Noise-Assisted Feedback Control of Open Quantum Systems for Ground State Properties

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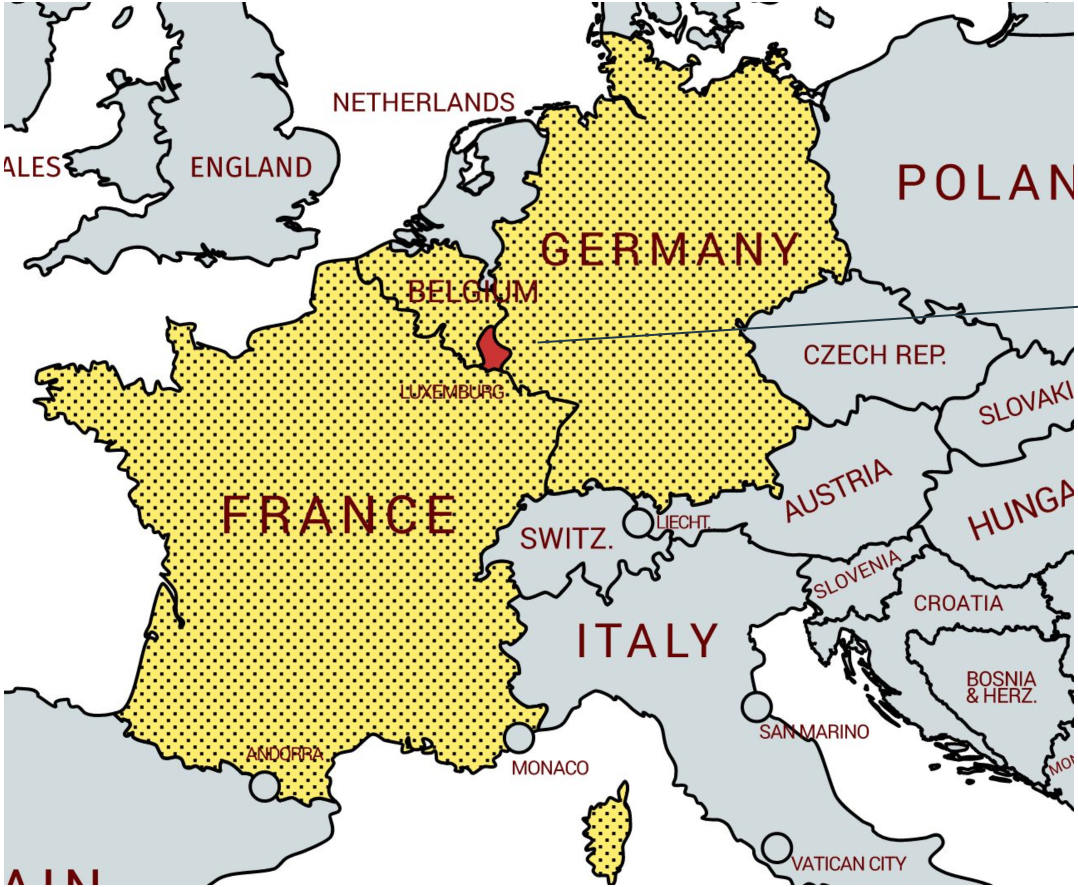

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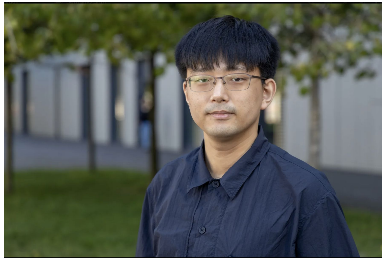
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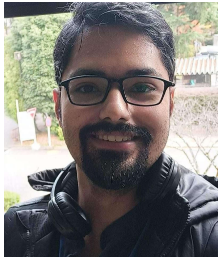
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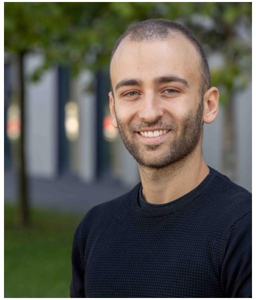
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Noise-Assisted Feedback Control of Open Quantum Systems for Ground State Properties

Kasturi Ranjan Swain, Rajesh K. Malla, Adolfo del Campo

Intrinsic noise in pre-fault-tolerant quantum devices poses a major challenge to the reliable realization of unitary dynamics in quantum algorithms and simulations. To address this, we present a method for simulating open quantum system dynamics on a quantum computer, including negative dissipation rates in the Gorini-Kossakowski-Sudarshan-Lindblad (GKSL) master equation. Our approach lies beyond the standard Markovian approximation, enabling the controlled study of non-Markovian processes within a quantum simulation framework. Using this method, we develop a quantum algorithm for calculating ground-state properties that exploits feedback-controlled, noise-assisted dynamics. In this scheme, Lyapunov-based feedback steers the system toward a target virtual state under engineered noise conditions. This framework offers a promising strategy for harnessing current quantum hardware and advancing robust control protocols based on open system dynamics.

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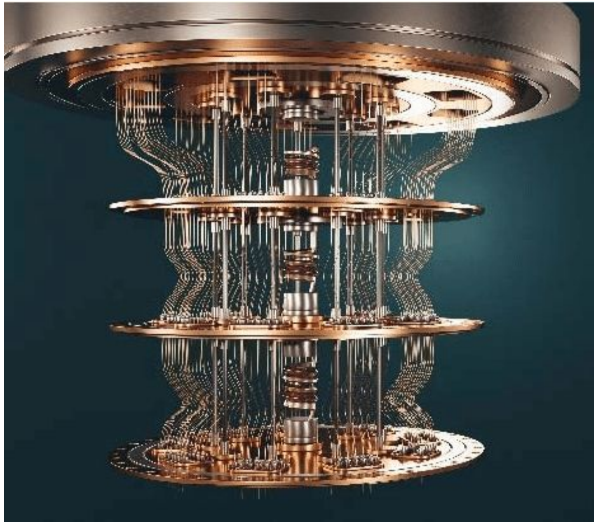
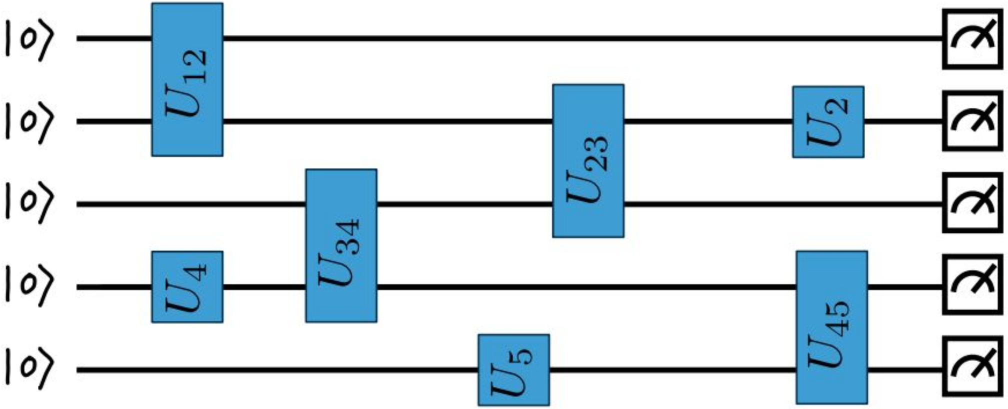
Aim

Finding the ground states of many-body Hamiltonians or solution to combinatorial optimization problems





Feedback-based quantum algorithms (FQAs)

Feedback-based quantum algorithm (FQA)

- Dynamics of a quantum system; $i\frac{d}{dt}|\psi(t)>=(H_p+H_d\beta(t))|\psi(t)>$

  H_P : Problem Hamiltonian, H_d : Control Hamiltonian

- Identify the controls to steer the dynamics towards the ground state.

- Objective is to minimize the function,

$$E_P(t) = \langle\psi(t)|H_P|\psi(t)\rangle \equiv \langle H_P\rangle_t$$

Alicia B. Magann, Kenneth M. Rudinger, Matthew D. Grace, and Mohan Sarovar, Phys. Rev. Lett. 129, 250502 (2022).

Feedback-based quantum algorithm (FQA)

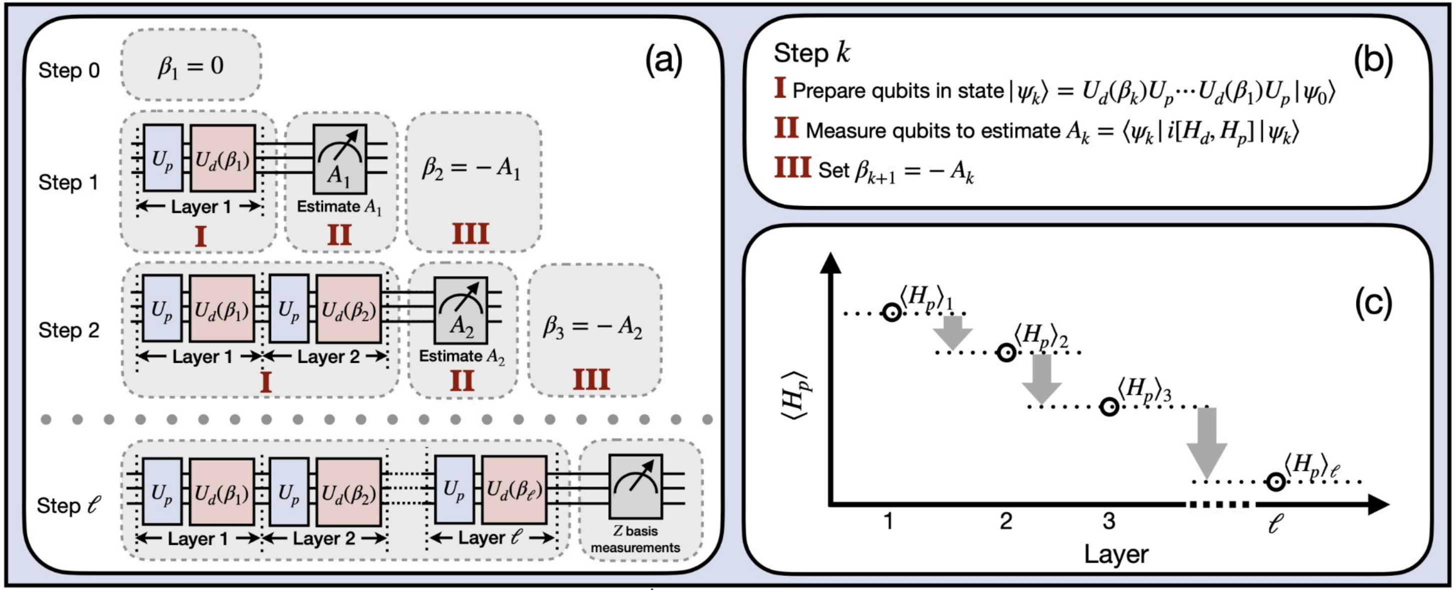
- We seek to design $\beta(t)$ such that the Quantum Lyapunov Control condition, $\frac{d}{dt}E_{\mathrm{p}} \leq 0, \quad \forall t \geq 0$ is satisfied.

$$\begin{aligned}\frac{dE_p}{dt} &= \langle\psi(t)|\, i[H_p + \beta(t)H_d, H_p]\, |\psi(t)\rangle \\ &= \langle\psi(t)|\, i[H_d, H_p]\, |\psi(t)\rangle\, \beta(t) \\ &= A(t)\beta(t),\end{aligned}$$

where, $A(t) \equiv \langle\psi(t)|\, i[H_d, H_p]\, |\psi(t)\rangle$.

- A convenient choice $\beta(t) = -A(t)$, such that the inequality holds at all times.

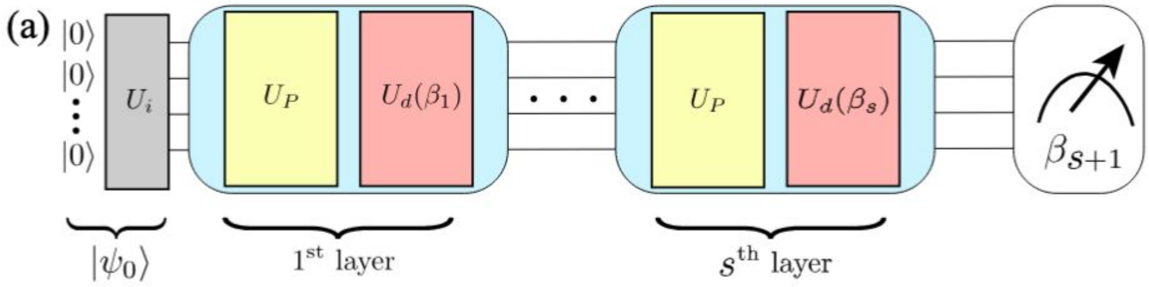
Feedback-based quantum algorithm (FQA)



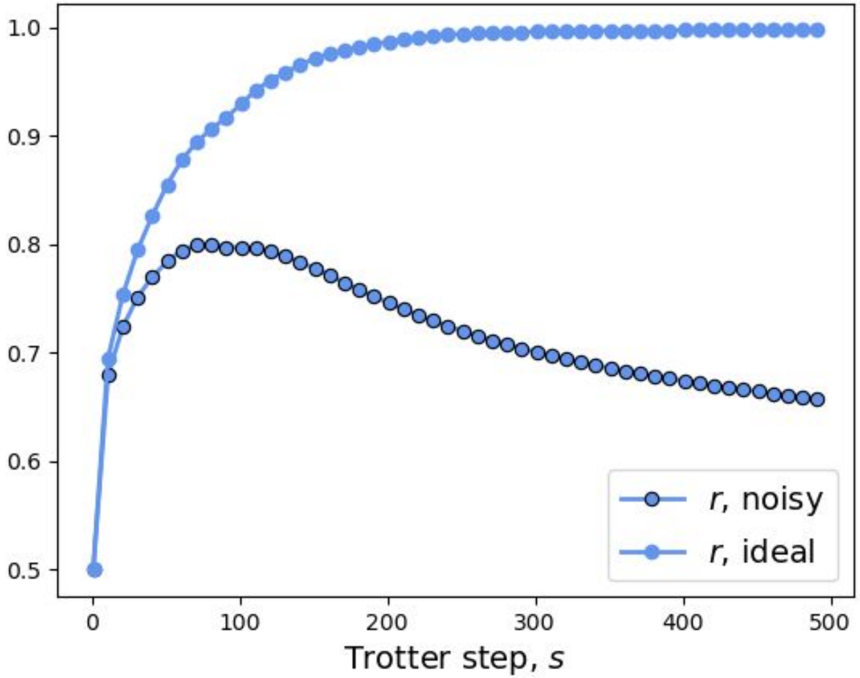
Schematic diagram from

Alicia B. Magann, Kenneth M. Rudinger, Matthew D. Grace, and Mohan Sarovar, Phys. Rev. Lett. 129, 250502 (2022).

Feedback-based quantum algorithm (FQA)



FQA in NISQ devices



Approximation ratio, $r = \langle H_p \rangle / \langle H_p \rangle_{\min}$

$$r \in [0, 1]$$

$$r \approx 1$$

corresponds to the approximate solution of the ground state.

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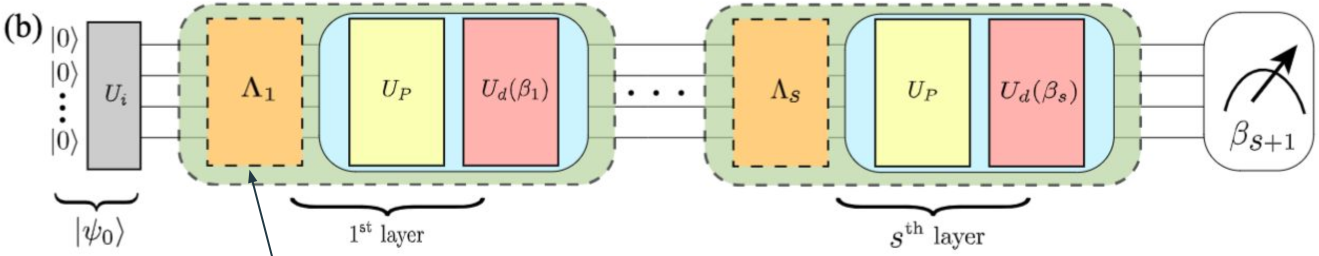
FQA in NISQ devices



Intrinsic noise
Multi-qubit noise channel
Inseparable from ideal gates

Our Work

Q1 : How to get better results for FQA in NISQ devices ?

- Noise in quantum hardwares

Q2 : Can we use noise as a resource ?

FQA for open quantum system

- Let us consider the dynamics of an open system, governed by the GKSL equation,

$$\frac{d\rho}{dt} = -i[H,\rho] + \mathcal{D}_{\text{int}}[\rho],\ \mathcal{D}_{\text{int}}[\rho] = \sum_i (L_i \rho L_i^\dagger - \frac{1}{2} L_i^\dagger L_i \rho - \frac{1}{2} \rho L_i^\dagger L_i)$$

- For the Pauli noise channels, $L_k = \sqrt{\lambda_k} P_k$ and $\{\lambda_k\}$are the error probabilities of the Pauli strings P_k .
- Hence, $\mathcal{D}_{\text{int}}[\rho] = \sum_{k \in \mathcal{K}} \lambda_k (P_k \rho P_k^\dagger - \rho)$.
- FQA Condition:

$$\frac{d}{dt} \langle H_p \rangle = \beta(t) \langle i[H_d, H_p] \rangle + \text{Tr}(\mathcal{D}_{\text{int}}[\rho] H_p) \leq 0.$$

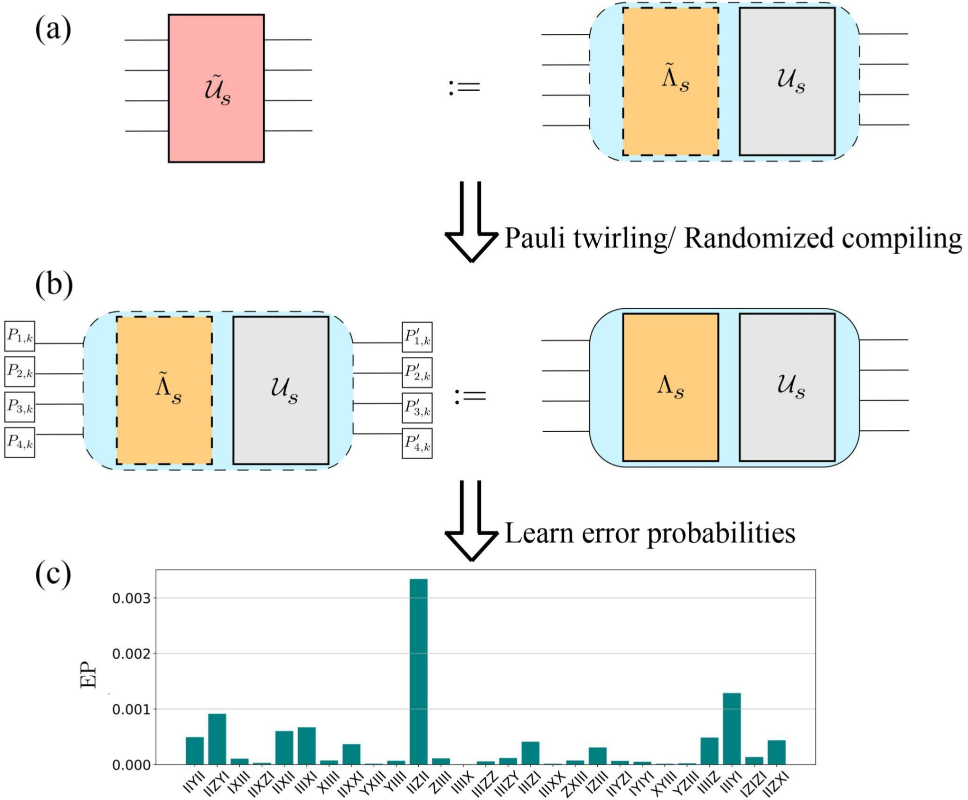
$$\frac{d}{dt} \langle H_p \rangle = \beta(t) \langle i[H_d, H_p] \rangle + \sum_{k \in \mathcal{K}} \lambda_k \left(\langle P_k^\dagger H_p P_k \rangle - \langle H_p \rangle \right) \leq 0.$$

Second term can be positive, and may explain the non-monotonic behavior of the energy as a function of the circuit depth

Pauli Twirling / Randomized Benchmarking

We assume that the noise in quantum hardware can be reliably learned.

$$\Lambda(\rho) = \prod_{k \in \mathcal{K}} \left(\omega_k \cdot + (1 - \omega_k) P_k \cdot P_k^{\dagger} \right) \rho$$



A. Hashim et al., Phys. Rev. X 11, 041039 (2021).

E. van den Berg, Z. K. Minev, A. Kandala, and K. Temme, Nature Physics 19, 1116 (2023).

Maxcut Problem

Problem Hamiltonian

$$H_p = -\sum_{i,j\in\mathcal{E}} \frac{1}{2}(1 - Z_i Z_j)$$

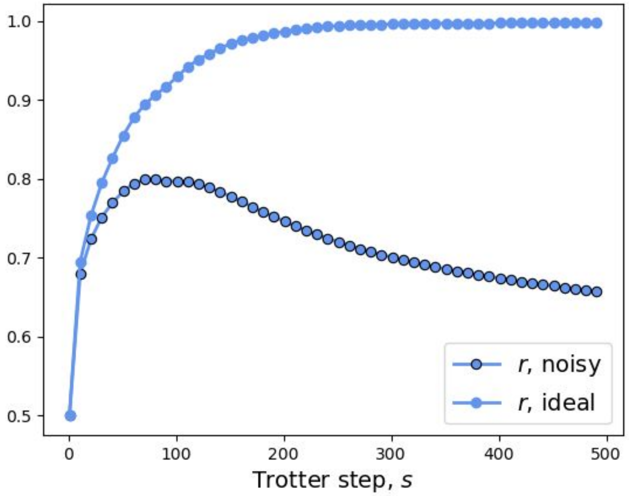
Control Hamiltonian

$$H_d = \sum_{j=1}^{N} X_j$$

Commutator

$$i[H_d, H_p] = \sum_{i,j\in\mathcal{E}} Y_i Z_j + Z_i Y_j$$

Figures of merit: Approximation ratio, $r = \langle H_p \rangle / \langle H_p \rangle_{\min}$



$r \in [0, 1]$

$r \approx 1$

corresponds to the approximate solution of the ground state.

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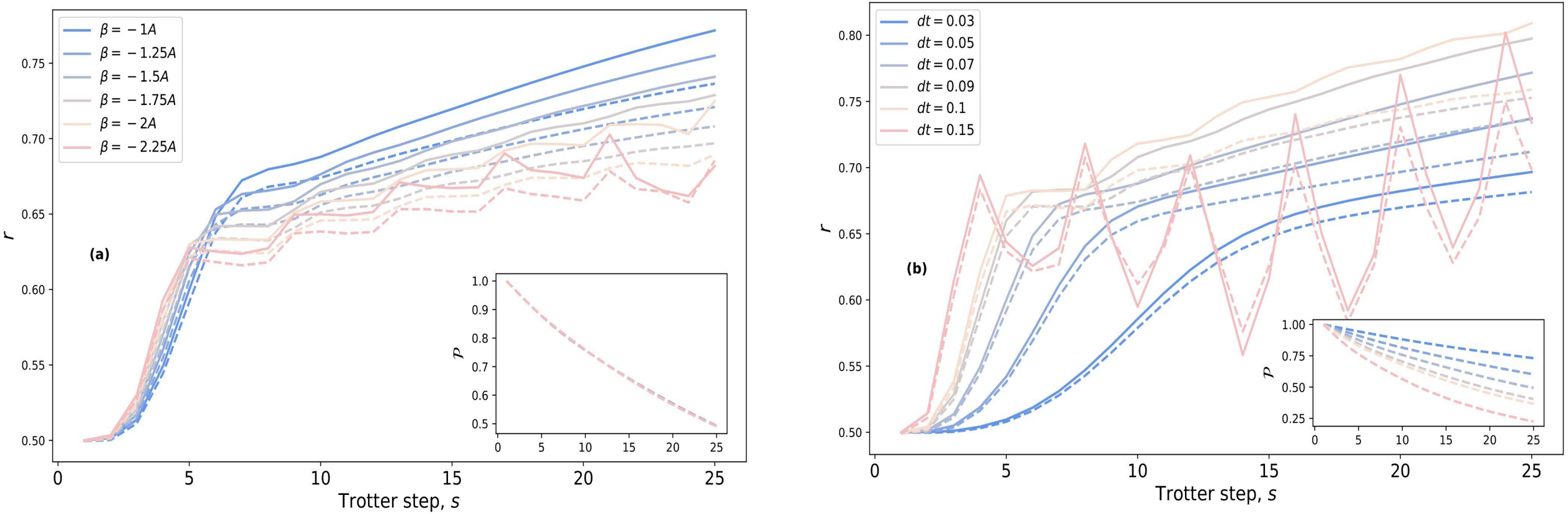
Maxcut Problem

Can we make $\beta(t)$ more negative to reach the ground state faster ?



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Better cooling strategy ?

(1) Quantum error mitigation[1]
(2) Pseudo Lindblad quantum trajectories[2]

$$\frac{d\rho}{dt} = -i[H,\rho] + \mathcal{D}_{\text{int}}[\rho], \ \ \mathcal{D}_{\text{int}}[\rho] = \sum_{k\in\mathcal{K}} \lambda_k (P_k \rho P_k^\dagger - \rho).$$

QLC Condition:

$$\frac{d}{dt}\langle H_p\rangle = \beta(t)\langle i[H_d, H_p]\rangle + \sum_{k\in\mathcal{K}} \lambda_k \left(\langle P_k^\dagger H_p P_k\rangle - \langle H_p\rangle\right) \leq 0.$$

If we keep the same control field, $\beta(t) = -A(t)$, we see non-monotonic behavior in energy.

Now, we want to introduce an additional Lyapunov control that depends on the modified error probabilities, $\{\Gamma_k(t)\}_{k\in\mathcal{K}}$ such that $\Gamma_k(t) = -\left(\langle P_k^\dagger H_p P_k\rangle - \langle H_p\rangle\right)_t$.

The time-local master equation corresponding to the layer-dependent decay rates becomes,

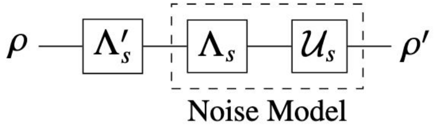
$$\frac{d\rho(t)}{dt} = -i[H(t),\rho(t)] + \sum_{k\in\mathcal{K}} \Gamma_k(t)(P_k\rho(t)P_k^\dagger - \rho(t))$$

This ensures the monotonic decrease in energy.

[1] Nature Physics 19, 1116 (2023), [2] PhysRevLett.131.160401 (2023).

Noise-Assisted Feedback-based quantum algorithm (NAFQA)

- Bringing the noise source of NISQ devices with additional noise bath such that the combined channel simulates the negative decay rates.



- The corresponding master equation is,

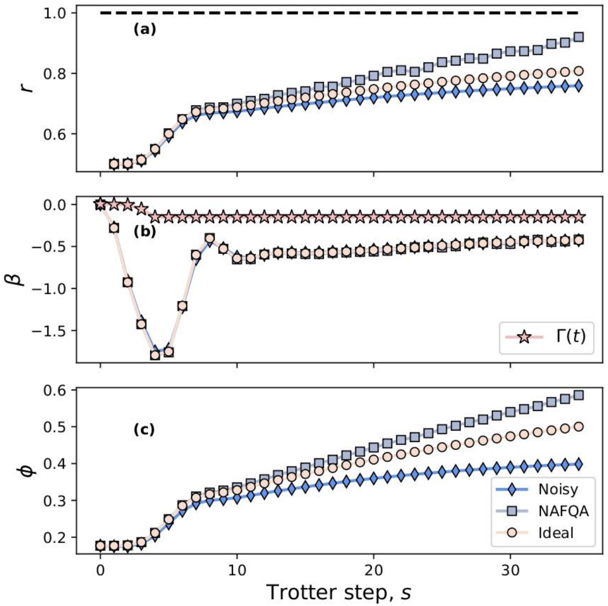
$$\frac{d\rho(t)}{dt} = -i[H(t),\rho(t)] + \mathcal{D}_{\rm int}[\rho(t)] + \mathcal{D}_{\rm eng}[\rho(t)]$$

Where $\mathcal{D}_{\rm eng}[\rho(t)] = \sum_{k\in\mathcal{K}} \nu_k(t)(P_k\rho(t)P_k^\dagger - \rho)$ and $\Gamma_k(t) = \lambda_k + \nu_k(t)$. → $\Gamma_k(t)$ coefficients are obtained using the feedback law.

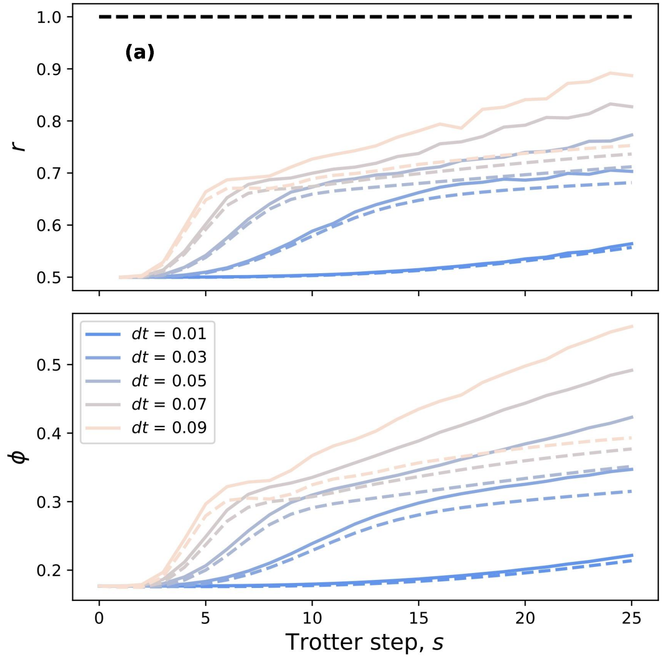
- The overhead cost is given by[1], $\mathcal{N}(T) = \exp\left[\sum_k \int_0^T (|\nu_k(t)| + \nu_k(t))\, dt\right]$.

[1] Hideaki Hakoshima, Yuichiro Matsuzaki, and Suguru Endo, Phys. Rev. A 103, 012611 (2021).

Results

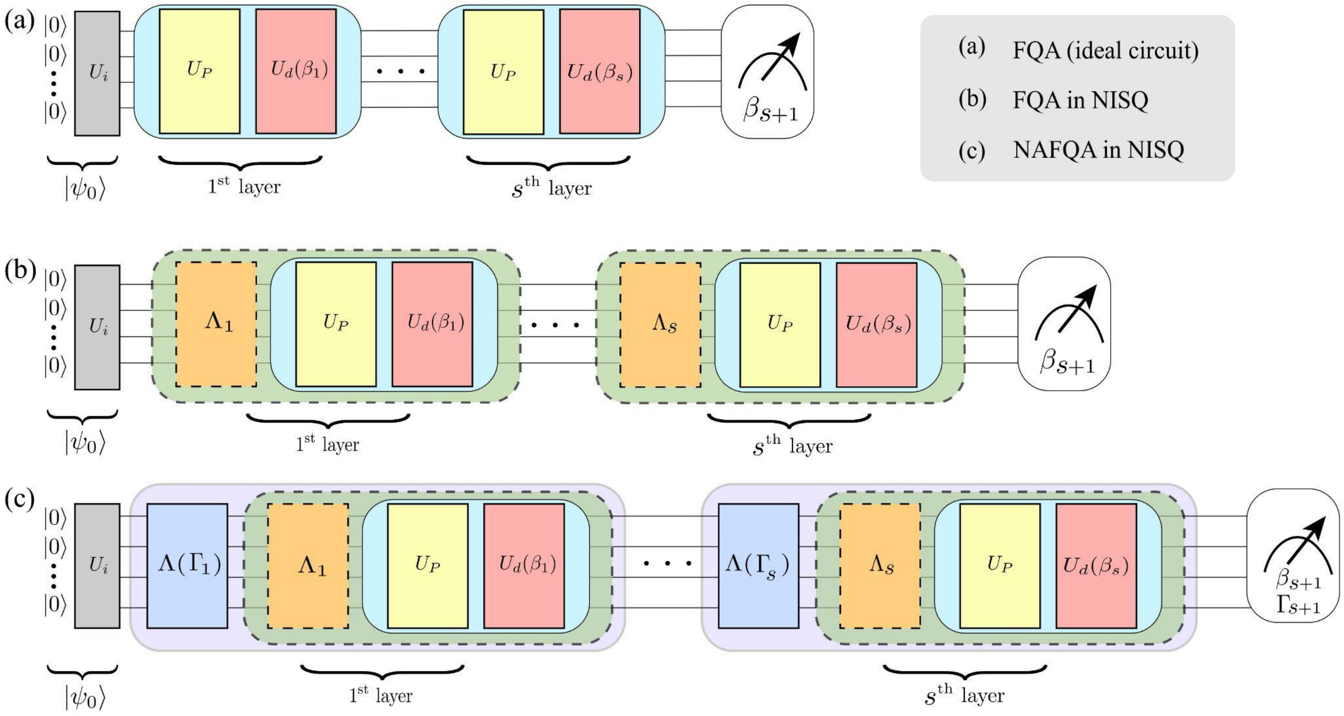


dt = 0.07



Success probability, $\phi = \langle \psi_{\mathrm{gs}} | \rho | \psi_{\mathrm{gs}} \rangle$

Overview



(a) FQA (ideal circuit)

(b) FQA in NISQ

(c) NAFQA in NISQ

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Thank you for your attention.

Happy to take any questions.

To know more about our work, please scan :

arXiv:2510.18984

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