nature portfolio

Peer Review File

Autonomous stabilization with programmable stabilized state

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

In this manuscript, the authors experimentally demonstrate a method to stabilize a continuous set of quantum states, including maximally entangled states, in a two-qubit system using superconducting circuits. They report stabilization fidelities of 82-85% for Bell states and demonstrate dissipative switching between even and odd Bell states with microsecond switching times. The application of dissipation engineering in this context is interesting, yet its role as a "precursor for new reservoir engineering-based error correction schemes" is unclear. It sounds that this technique could be help build error-corrected quantum computers, and I would appreciate further clarification from the authors on this point.

- Can this stabilization method correct errors without prior knowledge of the logical quantum state, which is required for quantum error correction? If not, I recommend clarifying this in the manuscript to avoid confusion for the readers.

- Can the methodology be expanded to stabilize more than two entangled qubits, and how scalable is this technique?

- How do the fidelity and switching speed of this technique compare with the requirements of autonomous quantum error correction (AQEC)?

Clarifications on these points in the manuscript would enhance its contribution to the field.

Overall, the experiments and analysis are clearly presented and the demonstrated technique is likely to be of wide interest to quantum information scientists from the perspective of dissipative engineering. Therefore, publication in Nature Communications is recommended.

Reviewer #2 (Remarks to the Author):

Review report

The research paper introduces an innovative method for the autonomous stabilization of quantum states within superconducting circuits, marking a significant advancement in quantum computing. This method is crucial as it addresses the challenge of preserving quantum states against environmental interference, which can lead to decoherence and loss of quantum information. The authors aim to stabilize quantum states in a programmable and continuous manner, overcoming the limitations of previous methods that were restricted to discrete entangled states. They achieve this by manipulating the system's Hamiltonian and using tailored dissipation. The paper is based on a solid theoretical framework that explains how the energy levels of the quantum system are engineered to direct the population towards a specific stabilized state. This is done by satisfying specific energy matching conditions derived from the system's Hamiltonian. The authors validate their theoretical claims through meticulous experiments, demonstrating high stabilization fidelity for odd and even-parity Bell states. The fast dissipative switching between these states highlights the effectiveness of the proposed method.

The work is well done and the paper is well written. If the authors are able to address my concerns (to follow) , then I would be able to recommend publication.

1.In the context of a manuscript intended for a general audience, it is advisable for the authors to employ terminology that is more accessible to non-specialist readers. For example, the concept of a "sideband," while well-established in quantum optics, may not be universally understood. Therefore, the authors should consider utilizing alternative, more comprehensible terms.

2.The parametric drives depicted in Figure 1 are identified as an essential element of the proposed control scheme. It is recommended that the authors incorporate clearer instructions within the main text and provide an exhaustive discussion in the supplementary material. Although sideband parametric drives are briefly addressed in Section III and the supplementary section, their explanation lacks clarity. The authors should elucidate the methodology of implementing the QR drive and the quantitative relationship between the drive strength W and the modulation amplitude ε. Additionally, the influence of this drive on the QQ interaction should be addressed. The authors should also discuss why the QR red sideband cannot be actuated via the flux line and the rationale behind the blue sideband's generation of rotating terms a_q1*a_q2 while suppressing counter-rotating terms. A more detailed exposition of the derivation would be beneficial.

3.Without the application of parametric drives, fulfilling the condition E_D + E_A = E_B + E_C for transmons with an effective ZZ interaction linked to anharmonicity is unfeasible. For scenarios involving parametric driving, it remains unclear whether anharmonicity adversely affects this condition. The disappearance of anharmonicity terms in Equation (1) is not evident, and the influence of the two-qubit ZZ coupling on stabilization requires further clarification.

4.The authors should delineate the types of quantum states that are not amenable to stabilization using the presented methodology.

5.In the experimental findings, the decay rates of the transmon are observed to be of the same order as the cavity's decay (~10 microseconds), which contradicts the theoretical requirement of κ >> γ. The authors are encouraged to discuss the ramifications of this discrepancy and provide an explanation for the experiment's success despite this theoretical non-alignment.

6.How are the fidelity measured and calculated in Fig.2 and Fig.3? Additionally, the authors should address the absence of error bars in the data presented, which is derived from 5000 repetitions of 9 distinct prerotations.

7.While the paper demonstrates impressive results for a two-qubit system, the scalability of this method to larger quantum systems remains to be seen. Is it possible to estimate the complexity scaling law?

8.Although the experimental outcomes substantiate the conceptual validity of the approach, the fidelity levels achieved in the context of state preparation are observed to be relatively modest. It would be beneficial for the authors to conduct a thorough analysis to identify and quantify the sources of error that contribute to this reduced fidelity. This could include examining potential discrepancies between theoretical predictions and experimental observations, as well as evaluating the impact of environmental factors, operational imperfections, and intrinsic quantum noise on the stabilization process.

Reply to Referees

We sincerely thank the Referees for their assessment and constructive remarks.

Below we address the comments of the Referees point-by-point and indicate the corresponding changes to the manuscript. We believe these remarks have contributed significantly to improving the quality of the manuscript. We hope you will consider this revised manuscript for publication in Nature Communications.

REFEREE A

In this manuscript, the authors experimentally demonstrate a method to stabilize a continuous set of quantum states, including maximally entangled states, in a two-qubit system using superconducting circuits. They report stabilization fidelities of $82 - 85\%$ for Bell states and demonstrate dissipative switching between even and odd Bell states with microsecond switching times. The application of dissipation engineering in this context is interesting, yet its role as a "precursor for new reservoir engineering-based error correction schemes" is unclear. It sounds that this technique could be help build error-corrected quantum computers, and I would appreciate further clarification from the authors on this point.

Response:

We thank the referee for understanding the demonstration and appreciating our work. We hope our responses and the modifications will satisfy the concerns raised by the referee while improving the quality of the manuscript.

Comment A.1:

- Can this stabilization method correct errors without prior knowledge of the logical quantum state, which is required for quantum error correction? If not, I recommend clarifying this in the manuscript to avoid confusion for the readers.

Response: This stabilization method cannot correct logical errors without prior knowledge. Larger code distance, such as using the $|f\rangle$ state in the protocol (Shown in reference 8), is promising for achieving autonomous quantum error correction.

Based on the referee's suggestions, We clarified this point in both the introduction and conclusion sections.

Comment A.2:

- Can the methodology be expanded to stabilize more than two entangled qubits, and how scalable is this technique?

Response: The generalization of this stabilization protocol is not trivial. The number of additional energy-matching conditions required grows exponentially with the increase in the number of qubits.

While scaling is beyond the scope of this paper, we list the sufficient conditions in Supplementary Section V based on the referee's suggestions. Providing a detailed, constructive example remains an objective for future work.

Comment A.3:

- How do the fidelity and switching speed of this technique compare with the requirements of autonomous quantum error correction (AQEC)?

Response: The current stabilization scheme cannot achieve AQEC. If the $|f\rangle$ state is included in the scheme, as discussed in reference 8, the switching rate is equivalent to the logical state refilling rate in this context. To realize AQEC, the refilling rate from the error state to the logical state should be much faster than the error rate. Typical transmon decay and dephasing error rates are less than 5kHz, and our switching rate, larger than 50kHz, is sufficient for AQEC.

While the exact stabilization fidelity threshold necessary for a break-even demonstration of AQEC is not intuitive, higher stabilization fidelity consistently benefits AQEC. The fact that fidelity remains nearly constant for at least 49μs shows the dissipative Floquet system remains effectively modeled after 49μs, leaving enough room for measuring AQEC logical state coherence.

We clarified these points in the conclusion based on the referee's suggestions.

Clarifications on these points in the manuscript would enhance its contribution to the field.

Overall, the experiments and analysis are clearly presented and the demonstrated technique is likely to be of wide interest to quantum information scientists from the perspective of dissipative engineering. Therefore, publication in Nature Communications is recommended.

Response: We are very thankful for the high assessment of our work and supporting publication in Nature Communications.

REFEREE B

The research paper introduces an innovative method for the autonomous stabilization of quantum states within superconducting circuits, marking a significant advancement in quantum computing. This method is crucial as it addresses the challenge of preserving quantum states against environmental interference, which can lead to decoherence and loss of quantum information. The authors aim to stabilize quantum states in a programmable and continuous manner, overcoming the limitations of previous methods that were restricted to discrete entangled states. They achieve this by manipulating the system's Hamiltonian and using tailored dissipation. The paper is based on a solid theoretical framework that explains how the energy levels of the quantum system are engineered to direct the population towards a specific stabilized state. This is done by satisfying specific energy matching conditions derived from the system's Hamiltonian. The authors validate their theoretical claims through meticulous experiments, demonstrating high stabilization fidelity for odd and even-parity Bell states. The fast dissipative switching between these states highlights the effectiveness of the proposed method.

The work is well done and the paper is well written. If the authors are able to address my concerns (to follow) , then I would be able to recommend publication.

Response: We thank the referee for understanding the demonstration and appreciating our work.

We hope our responses and the modifications will satisfy the concerns raised by the referee while improving the quality of the manuscript and will lead to a favorable recommendation.

Comment B.1:

In the context of a manuscript intended for a general audience, it is advisable for the authors to employ terminology that is more accessible to non-specialist readers. For example, the concept of a "sideband," while well-established in quantum optics, may not be universally understood. Therefore, the authors should consider utilizing alternative, more comprehensible terms.

Response: Based on the referee's suggestions, we have incorporated the following explanation into the main text to clarify the concept of 'sideband':

'In this context, 'sideband' refers to a two-photon process where either a single photon is exchanged at the frequency difference (known as the red sideband) or two photons are simultaneously driven at the frequency sum (referred to as the blue sideband).'

Additionally, we reference the first sideband experiments demonstrated in superconducting qubits, as cited in reference 26.

We hope this addition will make the manuscript comprehensible to non-specialist readers.

Comment B.2:

The parametric drives depicted in Figure 1 are identified as an essential element of the proposed control scheme. It is recommended that the authors incorporate clearer instructions within the main text and provide an exhaustive discussion in the supplementary material. Although sideband parametric drives are briefly addressed in Section III and the supplementary section, their explanation lacks clarity. The authors should elucidate the methodology of implementing the QR drive and the quantitative relationship between the drive strength W and the modulation amplitude ϵ. Additionally, the influence of this drive on the QQ interaction should be addressed. The authors should also discuss why the QR red sideband cannot be actuated via the flux line and the rationale behind the blue sideband's generation of rotating terms $a_{q1}a_{q2}$ while suppressing counter-rotating terms. A more detailed exposition of the derivation would be beneficial.

Response: We acknowledge that the distribution of equations related to the sideband rate across the Supplementary section may have made it difficult to follow. We have revised Supplementary Section I in response to the referee's recommendations. The theoretical sideband rates are listed explicitly in Supplementary Equation (7), (9) and (10).

The QR red and blue sidebands can both theoretically be realized via the flux line. In our experiments, however, we opted to drive only the QR red sideband through the flux line. This decision was driven by the hardware limitations of our Arbitrary Waveform Generator, which cannot accommodate the modulation frequencies required for the QR blue sideband (> 8 GHz). Consequently, we utilize charge drive modulation for the QR blue sideband, as it halves the required drive frequency, making it more feasible with our existing equipment.

The counter-rotating terms are neglected through Rotating Wave Approximation for a simple sideband rate expression. The effects of the counter-rotating terms are suppressed due to the large frequency detunings. Its experiment effect is AC stark shift: When all QQ and QR sidebands are on, their modulation frequency will differ slightly from the theoretical predicted value. The sidebands' modulation frequencies are re-calibrated by maximizing the stabilization fidelity. We have now included the discussion in the Supplementary Section I.

Comment B.3:

Without the application of parametric drives, fulfilling the condition $E_D + E_A = E_B + E_C$ for transmons with an effective ZZ interaction linked to anharmonicity is unfeasible. For scenarios involving parametric driving, it remains unclear whether anharmonicity adversely affects this condition. The disappearance of anharmonicity terms in Equation (1) is not evident, and the influence of the two-qubit ZZ coupling on stabilization requires further clarification.

Response: We thank the referee for highlighting these important points.

Indeed, fulfilling the condition $E_D + E_A = E_B + E_C$ while simultaneously engineering the desired target state $|A\rangle$ for stabilization is challenging without additional parametric drives. As noted in Supplementary Section IV, Equation 16, only all product states can be effectively stabilized.

The role of anharmonicity in the transmon is beneficial for the energy-matching condition and, therefore, for the stabilization. Anharmonicity α is omitted from Equation (1) by treating both transmons as two-level systems. The presence of anharmonicity effectively suppresses the higher energy levels' population in either transmon. The population transfer to the $|f\rangle$ state is proportional to $O\left(\frac{\Omega^2}{\alpha^2}\right)$. In our experiments, $\frac{\Omega}{\alpha} < 3\%$ ensures the higher states' population is negligible and validates the treatment as a two-level system. We have included the discussion in the main text.

We acknowledge that the energy matching condition cannot be fulfilled with stray ZZ coupling. Its impact is minimal when the ZZ coupling strength is less than the QR sideband rate W, a condition met in our experiments. We have expanded our discussion on the effects of ZZ coupling in detail in Supplementary Section III.

Comment B.4:

The authors should delineate the types of quantum states that are not amenable to stabilization using the presented methodology.

Response: We thank the referee for highlighting this important point. In Supplementary Section IV, all possible states to stabilize are described by Equation (24); therefore, the other states cannot be stabilized. We acknowledge that the form of Equation (24) is complex, and to aid understanding, we provide examples of states that are not amenable to stabilization in the following paragraph. We appreciate the opportunity to clarify this aspect of our work.

Comment B.5:

In the experimental findings, the decay rates of the transmon are observed to be of the same order as the cavity's decay ($\sim$ 10 microseconds), which contradicts the theoretical requirement of $\kappa \gg \gamma$. The authors are encouraged to discuss the ramifications of this discrepancy and provide an explanation for the experiment's success despite this theoretical non-alignment.

Response: We thank the referee for highlighting this point. In our experiments, the measured resonator decay rates, denoted by κ, are $2\pi\times 0.33, 0.43$ MHz, corresponding to $T_1 = 1/\kappa = 0.48, 0.37\mu$s. These rates are significantly faster than the qubit decay rate γ, which is approximately 10μs. This finding aligns with the theoretical requirement that $\kappa \gg \gamma$. We appreciate the opportunity to clarify this aspect and confirm the theoretical alignment in our experimental setup.

Comment B.6:

How are the fidelity measured and calculated in Fig.2 and Fig.3? Additionally, the authors should address the absence of error bars in the data presented, which is derived from 5000 repetitions of 9 distinct prerotations.

Response: Fidelities are calculated as $F = (\mathrm{tr}\sqrt{\sqrt{\rho_m}\rho_{th}\sqrt{\rho_m}})^2$, where σ is the target state and ρ is the tomography reconstructed density matrix. We calculate all error bars (one standard deviation) in the manuscript using the tomographer package from PRL 117, 010404 (2016). Error bars are smaller than the marker size.

We clarified these points in the caption of Figure 2, Figure 3, and Section III in the main text.

Comment B.7:

While the paper demonstrates impressive results for a two-qubit system, the scalability of this method to larger quantum systems remains to be seen. Is it possible to estimate the complexity scaling law?

Response: The generalization of this stabilization protocol is not trivial. The number of additional energy-matching conditions required grows exponentially with the increase in the number of qubits. While scaling is beyond the scope of this paper, we list the sufficient conditions in Supplementary Section V based on the referee's suggestions. Providing a detailed, constructive example remains an objective for future work.

Comment B.8:

Although the experimental outcomes substantiate the conceptual validity of the approach, the fidelity levels achieved in the context of state preparation are observed to be relatively modest. It would be beneficial for the authors to conduct a thorough analysis to identify and quantify the sources of error that contribute to this reduced fidelity. This could include examining potential discrepancies between theoretical predictions and experimental observations, as well as evaluating the impact of environmental factors, operational imperfections, and intrinsic quantum noise on the stabilization process.

Response: Based on the referee's suggestions, we have added a comprehensive error analysis as a new Section VII in the Supplementary Material. This section details the simulations used to extract the stabilization infidelities, identifying transmon decoherence as the predominant source of error. We believe this addition enhances our manuscript by clarifying the factors that impact the stabilization fidelities in our experiments.

REVIEWERS' COMMENTS

Reviewer #1 (Remarks to the Author):

The authors have addressed all of my questions and concerns satisfactorily. I strongly support the publication of the manuscript in Nature Communications.

Reviewer #2 (Remarks to the Author):

All my concerns and questions have been answered. The changes made in the main text and supplementary are well written. I don't have further comments. And I agree that the current version of the manuscript is ready for publication.

Reply to Referees

We sincerely thank the Referees for their assessment and constructive remarks.

REFEREE A

The authors have addressed all of my questions and concerns satisfactorily. I strongly support the publication of the manuscript in Nature Communications.

Response:

We thank the referee for appreciating our work.

REFEREE B

All my concerns and questions have been answered. The changes made in the main text and supplementary are well written. I don't have further comments. And I agree that the current version of the manuscript is ready for publication.

Response:

We thank the referee for appreciating our work.