Pseudo-Qubit Quantum Circuit Modelling: Enabling Large Scale Application Simulations

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Abstract

This abstract presents an innovative quantum circuit modelling approach, able to open large-scale simulations on commercial computers, and it shows as example an application for Quantum Machine Learning problems.
The simulation of a quantum circuit on classical computers is a challenging task due to the very peculiar physical properties occurring in quantum systems. The complex coefficient linear model typically used in simulation ([1]) is conceptually simple, but it grows exponentially with the size of a qubit register (qureg), and, consequently, it limits the general-purpose quantum circuits size to 30-35 qubits max on commercial computers ([2] and [3]).
To overcome this limitation, an innovative approach is proposed in this paper. The idea is to model a qureg through its elementary qubits instead of the states, and to effectively capture the cross-qubit entanglement relationships, when present. Based on that, a qureg state can be modelled as a linear combination of separable "pseudo" states, which are directly built from elementary qubit ones, embedding in them all the entanglement information. For this reason, the entities used in the model are called "pseudo-qubits", due to their conceptual deviation from the "standard" single state qubit physical model. This pseudo-qubit model supports, with proper internal terms manipulation, all 1-qubit single and 2-qubit controlled transformations in any layout (superset of universal gates), and it provides exact and general-purpose applicability to quantum circuits.
Compared with state-based models where the whole state is instantiated already at state preparation stage, this model makes a progressive use of the parameter space, encompassed with the transformation applications. This key difference has huge impacts in the simulation capabilities, allowing the modelling of very large quantum circuits, under a certain number of transformations limit, opening to research problems not accessible until now.
The pseudo-qubit model is in principle applicable to any circuit, and for its validation, various types of tests are ongoing, particularly in the area of on Quantum Machine Learning (QML) applications. Specifically, the model is being used for Earth Observation image classification problems using from 10 to 40 qubits, implementing different algorithms, in order to support cross validation of the new approach through toy and "realistic" examples, and to perform comparative analysis and discussion of QML enhanced models versus the traditional one.
the quantum advantage assessment on QML enhanced models vs. their "classical" ML counterpart.
The results collected so far are successful and promising for a general validity of the pseudo-qubit model, and its capability of outperforming state-based models in the simulation of large quantum problems (not only QML related) on commercial computers.

References

[1] Quantum Computing and Quantum Information, Nielsen and Chuang, 2017 §1.2 and §1.3
[2] Exploiting GPU-based Parallelism for Quantum Computer Simulation A Survey, S. Heng, Y. Han
[3] Available IBM Quantum simulators - IBM Quantum Documentation, https://docs.quantum.ibm.com/verify/cloud-based-simulators