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ResearchArticle

Reservoir-Engineered Feedback Control of Information Erasure in Quantum Internet of Things

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Abstract **–** In this work, we're looking at a simplified Hamiltonian model for information erasure in Quantum Internet of Things (QIoT) systems - basically just two qubits that interact with each other. We've set up a toy model where we continuously measure one qubit and use that info to control the other one. This basically lets us engineer the reservoir entropy before the environment starts messing things up. The feedback we engineer through the reservoir connects directly to how much energy it costs to erase information, and this lets us control how much mutual information the qubits share. We discuss both so-called 'conditional' (i.e., stochastic) and 'unconditional' (ensemble-averaged) master equations to describe the dynamics of the system under measurement-and-feedback protocol. This mutual information is quantified and embedded into a correlation-corrected Landauer bound, showing that quantum correlations can help us erase information using less work than the usual Landauer limit. A simple stability analysis shows the existence of an optimal feedback gain that maximizes the entropy transfer while maintaining system stability. So, our simple model here connects the quantum-level processes with the bigger thermodynamic picture - things like heat flow, entropy, and free energy when the system's out of equilibrium. We link explicitly feedback strength, dissipation rates, and correlation dynamics to provides a toy but physically intuitive model for the control in QIoT. Our model is based on the recent advances in quantum thermodynamics, reservoir engineering, and feedback-controlled quantum systems. This gives us a new way to think about building energy-efficient QIoT systems and opens some interesting possibilities for scaling more nodes, dealing with memory effects in the environment, and optimizing control across entire networks.

Keywords – Quantum Internet of Things, information erasure, reservoir engineering, feedback control, mutual information, QIoT ecosystem, sustainability

I. Introduction

In the modern technological paradigm of a Quantum Internet of Things (QIoT), distributed quantum devices, such as communication nodes, memristors, sensors, form networks that exploit different quantum effects (entanglement, superposition) to improve the communication capabilities and applications for sensing and computation beyond classical limits (e.g., [1,2]). The problem is that in such networks, one can face the information erasure, which resets operations and corrupts the memory management under energy constraints, and it becomes critical for large scale deployment.

A key insight in classical thermodynamics is the Landauer's principle, stating that erasing one classical bit of information in a system at the temperature T costs at least $k_BT\ln(2)$ of the dissipated heat [3]. In quantum systems, so-called mutual correlations and entanglement modify this bound, because the correlated information itself can effectively serve as a thermodynamic resource reducing the work cost of erasure [4,5]. Recent experiments confirm this in many body quantum systems and demonstrate the role of quantum correlations in the quantum thermodynamic processing [6,7].

The way to shape entropy flows in open quantum systems problem is to deliberate design of dissipation via continuous measurement and feedback via reservoir engineering. Such engineered feedback can stabilize the quantum states, extract coherence, and, thus, accelerate the reset operations [1,2]. In particular, as it was shown in [7,8], such approach is capable to modify the effective dissipation channels and enable quantum thermal machines with enhanced performance.

Nevertheless, most resent studies focused on single node dynamics or on specific platforms. Here, we develop a toy two node QIoT model to integrate explicitly the Hamiltonian dynamics with engineered reservoirs, and mutual information dynamics to control the thermodynamic cost of information erasure. Our approach is based on the fundamental principles of quantum thermodynamics together with feedback control, extending the present theoretical and experimental advances [9,10].

In Section 2, we construct our model Hamiltonian and formulate the principle of feedback control. Then we discuss the quantum mutual information between the nodes and demonstrate that reducing the correlations before erasure can lower the thermodynamic cost below the standard Landauer limit. The optimal feedback is defined in Section 3, and the main results are presented in Section 4, followed by the discussion in Section 5 and conclusions in Section 6.

II. MODEL

First, we formulate our toy model for QIoT and describe the feedback approach.

A. Model Hamiltonian

Let's suppose that each QIoT node is represented by a two-level quantum system with the energy structure as:

$$H_i = \frac{\hbar\omega_i}{2}\sigma_z^i \; ; \; i = A, B \quad , \tag{1}$$

where σ_z^i is the Pauli Z operator, and ω_i is the qubit transition frequency. The eigenstates $|0\rangle, |1\rangle$ represent the ground and excited quantum states used for memory encoding and operations [10].

Hamiltonian A has a matrix form for node A:

$$H_A = \frac{\hbar\omega_A}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} . \tag{2}$$

Hamiltonian H_B has the same stricture. Nodes A and B interact via an Ising coupling:

$$H_{\text{int}} = g\sigma_z^A\sigma_z^B \; . \tag{3}$$

Here g is the coupling parameter. The total Hamiltonian is given by:

$$H = H_A + H_B + H_{\text{int}} \; . \tag{4}$$

This coupling (3) generates correlations and entanglement between the nodes. As a result, the correlated joint energies shift the thermodynamic cost of transitions and influence the work required for correlated erasure processes [4,5].

A. Dissipation and Feedback Control

Now let's suppose that by the statement of thermodynamics, each node is coupled to its thermal environment at temperature T. The dissipative dynamics are described by the Lindblad form:

$$D[L]\rho = L\rho L^{+} - \frac{1}{2}\left\{L^{+}L, \rho\right\}, \tag{5}$$

where the dissipative term includes the jump operators such as σ_-^i, representing spontaneous emission into the environment. This local dissipation in (5) tends to corrupt excitations and correlations [2].

Suppose that node A is continuously monitored through the observable:

$$O_A = \sigma_Z^A \ , \tag{6}$$

with the measurement current given by:

$$I(t) = \left\langle \sigma_z^A \right\rangle_c + \xi(t) \ , \tag{7}$$

where $\langle ... \rangle_c$ is the conditional expectation, and $\xi(t)$ represents the Gaussian noise arising from shot noise or detector imprecision [1].

Our classical controller uses the current (7) to apply Hamiltonian feedback on node B:

$$H_{\text{fb}}(t) = \hbar \lambda I(t) \sigma_y^B \ , \tag{8}$$

with the feedback gain λ. This feedback effectively engineers a modified dissipative environment for node B, providing the correlation transfer and controlled entropy redistribution [2].

The conditional master equation holds an explicit dependence on the current (7) and captures individual measurement trajectories. For the energy accounting and network level description, we use here the unconditional master equation, which represents averaging over all measurement noise:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H,\rho] + \gamma_A D[\sigma_-^A]\rho + \gamma_B D[\sigma_-^B]\rho + \lambda^2 D[\sigma_y^B]\rho - i\lambda[\sigma_y^B, \sigma_z^A \rho + \rho \sigma_z^A] \ . \tag{9}$$

In (9), the feedback effect appears through additional dissipative terms and conditional commutators, originated in theories of feedback modified open quantum systems, see [4,8].

A. *Quantum Mutual Information*

The quantum mutual information between nodes A and B is given by:

$$I(A:B) = S(\rho_A) + S(\rho_B) - S(\rho_{AB}) \ , \tag{10}$$

where $S(\rho) = -\text{Tr}(\rho \log \rho)$ is the von Neumann entropy. Mutual information evaluates both classical and quantum correlations and instantly contributes to the thermodynamic bounds on processing costs [5].

In the presence of correlations, the minimum work required to erase qubit A can be determined as:

$$W_{\min} = \Delta F_A - k_B T \Delta I(A:B) \ , \tag{11}$$

where $F_A = \text{Tr}(\rho_A H_A) - k_B T S(\rho_A)$ is the non-equilibrium free energy. In (11), the mutual information term $\Delta I(A:B)$ enters with the negative sign, reflecting the fact that reducing correlations before erasure can lower the thermodynamic cost below the standard Landauer limit. This statement is consistent with the general framework of information thermodynamic resource theories [4,5].

I. Optimal Feedback

To simplify the stability analysis, let's study the system under the negligible interaction g = 0, and consider the linearized population dynamics as:

$$\frac{dp_A}{dt} = -\gamma_A p_A \ ; \qquad \frac{dp_B}{dt} = -\gamma_B p_b + \lambda^2 (1 - 2p_B) p_A \ . \tag{12}$$

Here p_A and p_B are the populations for nodes A and B, and γ_A and γ_B are their dissipation rates. The model (12) demonstrates how the feedback from A influences B's dynamics.

The joint population evolution is defined from the linear system matrix:

$$\mathbf{M} = \begin{pmatrix} -\gamma_A & 0 \\ \lambda^2 & -(\gamma_B + \lambda^2) \end{pmatrix}, \tag{13}$$

with eigenvalues $\mu_1 = -\gamma_A$; $\mu_2 = -(\gamma_B + \lambda^2)$. Both are negative for $\lambda > 0$, providing stability. We should mention here that stronger feedback accelerates effective decay of node B, redistributing entropy but possibly injecting additional noise [1].

Now let's evaluate when the entropy transfer rate from A to B reaches its maximum. It happens approximately when the feedback gain λ becomes of the same order as B's natural dissipation rate γ_B. This balance optimizes the entropy extraction without an extreme dissipation:

$$\lambda^* \approx \gamma_B \ . \tag{14}$$

The result (14) matches our control theoretic intuition that optimal feedback uses timescales comparable to intrinsic relaxation rates [2].

II. Results

The procedure of continuous measurement on node A combined with the feedback on node B (8) creates an engineered reservoir that actively transfers correlations and entropy between the nodes, while the mutual information (10) reduces the work needed for erasure, allowing the system to overcome the classical Landauer limit.

Linear analysis evaluates an optimal feedback gain (14) that maximizes the entropy transfer while keeping the system stable.

The feedback transforms quantum correlations into a thermodynamic resource, directly linking microscopic quantum dynamics to the work costs.

Finally, our toy two-node model provides a scalable design for energy-efficient quantum networks, demonstrating how the measurement-and-feedback protocol can control the information erasure in practical QIoT implementations.

III. DISCUSSION

A. *Physical Insights*

First of all, our model demonstrates how the engineered feedback can transform quantum correlations into thermodynamic resources. The feedback not only reshapes the dissipation channels but also actively redistributes entropy before environmental losses. Thus, such control can significantly reduce the erasure cost below naive free energy limits.

Employment of reservoir engineering and feedback in the current experimental devices, such as superconducting circuits, trapped ions, and quantum dots, allows to stabilize quantum states and reset nods based on the mechanisms described in [6,7].

Our future research should cover multi-node networks with non-Markovian reservoirs, explicitly modeling the control hardware energy cost, and develop resource theoretic analyses of QIoT thermodynamics, generalizing results in [1,4,5].

B. *Reservoir-Engineered Information Erasure Feedback Control and the QIoT Ecosystem*

One can say that the reservoir-engineered feedback control on the information erasure forms the thermodynamic regulation layer QIoT ecosystem. As we know, distributed quantum devices continuously accumulate entropy through environmental interactions and information processing, which leads to decoherence and degradation of their operational performance. Our approach enables controlled entropy extraction by tailoring dissipation channels, such that the quantum nodes reset their states in a thermodynamically consistent manner and, at the same time, they preserve their operational functionality.

This controlled erasure provides the continuous re-use of quantum memory resources and prevents the entropy saturation. It is a straight analogy to memory reset mechanisms in classical systems, but it is implemented at the quantum physical level. In addition to such enabling state reset, the reservoir engineering can stabilize coherent and entangled states by driving the system toward a target operational configuration. Feedback control enhances this process by adaptively engineering system-reservoir interactions based on measurement outcomes, enabling autonomous stabilization and entropy redistribution across the network nodes.

At the whole network level, our approach ensures sustained operation, improves robustness against the environmental noise, enables scalable deployment of distributed quantum devices, and supports secure information managing by achieving physically reliable erasure of quantum states. Finally, reservoir engineering transforms dissipation from a limiting factor into a controllable thermodynamic resource, enabling stable, autonomous, and energy-efficient operation of large-scale QIoT systems.

C. *Sustainability Perspective*

The controlled removal of entropy and autonomous stabilization of quantum states made in our approach optimizes the energy cost of information processing and prevents the accumulation of thermodynamic inefficiencies that would otherwise restrict system scalability and lifetime. This, we believe, allows quantum devices to operate continuously with reduced energy consumption and improved durability.

As a result of feedback, the autonomous stabilization reduces the need for frequent maintenance and hardware replacement, and by that contributes to material sustainability and operational flexibility. Furthermore, efficient and controlled information erasure provides responsible information lifecycle and prevents unnecessary resource expenditure associated with persistent storage.

All this establishes reservoir-engineered control as a key concept for the long-term technological and environmental sustainability of Quantum Internet of Things.

IV. CONCLUSION

We presented a basic model for reservoir-engineered feedback control of information erasure in a simplified two-node QIoT setting. By combining open-system dynamics, mutual information tracking, and feedback optimization, we demonstrated how the reservoir engineering reduces the thermodynamic cost of erasure below the standard Landauer bound. Stability analysis and feedback gain optimization provide concrete design principles for QIoT elements.

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