Autonomous stabilization of an entangled state of two transmon qubits

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“back-action” : in general, measuring the state of a quantum system can perturb it.
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Challenge ➔ design feedback such that back-action absent when in desired state.
Resources for quantum computing

Qubit: two level quantum system

\[ |g\rangle, |e\rangle \]

System state: \[ |\psi\rangle \]

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|g\rangle + |e\rangle) \]

\[ \langle Z \rangle = 0, \langle X \rangle = 1 \]

Measure Z \(\Rightarrow\) back-action randomly gives +1 or -1, average = 0

Measure X \(\Rightarrow\) No back-action, X = +1 always
Resources for quantum computing

2-qubit system

|ψ⟩ = \frac{1}{\sqrt{2}}(|ge⟩ - |eg⟩)

⟨Z_A⟩ = ⟨Z_B⟩ = 0, ⟨Z_AZ_B⟩ = −1
⟨X_A⟩ = ⟨X_B⟩ = 0, ⟨X_AX_B⟩ = −1

Measure individual qubits \(\Rightarrow\) back-action gives +1 or -1 randomly

Measure joint parity \(\Rightarrow\) no back-action, parity = -1 always
Challenges: decoherence

Environmental noise

\[ |g\rangle + |e\rangle \]
\[ \frac{|g\rangle - |e\rangle}{\sqrt{2}} \]

Relaxation: \( T_1 \)

Dephasing: \( T_\phi \)
Challenges: decoherence

Environmental noise

\[ |e\rangle \quad \rightarrow \quad |g\rangle \]

Relaxation: \( T_1 \)

\[
\frac{|g\rangle + |e\rangle}{\sqrt{2}} \quad \rightarrow \quad \frac{|g\rangle - |e\rangle}{\sqrt{2}}
\]

Dephasing: \( T_\phi \)

Solution: Quantum feedback

\( \Rightarrow \) maintain superposition/entanglement against decoherence
Circuit QED architecture


T \sim 20 \text{ mK}

3D microwave rectangular cavity
10 \text{ mm}

Superconducting transmon qubit

Josephson junction

200 \mu m

200 \text{ nm}
Superconducting transmon qubit

Josephson junction with shunting capacitor → anharmonic oscillator

\[ \phi = \int V dt \]

\[ L = \frac{L_J}{\cos(\phi/\phi_0)}, \quad \phi_0 = \frac{\hbar}{2e} \]

Qubit frequency $\sim 4 – 10$ GHz, $T_1, T_\phi \sim 10 – 100$ µs

How do we measure the qubit: dispersive readout

\[ \theta = 2 \tan^{-1} \left( \chi / \kappa \right) \]

"Quantum non-demolition" measurement of $Z$

$\Rightarrow$ No back-action if state is $|g\rangle$ or $|e\rangle$

Multiple single-qubit feedback experiments: ENS, Berkeley, Delft, Yale, ETH
Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$

Z. Lehtas et al., PRA (2013)

- 2 individually addressable transmons in one cavity
- Almost equal and large dispersive shifts ($\chi_{Alice} \sim \chi_{Bob} > \kappa$)
- Autonomous $\Rightarrow$ No external controller
Why $\chi_{Alice} \sim \chi_{Bob}$ : quasi-parity measurement

- Distinguish even and odd parity
- No back-action if state is $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$
Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$
Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$

- Select even parity: $|gg, 0\rangle$, $|ee, 0\rangle$
pumped to $n$ photon manifold
  – cavity drives with average $\bar{n}$ photons ($n \sim \bar{n}$)
Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$

- Select even parity: $|gg, 0\rangle$, $|ee, 0\rangle$ pumped to $n$ photon manifold – cavity drives with average $\bar{n}$ photons ($n \sim \bar{n}$)
Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$

- Select even parity
- Select Bell state: $|\phi_+, 0\rangle$ pumped to $n$ photon manifold
  - by phase of drives
Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$

- Select even parity
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  - by phase of drives
Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$

- Select even parity
- Select Bell state
- Pump $|gg, n\rangle$, $|ee, n\rangle$ into $|\phi_-, n\rangle$
  - one drive phase $\pi$ shifted
Autonomous stabilization of Bell state \( |\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2} \)

- Select even parity
- Select Bell state
- Pump \(|gg, n\rangle, |ee, n\rangle\) into \(|\phi_-, n\rangle\)
  - one drive phase \(\pi\) shifted
Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$

- Select even parity
- Select Bell state
- Pump $|gg, n\rangle, |ee, n\rangle$ into $|\phi_, n\rangle$
- Cavity relaxes irreversibly to $|\phi_-, 0\rangle$ – rate $\kappa$
Autonomous stabilization of Bell state $|\phi_-\rangle = \{|ge\rangle - |eg\rangle\}/\sqrt{2}$

Quasi-parity measurement

Conditional Rabi drives
System-reservoir characteristics

Cavity transmission

\[ \chi_{\text{Alice}}/2\pi = 6.5 \text{ MHz} \]
\[ \chi_{\text{Bob}}/2\pi = 5.9 \text{ MHz} \]
\[ \kappa/2\pi = 1.7 \text{ MHz} \]

<table>
<thead>
<tr>
<th></th>
<th>Qubit frequency (GHz)</th>
<th>( T_1 ) (( \mu s ))</th>
<th>( T_\phi ) (( \mu s ))</th>
<th>( \kappa T_1 )</th>
<th>( \kappa T_\phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alice</td>
<td>5.238</td>
<td>16</td>
<td>11</td>
<td>170</td>
<td>120</td>
</tr>
<tr>
<td>Bob</td>
<td>6.304</td>
<td>9</td>
<td>36</td>
<td>100</td>
<td>380</td>
</tr>
</tbody>
</table>

Achieve \( \kappa T_1, \kappa T_\phi > 100 \)


**Experiment protocol**

Stabilization drives ON

Two qubit tomography

Measure 15-component Pauli vector

Stabilization time \( T_S \) = 500 ns

\[ |gg\rangle \quad |\phi_-\rangle \]

\( T_S = 0 \)

\( T_S \gg 10 \kappa^{-1} \)

\[ \text{IZ} \quad \text{ZI} \quad \text{ZZ} \]

Increasing \( T_S \)...
Tomography results vs $T_S$

Converges to $|\phi_-\rangle$
Tomography results vs $T_S$

- $\langle ZZ \rangle$
- $\langle XX \rangle$
- $\langle YY \rangle$
- $\langle ZI \rangle$
- $\langle IZ \rangle$

Converges to $|\phi_-\rangle$

And remains stable much longer than $T_1, T_\phi$
Fidelity to Bell state

Exponential rise, $\tau = 960$ ns $\sim 10\kappa^{-1}$

- Improved to 77 % by monitoring cavity output
- Expect above 90 % in future version with improved $T_1$

Thank you