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Exploring multi-programming for quantum algorithms

Siyuan Niu and Aida Todri-Sanial

LIRMM, University of Montpellier, CNRS, 34090, Montpellier, France

Today's quantum computing is performed on Noisy Intermediate-Scale Quantum (NISQ) hardware. The NISQ era allows for a limited number of qubits with several physical limitations. As NISQ devices have unavoidable noisy quantum operations, we can execute only small circuits on a quantum machine to get reliable results. But, this leads to the quantum hardware under-utilization issue. With the increase of hardware qubit number and the improvement of error rates, it becomes possible to execute multiple circuits on a quantum chip simultaneously, enhancing the throughput and the utilization of NISQ hardware. Thus, we address a timely problem on how to execute reliably multiple quantum programs on given quantum hardware. This is the first attempt to propose a complete multi-programming process flow for executing an optimal number of workloads in parallel, ensuring output fidelity by analyzing the hardware limitations.

The multi-programming mechanism can be particularly interesting for some specific quantum algorithms like VQE and VQLS, which can prepare several ansatz states simultaneously by executing them in parallel in one quantum processor. The proposed flow is also general enough to be applied to other quantum circuits requiring parallel sub-problem executions regardless of applications or algorithms.

Our main contributions can be listed as follows.

- 1). We introduce a **parallelism manager** that can optimally select the number of circuits being executed on the quantum hardware simultaneously.
- 2). We propose two different **qubit partition algorithms**, which are part of a hardware-aware multi-programming compiler. One is greedy and aims to provide the optimal partitions for multiple circuits. The other one is a heuristic that can give nearly optimal results and significantly reduce the time complexity.
- 3). We use the Simultaneous Randomized Benchmarking protocol to characterize the crosstalk properties and consider them in the qubit partition process to **avoid the crosstalk** effects during simultaneous executions.
- 4). We enhance the **mapping transition algorithm** included in the scheduler by reducing the number of inserted gates to make quantum circuits executable on real quantum devices.
- 5). We execute circuits of different sizes simultaneously on IBM quantum hardware and compare it with other methods found in the literature. To the best of our knowledge, this is the first attempt **to report less than 10% fidelity loss when executing simultaneously four independent circuits** on a quantum chip. We also **apply multi-programming to the VQE algorithm** to show its potential interest.

We execute four different quantum circuits on IBM Q 65 Manhattan and obtain circuit fidelity improvement by 51.8% and the reduction of the additional gate by 53.9 % compared to state of the art. We also investigate our multi-programming approach on the VQE algorithm and perform experiments on IBM Q 65 Manhattan to estimate deuteron's ground state energy. We execute four optimizations (eight circuits) simultaneously with an error rate of 7% compared to the theory result. The number of required circuits is reduced by eight times compared to the Pauli grouping measurement method and 16 times compared to the naive measurement approach. It demonstrates the possibility of enabling a multi-programming mechanism for quantum algorithms.