Hybrid digital-analog simulation of many body dynamics using quantum superconducting processors

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In this work we provide an example of the mixed algorithmic-analog simulation approach by using residual couplings (crosstalks) between fixed frequency superconducting qubits connected by resonators. We illustrate our ideas with superconducting quantum processors of IBM Quantum Experience. Basically, the crosstalks are responsible for additional errors in digital quantum computation. In contrast, we here use them to simulate many body systems with Hamiltonians, which have interaction terms similar to these couplings. Within this approach, we avoid execution of two-qubit quantum gates, thus reducing error accumulation. Our results for the dynamics of 14-spin transverse-field Ising cluster under several Trotter steps are much more accurate than the results of a similar computation with standard CNOT gates on the same quantum processor. We stress that these results are obtained with the available quantum processor where crosstalks are intentionally suppressed, but in principle a hardware can be optimized to improve a quality of such a mixed quantum computation approach.

Superconducting fixed-frequency qubits and the origin of their residual interaction

The residual couplings between fixed frequency transmons are characterized with the Hamiltonian

$$H_{qubit-qubit} = H_{qubit1} + H_{qubit2} + \frac{\zeta}{4}ZZ, \qquad \zeta = -\frac{2J^2(\delta_1+\delta_2)}{(\Delta_{12}+\delta_1)(\delta_2-\Delta_{12})}.$$

The source of these couplings is a partial excitation of transmon qubits higher energy levels.

Trotterized evolution within mixed algorithmic-analog approach

We focus on the most straightforward example — simulation of spin clusters described by transverse-field Ising model with Hamiltonian

$$H = -\sum_j h_j\sigma_j^x - \sum_{<ij>} J_{ij}\sigma_i^z\sigma_j^z.$$

The Trotter decomposition for the Hamiltonian $H = H_A + H_B$ is

$$e^{-it(H_A+H_B)} \approx (e^{-iH_A\frac{t}{n}}e^{-iH_B\frac{t}{n}})^n.$$

For transverse field Ising Hamiltonian, an appropriate splitting of the full Hamiltonian is

$$H_A = -\sum_j h_j\sigma_j^x, \qquad H_B = -\sum_{<ij>} J_{ij}\sigma_i^z\sigma_j^z.$$

Toy model: two spins

For the case of two qubits of quantum processor our approach is able to correctly reproduce dynamics of transverse field Ising system for initial basis states (e.g. 00 and 11) much better compared to the standard digital approach based on CNOT gates. We used 6-step Trotter decomposition to study the dynamics of the two-qubit system, the number of Trotter steps was chosen through a comparison with exact solution of the Schrodinger equation. The comparison of experimental data with theory is made by taking into account in the model the presence of the surrounding qubits.

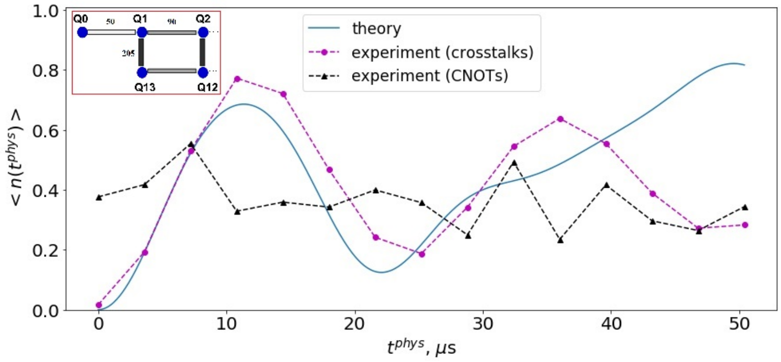

Figure 1: Dynamics of the mean excitation number for two-spin transverse field Ising cluster during the free evolution from the initial state 00. Physical time t^{phys} defines total time of algorithm execution within the mixed algorithmic-analog approach, which gives rise to ZZ interaction of qubits. Inset: A schematic view of a part of IBM QX4 quantum processor utilized for simulation of the two-spin system (Q0 and Q1 are used). CNOT gates can be applied directly between those qubits which are connected by lines. Qubits connected by these lines experience pairwise ZZ interaction of Ising type due to the presence of resonator they share. Numbers placed between qubits show corresponding values of coupling constants (in kilohertz).

Dynamics of 14-spin cluster

In order to test our idea further we use again 14-qubit processor IBM QX14. A full connectivity map of this processor is provided on the inset of the fig. . We exploited all qubits of this quantum chip to model a temporal evolution of a spin cluster forming a ladder. We again assumed homogeneous field — all parameters h_j are the same and equal to the averaged over the cluster $2J_{ij}$.

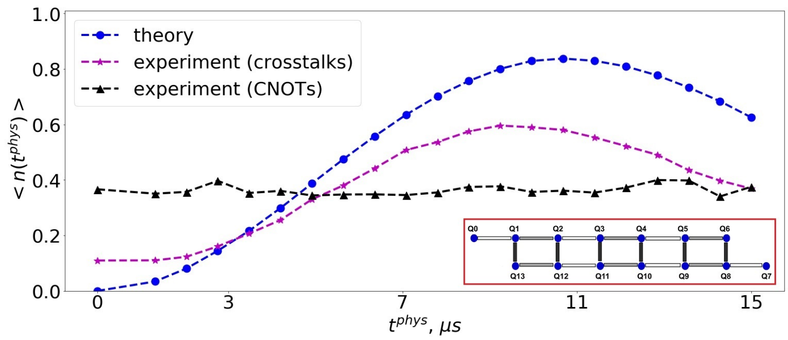

Figure 2: Dynamics of the mean excitation number for 14-spin transverse field Ising ladder during the free evolution from the initial state 00. Shown are the results of the same approximation level (3 Trotter steps) obtained theoretically (blue color), experimentally within the mixed algorithmic-analog approach (magenta color) and experimentally within the purely algorithmic approach (black color). Physical time t^{phys} defines total time of algorithm execution within the mixed algorithmic-analog approach, which gives rise to ZZ interaction of qubits. For both theoretical result and the result of experimental implementation of algorithmic approach, t^{phys} must be mapped on time $t = J_{ij}^{phys} t^{phys} / J_{ij}$ from the simulated model. Inset: A topology of IBM QX14 quantum processor, which determines the connectivity map of 14-qubit cluster we simulate.

These results illustrate that mixed algorithmic-analog computation schemes are attractive for NISQ devices. Particularly, the ideas presented above highlight a perspective of using mixed algorithmic-analog approaches for simulation of many-body systems. We believe that it is possible to manufacture quantum devices and tune their controlling parameters in such a way as to make investigation of more interesting regimes possible within the mixed approach.