

Prioritized Workflow Summary

1. **SPAM Calibration:**
    - Build confusion matrices; implement active reset.
2. **Intrinsic Decoherence:**
    - Measure T_1 and T_2; perform noise spectroscopy.
3. **Gate Error Diagnostics:**
    - Calibrate pulses (Rabi, Ramsey, DRAG); benchmark via RB/GST.
4. **Leakage Detection:**
    - Use modified readout/tomography; optimize pulse shaping.
5. **Crosstalk Analysis:**
    - Characterize with simultaneous RB & cross-correlation studies.

Conclusion

- Prioritize SPAM & intrinsic decoherence measurements to establish a baseline.
- Use a combination of spectroscopic, benchmarking, and tomography techniques to diagnose control errors and leakage.
- Characterize crosstalk using simultaneous multi-qubit measurements.
- Iteratively apply context-aware mitigation (CA-DD/CA-EC) based on these diagnostics.

References

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