R&D Theme

Development of quantum error correction schemes and analysis of performance

Progress until FY2022

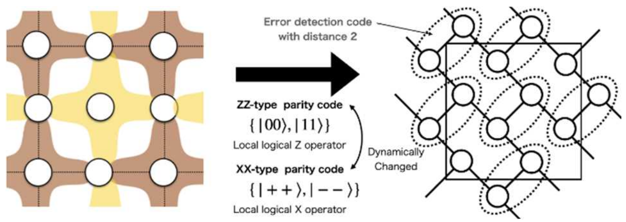
1. Outline of the project

In order to relax hardware requirements and improve the performance of fault-tolerant quantum computers (FTQC), it is essential to add new options at each layer, not just a combination of existing schemes. Under this theme, we will pioneer new schemes for quantum error correction and fault-tolerant quantum computation architectures through various approaches.

2. Outcome so far

1) New quantum error correction scheme to relax physical constraints

By reducing the connectivity of the qubits, the frequency assignment of each superconducting qubit becomes easier, and high-precision quantum operations can be achieved. In this research, we proposed a new method to perform quantum error correction by connecting each qubit to only three adjacent qubits by combining a small error detection code. Numerical simulations confirmed that the proposed method is also highly error tolerant because of the additional error detection functionality. Using the knowledge obtained here, we aim to improve the error tolerance of the color codes, which has a good property for transversal logical operations, providing a new alternative to surface codes.

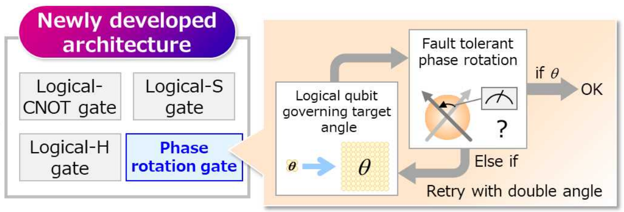


2) Bridging the gap between NISQ and FTQC

There is a gap of several orders of magnitude in the number of qubits that can be meaningfully utilized or necessarily required for NISQ (Noisy Intermediate-Scale Quantum computer) (around 100 qubits) and FTQC (around 1 million qubits). In this research, we have been working to fill those gaps.

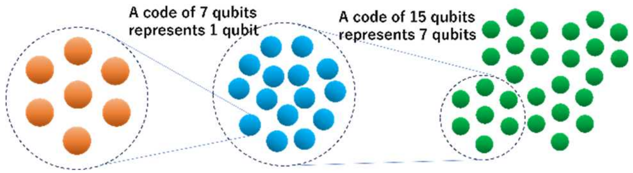
As a software approach, we have developed a framework for applying quantum error mitigation method conventionally applied for NISQ to logical qubits encoded in error-correcting codes and have shown that sufficiently high computational accuracy can be achieved even with small size codes. Then, the number of physical qubits required can be reduced by as much as 80% in the area where the proposed method works most effectively [PRX Quantum, 2022].

As an architectural approach, we developed a new concept, early-FTQC architecture. There, only Clifford operations, which are relatively easy to be protected, are protected by error correction, and non-Clifford operations are performed by generating special ancilla states with high accuracy via error detection. It was shown that even with an error probability of 10^4 and 10,000 physical qubits, a quantum volume of 2^{64} can be achieved (QV=2^{37} is the limit in NISQ). This indicates that deeper quantum computation, which is difficult to simulate even with a classical supercomputer, can be achieved even on a 10,000-qubit scale.



3) Ultimate efficiency of FTQC in the large-scale limit

The FTQC fights against errors by using redundant qubits and carrying out extra computational steps. Seeking the minimum of these overheads in space and time is one of the fundamental questions on FTQC. We have proposed a new architecture based on concatenation of simple error correcting codes with growing sizes and showed that its space and time overheads are smaller than any other known architectures.



3. Future plans

We seek to provide new options for cross-layer co-design by not only improving surface codes but also exploring new quantum error correction codes such as topological color codes and more general quantum LDPC codes. For the application of quantum error mitigation to FTQC, we aim to further reduce the overhead by investigating application of other NISQ-aware techniques. For early-FTQC architecture, we will start research to find feasible and quantum advantageous applications with the near-future goal of 10,000 qubit scale.