Full State Quantum Circuit Simulation by Using Lossy Data Compression

Extended Abstract

Xin-Chuan Wu
Department of Computer Science,
University of Chicago
Argonne National Laboratory
xinchuan@uchicago.edu

Sheng Di
Argonne National Laboratory
sdi1@anl.gov

Franck Cappello
University of Illinois
Urbana-Champaign
Argonne National Laboratory
cappello@anl.gov

Hal Finkel
Argonne National Laboratory,
Leadership Computing Facility
hfinkel@anl.gov

Yuri Alexeev
Argonne National Laboratory,
Leadership Computing Facility
yuri@alcf.anl.gov

Frederic T. Chong
Department of Computer Science,
University of Chicago
Argonne National Laboratory
chong@cs.uchicago.edu

ABSTRACT

In order to evaluate, validate, and refine the design of a new quantum algorithm or a quantum computer, researchers and developers need methods to assess their correctness and fidelity. This requires the capabilities of simulation for full quantum state amplitudes. However, the number of quantum state amplitudes increases exponentially with the number of qubits, leading to the exponential growth of the memory requirement. In this work, we present our technique to simulate more qubits than previously reported by using lossy data compression. Our empirical data suggests that we can simulate full state quantum circuits up to 63 qubits with 0.8 petabytes memory.

KEYWORDS

Quantum Computing, Simulation of Quantum Circuits, Lossy Data Compression, OpenMP, MPI

1 INTRODUCTION

Using classical computing systems to simulate quantum computers is important for better understanding the operations and behaviors of quantum systems. Such simulations allow researchers to evaluate the complexity of new quantum algorithms and validate the design of quantum circuits. Since the scale of the simulation determines the scale of the quantum algorithms we can validate, it is a fundamental goal to have the capability of simulating larger quantum systems. To describe a quantum system, we use complex double precision amplitudes to represent the state of the quantum system. Given n quantum bits (qubits), we need 2^n amplitudes to describe the quantum system. Since the number of quantum state amplitudes grows exponentially with the number of qubits in the system, the size of the quantum computing simulation is limited by the memory capacity of the classical system. For example, to store the full quantum state, the memory requirement is 0.5 petabytes for a 45-qubit system and 1 petabyte for a 46-qubit system. Thus, using the limited memory capacity to simulate more qubits is a crucial research problem.

SC18, Dallas, TX, USA
2018. 978-x-xxxx-xxxx-x/YY/MM…$15.00
DOI: 10.1145/nnnnnnn.nnnnnnn

Table 1: Examples of supercomputers.

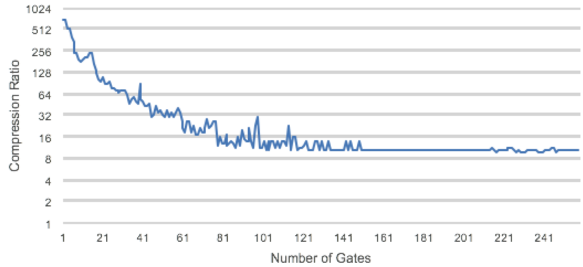
System	Memory (PB)	Max Qubits
TACC Stampede	0.192	43
Titan	0.71	45
Theta	0.8	45
K computer	1.4	46
Exascale	4-10	48-49

Table 1 shows examples of several supercomputers in the TOP500 list. 46-qubit full state simulation can be achieved with 1.4 petabytes, and we will have 48-49 qubits simulation capabilities when we have exascale supercomputers.

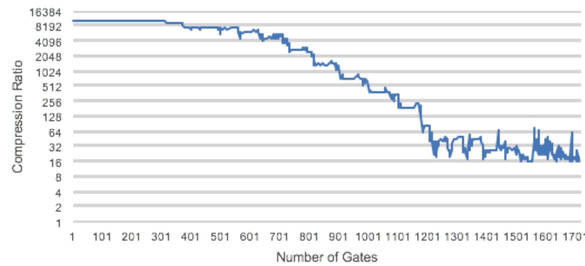
In this work, we incorporate HPC lossy data compression techniques to Intel-QS [3]. Intel-QS is a distributed high performance quantum circuits simulator using message-passing-interface (MPI) protocols to store and manipulate the quantum state. Since Intel-QS uses full state amplitude-vector update technique to run the simulation, Intel-QS is capable of high depth quantum circuits simulation.

By using data compression to reduce the memory requirement of storing the full quantum state, we are able to simulate larger quantum systems within the same memory capacity. The scalability of this approach is determined by the quantum state vector compression ratio. Compared to lossless compression, lossy compression algorithms achieve more significant compression ratios in general. Thus, we employ the the SZ lossy compressor [1, 4, 5] to our quantum circuits simulation framework.

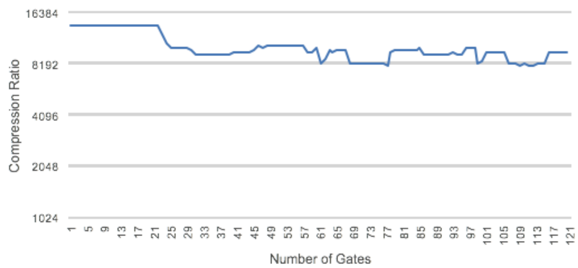
The full quantum state vector is divided into several blocks. Each block is compressed and stored on memory. In order to maintain the simulation performance, we do not swap any state vector block to hard disks. To apply a quantum gate during the simulation, each block is decompressed to perform the computation, and then compressed again after the computation. So each block is compressed and decompressed repeatedly.



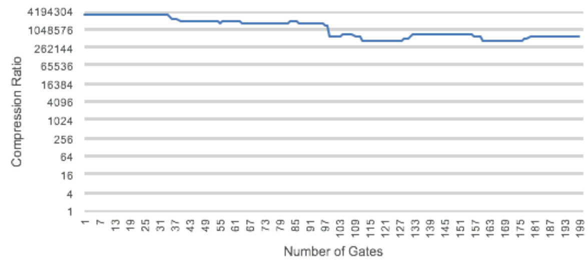
(a) QAOA - Compression Ratio.



(b) QFT - Compression Ratio..



(c) Grover (17q) - Compression Ratio.



(d) Grover (30q) - Compression Ratio.

Figure 1: Compression ratio results.

Lossy compression techniques introduce undesired compression errors into the quantum state, and the operations of compression and decompression cause performance overhead in the simulation. We must control the error bound to maintain the state fidelity [2], as well as parallelize the compression, decompression, and computation to minimize the performance overhead.

2 RESULTS

We develop and perform the full state quantum circuits simulation on Argonne Theta supercomputer. We evaluate our approach with two quantum algorithms, (1) Quantum approximate optimization algorithm (QAOA), (2) Quantum Fourier Transform (QFT), and (3) Grover's search algorithm. For Grover's search, we run the experiments with 17 qubits and 30 qubits. QAOA is one of the most popular quantum applications, QFT is kernel function of several quantum algorithms, and Grover's search algorithm is one of the most famous quantum algorithms. We assess the simulation quality by the state fidelity, the compression ratio, and the simulation time. Fidelity is a measure of the similarity of two quantum states [2]. If the fidelity value is 1, then the two quantum states are identical. The compression ratio determines how many extra qubits we can simulate.

Figure 1 shows the simulation results of all benchmarks. For QAOA (Figure 1a), the compression ratio is above 8, and the final state fidelity are 92.5%, so this simulation result is acceptable even with the presence of compression errors. For QFT (Figure 1b), the compression ratio is above 16, and the fidelity is 99.9%.

In the simulation of Grover's search algorithm (Figure 1c, 1d), most of the state amplitudes are 0's during the simulation. Such state vectors allow the SZ compressor to perform higher compression ratios. For Grover's search with 30 qubits, the compression ratios during the simulation are always higher than 445144, meaning that we can add 18 qubits to our simulation. We achieve 99.9% fidelity for both Grover's search algorithm simulations. The simulation time is 19x in this case.

The supercomputer, Theta, is able to simulate a 45-qubit quantum system with 0.8 petabytes memory. Our experimental results suggest that we are able to compress the state and get 18 more qubits for Grover's search algorithms simulation. Thus, our ongoing work is to simulate 63-qubit Grover's search algorithms on Theta.

3 CONCLUSION

The simulation of quantum circuits is an important topic to advance the quantum computing research. The capability of the simulation is limited by the memory capacity of the classical computer. We present a full state quantum circuits simulation technique to simulate more qubits than previously reported by using lossy data compression. Since we know most of the quantum state amplitudes in different quantum algorithms are close to 0, similar to the benchmarks we showed in this paper, we expect our technique can be widely used for simulating various quantum algorithms. Our approach compress the state vector to reduce the memory requirement, so the we can simulate a larger quantum system with the same memory capacity. Lossy data compression introduces errors to the simulation. This error could potentially model the presence of the physical noise in the quantum circuits. In the future work, we plan to run 63-qubit simulation on Theta, analyze the effect of compression errors and relationships to real physical noise, integrate our technique with other approximate simulation techniques, and evaluate different compression algorithms for quantum state amplitudes.

4 ACKNOWLEDGMENTS

This research used resources of the Argonne Leadership Computing Facility, which is a DOE Office of Science User Facility supported under Contract DE-AC02-06CH11357. This research was supported by the Exascale Computing Project (ECP), Project Number: 17-SC-20-SC, a collaborative effort of two DOE organizations - the Office of Science and the National Nuclear Security Administration, responsible for the planning and preparation of a capable exascale ecosystem, including software, applications, hardware, advanced system engineering and early testbed platforms, to support the nation's exascale computing imperative. The material was supported by the U.S. Department of Energy, Office of Science, and supported by the National Science Foundation under Grant No. 1619253. This work is funded in part by EPiQC, an NSF Expedition in Computing, under grant CCF-1730449. This work is also funded in part by NSF PHY-1818914 and a research gift from Intel.

REFERENCES

[1] Sheng Di and Franck Cappello. 2016. Fast error-bounded lossy HPC data compression with SZ. In *2016 IEEE International Parallel and Distributed Processing Symposium (IPDPS)*. IEEE, 730–739.

[2] Michael A Nielsen and Isaac Chuang. 2002. Quantum computation and quantum information. (2002).

[3] Mikhail Smelyanskiy, Nicolas PD Sawaya, and Alán Aspuru-Guzik. 2016. qHiPSTER: the quantum high performance software testing environment. *arXiv preprint arXiv:1601.07195* (2016).

[4] Dingwen Tao, Sheng Di, Zizhong Chen, and Franck Cappello. 2017. Significantly improving lossy compression for scientific data sets based on multidimensional prediction and error-controlled quantization. In *Parallel and Distributed Processing Symposium (IPDPS), 2017 IEEE International*. IEEE, 1129–1139.

[5] Dingwen Tao Zizhong Chen Franck Cappello Xin Liang, Sheng Di. 2018. Efficient Transformation Scheme for Lossy Data Compression with Point-wise Relative Error Bound. In *CLUSTER*. IEEE.