DEPOLARIZATION:UNIVERSAL COPE WITH QUANTUM NOISE IN PARAMETRIC QUANTUM CIRCUITS

Xiaoyang Wang

Peking University

In collaboration with

Xu Feng, Lena Funcke, Tobias Hartung, Karl Jansen, Stefan Kühn, Georgios Polykratis, Paolo Stornati, Tom Weber

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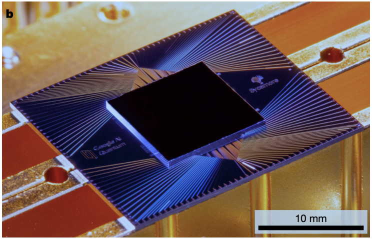
Outline

Quantum Computer in NISQ era

Sycamore:Google 53 bits superconducting quantum chip
(F. Arute et.al., Nature 2019)



JiuZhang: USTC 76 bits photonic quantum chip
(H-S. Zhong et.al., Science 2020)

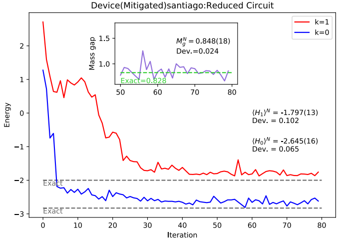
Noisy Intermediate-Scale Quantum(NISQ) device is NOISY.

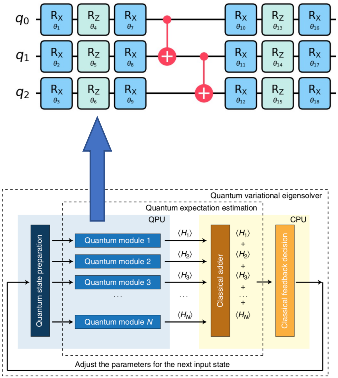
Quantum Noise in Variational Quantum Eigensolver(VQE)

$$H = \sum_{i\alpha} h^i_\alpha \, \sigma^i_\alpha + \sum_{ij\alpha\beta} h^{ij}_{\alpha\beta} \, \sigma^i_\alpha \sigma^j_\beta$$

Search the ground state of H according to variational method:

$$\min_{\theta_\alpha} \langle \psi_{\theta_\alpha} | \mathrm{H} | \psi_{\theta_\alpha} \rangle \gtrsim E_0$$



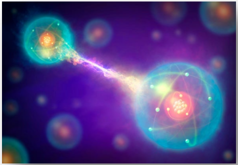


Mitigated:Bit-flip correction talk by Karl Jansen; Tue 29^{th} 7:30 AM and Georgios Polykratis; Tue 29^{th} 7:45 AM.

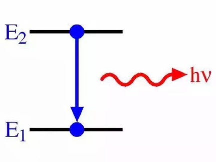
Reduced: Expressivity Analysis talk by Tobias Hartung; Wed 28^{th} 13:30 PM.

Quantum Noise

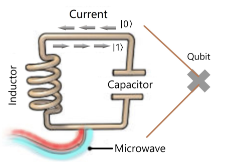
Entanglement



Spontaneous transition



Operation, Read-out error

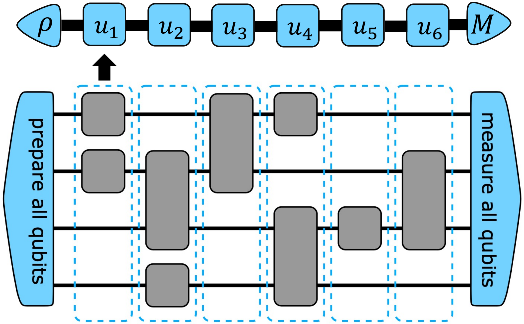


Quantum Channel & Kraus Operator:

$$\rho \to \mathcal{E}(\rho) = \sum_k E_k \rho E_k^\dagger$$

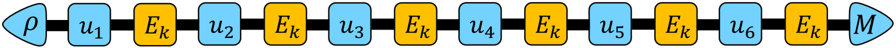
Quantum Noise between Circuit Layers

Circuit Layer



$$\rho \to \mathcal{E}(\rho) = \sum_k E_k \rho E_k^\dagger$$

Quantum Noise between Circuit Layers



Incoherent Noise:

$$E_k = \begin{cases} I, & 1-p \\ E_k, & p \end{cases}$$

$$\rho \to \mathcal{E}(\rho) = \sum_k E_k \rho E_k^\dagger$$

Outline

Depolarizing noise mitigation

Depolarizing noise is modeled by

$$\rho \to \mathcal{E}(\rho) = (1-\epsilon)\rho + \epsilon \frac{\mathbb{1}}{2^N} \tag{1}$$

True expectation value $\mathrm{Tr}(\rho O)$ can be obtained from noisy expectation value $\mathrm{Tr}(\rho' O)$

$$\mathrm{Tr}(\rho O) = \frac{\mathrm{Tr}(\rho' O) - \epsilon \mathrm{Tr}(O)/2^N}{1-\epsilon} \tag{2}$$

Assuming traceless Hamiltonian

$$H = \sum_{i\alpha} h^i_\alpha \sigma^i_\alpha + \sum_{ij\alpha\beta} h^{ij}_{\alpha\beta} \sigma^i_\alpha \sigma^j_\beta + \dots \tag{3}$$

The energy spectrum can be easily corrected by

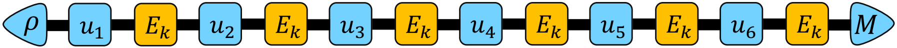
Correction formula

$$E'_n \longrightarrow E_n = \frac{E'_n}{1-\epsilon}$$

where ϵ can be obtained by measuring purity $\mathrm{Tr}(\mathcal{E}(\rho)^2)$

$$\epsilon = \frac{1 - \mathrm{Tr}(\mathcal{E}(\rho)^2)}{2(1-1/2^N)} + \mathcal{O}(\epsilon^2) \tag{4}$$

Depolarization



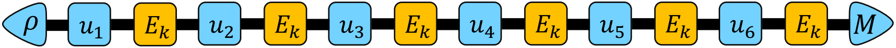
Incoherent Noise:

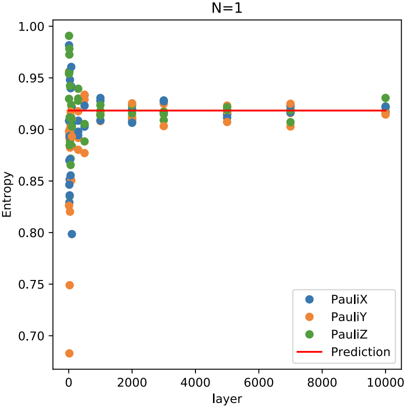
$$E_k = \begin{cases} I, & 1-p \\ X/Y/Z, & p \end{cases}$$

$$P(\text{ X} - \text{insertion number} = m) = \binom{6}{m} p^m (1-p)^{6-m}$$

If $p \to 0$, single insertion dominate.

Depolarization

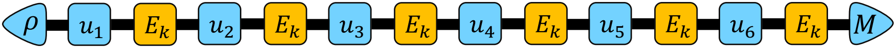




$P($ X − i … $l - p)^{6-m}$

If $p \to 0$

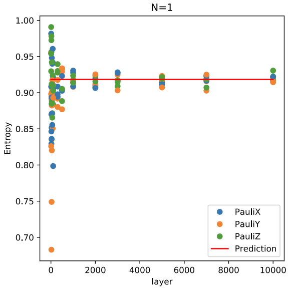
Depolarization



$$\mathcal{U}_i' = u_L \dots u_{i+1}\ v\ u_i \dots u_1$$
$$= \mathcal{U}\ \mathcal{D}_i^\dagger\ v\ \mathcal{D}_i$$

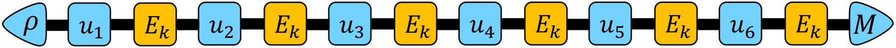
Random insertion ⇒ Random sampling

$$\lim_{N_s' \to \infty} \frac{1}{N_s'} \sum_{i=1}^{N_s'} \mathcal{D}_i^\dagger\ v\ \mathcal{D}_i \sigma \mathcal{D}_i^\dagger\ v^\dagger\ \mathcal{D}_i$$
$$= \int_{U(2^N)} U^\dagger v U \sigma U^\dagger v^\dagger U$$
$$= \alpha(N)\sigma + (1 - \alpha(N))\frac{\mathbb{1}}{2^N} \quad \Rightarrow S = S(N)$$



eg: $S(N = 1) = 0.918$

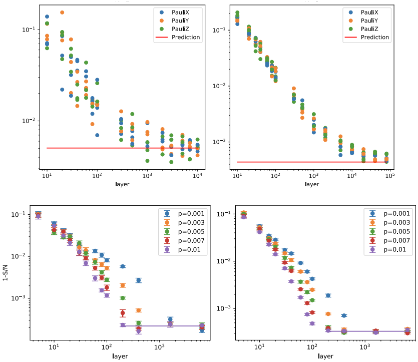
Depolarization



Work for

- Larger number of Qubits

- Multi-insertions



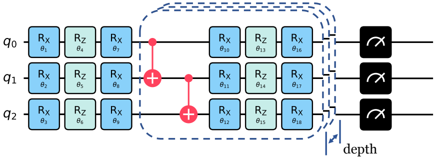
N=2 N=3

Outline

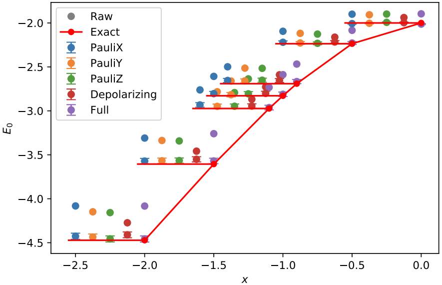
1. Quantum noise in Parametric quantum circuits
2. Depolarization of quantum noise
3. Experiments on VQE algorithm

Numerical simulation

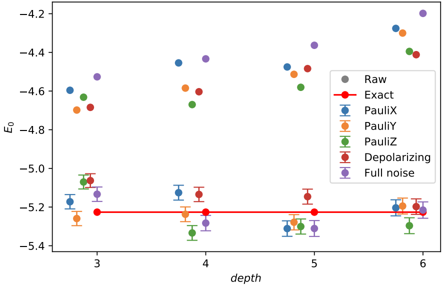
$$H = x \sum_{i=0}^{N-1} X_i X_{i+1} - \sum_{i=0}^{N-1} Z_i$$



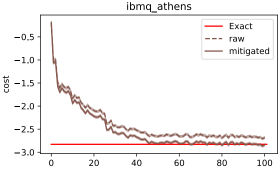
$N = 2$

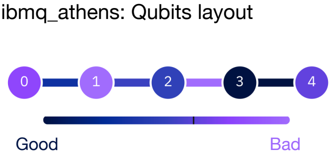


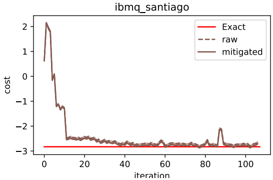
$N = 4$

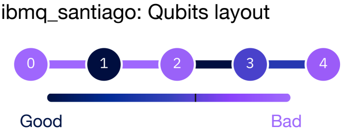


Hardware results









Conclusion and outlook

- Depolarizing noise can be mitigated in a simple way
- Parametric quantum circuit could scramble the incoherent quantum noise into depolarizing noise

- Unitary 2-design is a very large set. Can the convergence be faster?
- Relationship between Depolarization and quantum scrambling?

Thanks for listening

BACKUP-Fidelity in depth-experiments