Efficient Accelerators for Emulating Quantum Systems

Name: Vu Tuan Hai

Laboratory’ｓ name: Computing Architecture

Supervisor’ｓ name: Yasuhiko Nakashima

Abstract: : As quantum computing advances toward the Fault - Tolerant Quantum Computing (FTQC) era, classical simulation and emulation of quantum systems remain crucial for quantum algorithm development, verification, and optimization. However, current software - based simulators running on CPUs face limitations in scalability and energy efficiency, especially as the number of qubits increases. To address these challenges, we introduce novel architectures and implementation strategies for quantum simulation based on three approaches: density matrix (QEA), wave function (FQsun), and stabilizer formalism (Qimax). QEA and FQsun are implemented on the ZCU102 FPGA using four innovative techniques: efficient memory organization, a configurable Quantum Gate Unit, optimal work scheduling, and support for multiple numeric precisions. Qimax leverages GPUs with a new parallel algorithm that enhances the existing serial extended stabilizer formalism, utilizing an encoder–decoder architecture and tensor computation. Each simulation approach targets different classes of quantum circuits and compensates for the weaknesses of the others. Extensive comparisons on standard benchmarks against state-of-the-art simulators and emulators - including Qiskit, Pennylane, ProjectQ, and NVIDIA cuQuantum - demonstrate that the proposed accelerators provide a compelling balance of energy efficiency, performance, precision, and scalability. QEA, FQsun, and Qimax represent promising candidates for quantum simulation in the green computing era. Beyond fundamental architectural contributions, this work also explores practical applications deployed on the simulators/emulators, including quantum battery optimization, a fast parameter - shift rule, and hybrid quantum–classical image compression.