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Quantum Computing Reliability: Problems, Tools, and Potential Solutions

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Duration: half a day.

I. Short overview

Quantum computing is a new computational paradigm, expected to revolutionize the computing field in the next few years. Qubits, the atomic units of a quantum circuit, exploit the quantum physics properties to increase the parallelism and speed of computation. Unfortunately, qubits are both intrinsically noisy and highly susceptible to external sources of faults, such as ionizing radiation. The latest discoveries highlight a much higher radiation sensitivity of qubits than traditional transistors and identify a much more complex fault model than bit-flip. The observed error rate is so high that researchers are questioning the large-scale adoption of quantum computers. The reliability and dependability community is asked to act to find innovative solutions to improve the reliability of quantum applications. This tutorial aims at providing the DSN community with the tools to do so and to train the attendees on *quantum* fault injection.

This tutorial provides the audience with all information and background needed to understand quantum computing basics, to design a quantum circuit, to simulate a quantum execution, and to understand the obtained result. We treat quantum computing as an operative computing architecture, focusing on its utilization rather than on its physical and technological implementation. Then, we will present the available correction codes and the open challenges that the reliability community is asked to address. The tutorial considers both the intrinsic noise, that has a predictable and incremental effect, and radiation-induced transient faults, that are stochastic and modify the qubit in an unpredictable way.

After completing the overview of available technology and of the open challenges, this tutorial presents, with an hands-on session that include examples of utilization, the Quantum Fault Injector (QuFI) framework. QuFI is an easy-to-use fault injector able to identify the quantum circuits sensitivity to faults and the probability for a fault in a qubit to propagate to the output. Based on the latest studies and radiation experiments performed on real quantum machines, QuFI models the transient faults in a qubit as a phase shift with a parametrized magnitude. QuFI is highly flexible, as it can be used on both quantum circuit simulators and real quantum machines. As we show, this framework allows to choose any quantum algorithm to be analyzed, and it is possible to identify the faults and qubits that are more likely to impact its output. The tutorial will have the following structure:

- **Introduction** (10 min) by Paolo Rech: Welcome, description of the tutorial schedule, and speakers presentation.
- **Quantum Computing essentials** (20 min) by Qiang Guan: what is Quantum Computing, and what are the current perspectives and constraints? We will explain the basic properties of quantum computing are superposition, entanglement, and interference.
- **Quantum Noise Mitigation** (30 min) by Devesh Tiwari: the existing quantum computers - aka Noisy Intermediate-Scale Quantum (NISQ) machines are intrinsically highly error-prone and produce output that can be far from the correct output of the quantum algorithms. We will primarily discuss the mitigation techniques for the noisy output and the role of quantum system software in making erroneous quantum devices more usable and meaningful.
- **Radiation-Induced Quantum Transient Faults** (30 min) by Paolo Rech: the reliability issue posed by radiation impacts on the quantum circuit output will be detailed. This topic will be discussed in a bottom-up approach: from the impact of particles in the quantum device structure to the qubit status modification and the possible effect on the quantum application correctness.
- **QuFi presentation and description** (30 min) by Edoardo Giusto: The quantum fault injector open source framework will be presented. The main characteristics and interoperability features will be highlighted, as well as the operating logic of the software.
- **QuFI hands on:** (45 min) by Emanuele Dri and Betis Baheri: installation of the tool from the online repository; example of use on well known quantum algorithms at participant's will; analysis of the impact of injected faults for the chosen circuit.
- **Conclusions and future perspectives** (15 min) by Paolo Rech: a wrap-up of the issue, available solutions, and future challenges will be presented. A particular focus will be given to the open questions and research possibilities in the field of quantum computing reliability.

II. Objectives

The goal of this tutorial is to trigger the interest of the DSN community in quantum computing reliability. We aim at easing the transition to quantum circuit and quantum technology

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and to provide the tools to start being productive in the understanding and mitigation of quantum errors.

The main objectives of this tutorials are:

- Give a clear and deep understanding of the potentials of quantum computing and of the related reliability issues.
- Provide an easy-to-follow training on quantum algorithm design, quantum circuit implementation and simulation.
- Provide a *hands-on* lesson on the Quantum Fault Injector, with easy-to-reproduce examples.

III. Supporting Materials and Target Audience

Slides and link to repository, simple case study to illustrate the capabilities of the tool.

The tutorial is aimed for anyone interested in understanding the potential and the challenges of quantum computing. No previous experience or knowledge about quantum computing is required. Anyone excited about reliability, error detection & correction, and novel technology is welcome.

IV. Resume of presenters

Edoardo Giusto Edoardo Giusto, PhD (Member IEEE) obtained the B.S. degree in 2015, M.S. degree in 2017, and PhD degree in 2021 from Politecnico di Torino. He is currently a PostDoctoral Research Assistant at the Department of Control and Computer Engineering at Politecnico di Torino. His research interests include Internet of Things and Quantum Computing. He is a Lecturer for the 2nd level Master Course *Quantum Communication and Computing* organized by TIM S.p.A. and Politecnico di Torino.

Emanuele Dri is a Ph.D. student in Quantum Computing at Politecnico di Torino, Italy, since 2021. He received his master's degree in Data Science and Engineering at Politecnico in 2021, with a thesis on Machine Learning for text classification. Recently, his research focused on the reliability of quantum circuits with respect to transient faults and on developing and adapting quantum algorithms for the finance sector, helping in bridging the gap between academic research and industry.

Devesh Tiwari is educator and researcher at Northeastern University where he directs the Goodwill Computing Lab. His group innovates new solutions to make large-scale classical computing systems and quantum computing systems more efficient, reliable, and cost-effective. Before joining the Northeastern faculty, Devesh was a staff scientist at the United States Department of Energy (DOE) Oak Ridge National Laboratory. Devesh was recognized with multiple awards including the DSN Dependability Rising Star Award, the NSF CAREER Award, and the Facebook Faculty Research Award. Devesh's research group has lowered the barrier to entry and accelerated the R&D efforts in multiple emerging computer systems areas including HPC, quantum system software, serverless computing, and AI-driven data center optimizations, via open-sourcing novel software artifacts and datasets. He was recognized with the TPDS Editorial Excellence Award for his exceptional contributions to the TPDS journal as an editor, and as the Professor of Year at Northeastern University IEEE Student Chapter.

Betis Baheri received his B.S. degree in Computer Science from Kent State University, in 2018, and the M.S in computer science from Kent State University in 2020. His area of research while he was in Undergraduate was security and privacy. For his master he focused on HPC systems. Previously he was working on HPC scheduler and currently he is pursuing Ph.D. degree in Computer Science at same university in quantum computing and HPC systems. His main research focus is quantum error correction, quantum deep learning, and quantum machine learning on NISQ and Ion based quantum computers.

Qiang Guan received his Ph.D. degree from the University of North Texas, in 2014. Since 2018, Qiang is an assistant professor at Kent State University in the department of computer science. Qiang was a computer scientist at the Los Alamos National Laboratory. Qiang is the recipient of the NSF CAREER Award in 2023. He has been awarded more than $3.5 Millions from the National Science Foundation (NSF) across the areas of High Performance Computing, Quantum Computing, AI, and VR/AR.

Bartolomeo Montrucchio received the M.Sc. degree in electronic engineering and the Ph.D. degree in computer engineering from Politecnico di Torino, Turin, Italy, in 1998, and 2002, respectively. He is currently a Full Professor of Computer Engineering with the Dipartimento di Automatica e Informatica, Politecnico di Torino. His current research interests include image analysis and synthesis techniques, scientific visualization, sensor networks, RFIDs, and quantum computing.

Paolo Rech received his master and Ph.D. degrees from Padova University, Padova, Italy, in 2006 and 2009, respectively. Since 2022 Paolo is an associate professor at Università di Trento, Italy, and since 2012 he is an associate professor at UFRGS, Brazil. He received 5 best paper awards, including the best paper at the 2022 IEEE Nuclear and Space Radiation Effects Conference for the paper "Radiation-Induced Faults Propagation in Quantum Bits and Quantum Circuits". He is the 2019 Rosen Scholar Fellow at the Los Alamos National Laboratory, he received the 2020 impact in society award from the Rutherford Appleton Laboratory, UK and the Marie Curie Fellowship from the European Commission.

Previously organized tutorials:

- DSN 2015 in Rio de Janeiro, "Mitigation of soft errors: from adding selective redundancy to changing the abstraction stack", about 20 attendees.
- ESWEEK 2014 in New Delhi, "Mitigation of soft errors: from adding selective redundancy to changing the abstraction stack", about 15 attendees.
- IEEE Quantum Week 2022 in Broomfield, CO, "QuantumFlow+VACSEN: A Visualization System for Quantum Neural Networks on Noisy Quantum Devices", about 15 attendees.
- ESWEEK 2022 in Shanghai, "Tutorial on QuantumFlow+VACSEN: A Visualization System for Quantum Neural Networks on Noisy Quantum Device", about 50 attendees.