Project progress (mid-term)

Reminder of project objectives and summary of the project progress

The last years have seen significant advances in the field of quantum technologies, consolidating the development of basic requirements for quantum computation. Protecting the quantum computation from noise and decoherence has become more topical than ever, challenging and bringing quantum error correction (QEC) fairly close to the integration into practical quantum computers. To make such an integration viable, the EQUIP project aims at (1) providing radically new solutions to fault tolerant quantum computation, covering both intermediate and large-scale quantum systems, and (2) bridging the critical gap between algorithmic solutions and latency-power-scalability constrained hardware designs.

To achieve these goals, the project brings together interdisciplinary expertise, extending from the computer science foundations of quantum error correction and fault-tolerant computation, to algorithmic aspects, computer architectures, and hardware designs.

First, the project aims at developing optimised low-qubit overhead solutions, suited but not restricted to intermediate scale quantum systems, including application-aware and software-based error mitigation techniques, and flag error correction protocols.

During the first half of the project, following an analysis of existing error-aware compilation techniques, the consortium developed a platform for unbiased comparison, ensuring fair conditions by utilizing the same quantum device, calibration, and environmental settings to evaluate a wide range of quantum error mitigation (QEM) solutions. The objective was to analyse their performance and draw preliminary conclusions. This first prototype serves a dual purpose. It not only facilitates the integration of novel error-aware compilation techniques from the project but also enables automatic comparisons with state-of-the-art methodologies. The framework is currently operational on selected IBM backends, but we have plans to extend its compatibility to other vendors and IBM's diverse architectures. The platform also includes performance metrics such as success rates for deterministic and non-deterministic circuits and circuit cost. This framework tries to align QEM techniques with specific applications. Initial findings reveal no clear winner for all scenarios, when the QEM techniques are evaluated, emphasizing the platform's role in refining these matches. The platform will be useful for the NISQ (Noisy Intermediate-Scale Quantum) user community. They stand to benefit significantly by gaining access to multiple error-aware techniques, thereby enhancing the success rates of the executed circuits.

Further, the consortium developed a novel error mitigation technique that allows to reduce the noise in syndrome measurements via a calibration experiment and a post-processing step. For the investigated instances, our method produces comparable results with state-of-the-art approaches like readout-error mitigation, with significantly lower complexity and resource requirements. In particular, it only needs a single calibration experiment, which is beneficial in practice. We also demonstrated the approach is applicable to low qubit overhead QEC with flag qubits, contributing towards our goal to investigate and develop new strategies to implement flag-based QEC circuits on resource-constrained quantum devices.

Project partners also established a baseline of tools required for automating the compilation of fault-tolerant quantum circuits and for the detection and correction of errors within the circuits. To this end, we employed classical heuristics as well as machine learning. Our main results include the development of state-of-the art compilers and neural network decoders. Although preliminary, our results are very promising with respect to achievable fault-tolerance and scalability. We achieved our original goals, and future work will focus on increasing robustness and performance of our tools.

Second, for large-scale systems, the project aims at developing thoroughly new approaches to accurate and hardware friendly decoding of quantum low-density parity-check (LDPC) codes, and explores pioneering approaches relying on quantum polar codes.

During the first half of the project, the consortium introduced innovative post-processing techniques for iterative message-passing decoders, able to handle the degeneracy of quantum LDPC codes with low computational complexity. The analysis carried out in the project, along with the devised architectural optimisations and the derived hardware implementations, showed that our solutions can meet latency constraints of a wide range of quantum technologies, while providing state of the art error-correction performance, with hardware-accurate, finite-precision arithmetic.

Alternative decoding solutions based on neural-networks have also been investigated, including neural belief propagation and graph neural networks. The outcomes of our work pave the way for flexible and scalable decoders in the near future. Further, the consortium also looked into two new constructions of quantum LDPC codes. Moderate length codes from the constructed families, that could be applied in quantum computers or memories available in the not too far future, exhibit a remarkable performance under belief propagation decoding, beating other codes from different families with similar parameters.

In a parallel line of work, the consortium investigated a new approach to fault-tolerant quantum computation relying on quantum polar codes. We proposed a two-qubit Pauli measurement procedure for the preparation of quantum polar codes and demonstrated their potential for fault-tolerant quantum computation. In particular, it was shown that logical error rates currently estimated to be required for large-scale fault-tolerant quantum computation may be achieved by rather short codes, and for physical error rates in a practically interesting range.

Significant results

RESULT 1: UPV and UCM collaborated to develop a hardware platform to evaluate various software-based error mitigation techniques. This platform offers a versatile environment for testing and comparing different error mitigation strategies, as there are no analytical processes that allow to predict the success rate of the quantum algorithms in the NISQ devices for different compilation techniques. This first prototype serves a dual purpose. It not only facilitates the integration of novel error-aware compilation techniques from the project but also enables automatic comparisons with state-of-the-art methodologies. The framework is currently operational on selected IBM backends, but we have plans to extend its compatibility to other vendors and IBM's diverse architectures. The platform includes performance metrics such as success rates for deterministic and non-deterministic circuits and circuit cost. In the coming months, we anticipate making the QEM platform accessible through GitHub. This repository will serve as a valuable resource for researchers and practitioners interested in error mitigation techniques in quantum computing.

RESULT 2: DLR-SC proposed a new error mitigation technique, based on a method that allows calibration of syndrome measurements in a single experiment. The scientific software written in this context will be published when it is fully integrated in the compilation framework. However, the software and the produced data can be obtained from the corresponding author for now.

RESULT 3: AAU employed classical heuristics as well as machine learning to establish a baseline of tools required for automating the compilation of fault-tolerant quantum circuits and for the detection and correction of errors within the circuits. Main results include the development of state-of-the art compilers and neural network decoders. Although preliminary, our results are very promising with respect to achievable fault-tolerance and scalability.

RESULT 4: CEA and UCM introduced innovative decoding algorithms and post-processing techniques to handle the degeneracy of quantum LDPC codes with low computational complexity. The outcomes of our work pave the way for flexible and scalable decoders in the near future. In addition, in collaboration with the University of Arizona, UCM also proposed a hardware-friendly decoding algorithm to effectively deal with noisy syndromes, and derived efficient hardware implementations.

RESULT 5: CEA, UCM, and UPV introduced the check-agnosia decoding for quantum LDPC codes, a new post-processing method improving on the state of the art from a hardware-oriented viewpoint. The analysis carried out in our work, along with the derived architectural optimisations and hardware implementation results, showed that our solution can meet latency constraints of a wide range of quantum technologies, while providing state of the art error-correction performance, with hardware-accurate, finite-precision arithmetic. An FPGA-based platform has also been designed and implemented, providing the ability to accelerate the hardware implementation of quantum LDPC decoders.

RESULT 6: DLR-KN devised a new family of quantum CSS LDPC codes. These codes are constructed as the tensor product of smaller CSS codes (component codes). A particular code from this family which is obtained as the 3-fold product of single parity-check codes, and has parameters [[512, 174, 8]] has been shown to outperform codes from other families with similar parameters under low-complexity belief-propagation decoding. Another significant outcome has been the fact that toric codes can be close to optimally decoded using neural belief propagation decoding, with a rather low-complexity.

RESULT 7: CEA proposed a two-qubit Pauli measurement procedure for the preparation of quantum polar codes and demonstrated their potential for fault-tolerant quantum computation. In particular, it was shown that a polar code of length 256 qubits achieves logical error rates around 1E−11 and 1E−15, for physical error rates of 1E−3 and 3E−4, respectively. Thus, logical error rates currently estimated to be required for large-scale fault-tolerant quantum computation may be achieved by a rather short code and for physical error rates in a practically interesting range.