QI 3: Certification and Benchmarking of Quantum Systems

Time: Monday 15:00–18:00 Location: H8

Invited Talk QI 3.1 Mon 15:00 H8

Generalized randomized benchmarking with short random quantum circuits — Markus Heinrich[1], •Martin Kliesch[1], and Ingor Roth[2] — [1]Heinrich Heine University Düsseldorf, Germany — [2]Technology Innovation Institute, Abu Dhabi, United Arab Emirates

The characterization of the quality of quantum gate implementations is among the most important certification tasks in the quantum sciences. State preparation and measurement errors render this task a challenge, in particular for large qubit numbers. Randomized benchmarking (RB) is among the most popular approaches to address this challenge. Rigorous theoretical guarantees for RB methods rely on sequences of unitary operations each of which is drawn uniformly from a group, often the Clifford group. Due to compiling, such RB strategies effectively require the implementation of quantum circuits with an unfavourable scaling of the circuit depth with the number of qubits. In practice, this scaling results in a restriction to a few qubits.

This talk starts with an introduction to RB, a generalized version thereof and a review of the idea of drawing the unitaries from a generating gate set of the group rather than from its uniform distribution in order to reduce the required circuit depths. Then we show analytically how this changes the exponential decay behaviour observed in RB. In particular, shorter circuits can result in decays that are a combination of the usual RB decay plus a decay corresponding to mixing properties (spectral gap of the moment operator) of the gate set. In this way, we shine new light on the important question of how quantum gates can be certified using short circuits.

QI 3.2 Mon 15:30 H8

Compressive gate set tomography — •Raphael Brieger[1], Ingo Roth[2], and Martin Kliesch[1] — [1]Quantum technology, Heinrich Heine University Düsseldorf, Germany — [2]Quantum Research Centre, Technology Innovation Institute, Abu Dhabi, UAE

Flexible characterization techniques that identify and quantify experimental imperfections under realistic assumptions are crucial for the development of quantum computers. Gate set tomography is a characterization approach that simultaneously and self-consistently extracts a tomographic description of the implementation of an entire set of quantum gates, as well as the initial state and measurement, from experimental data. Obtaining such a detailed picture of the experimental implementation is associated with high requirements on the number of sequences and their design, making gate set tomography a challenging task even for only two qubits. In this work, we show that low-rank approximations of gate sets can be obtained from significantly fewer gate sequences and that it is sufficient to draw them randomly. To this end, we formulate the data processing problem of gate set tomography as a rank-constrained tensor completion problem. We provide an algorithm to solve this problem while respecting the usual positivity and normalization constraints of quantum mechanics by using second-order geometrical optimization methods on the complex Stiefel manifold. Besides the reduction in sequences, we demonstrate numerically that the algorithm does not rely on structured gate sets or an elaborate circuit design to robustly perform gate set tomography and is therefore more broadly applicable than traditional approaches.

QI 3.3 Mon 15:45 H8

Spin squeezing inequalities meet randomized measurements — •Jan Lennart Bönsel, Satoya Imai, Ye-Chao Liu, and Otfried Gühne — University of Siegen, Siegen, Germany

Due to the recent advances in quantum control, large quantum systems containing thousands of atoms can nowadays be prepared in the lab. Here, the characterization of quantum correlations is of special interest. For systems where the individual atoms are difficult to address, the measurement of collective angular momentum observables and the evaluation of the corresponding spin squeezing inequalities are a possibility to characterize entanglement and its usefulness for metrology.

In this contribution, we first study the number of quantum state samples that are necessary to verify entanglement with a certain confidence. For this purpose, we compare different estimators of spin squeezing parameters. We characterize the probability that the estimator deviates from its mean using simulations as well as analytical bounds derived from concentration inequalities, like Cantelli's and Hoeffding's inequality. Second, we analyse if it is possible to obtain a good estimate from fewer measurements made only on a randomly chosen subset of the atoms.

QI 3.4 Mon 16:00 H8

Machine learning approaches to Optimal Gate Sequences for Quantum State Tomography under Noise — •Violeta N. Ivanova-Rohling[1,2,3], Niklas Rohling[1], and Guido Burkard[1] — [1]Department of Physics, University of Konstanz, D-78457 Konstanz — [2]Zukunftskolleg, University of Konstanz, D-78457 Konstanz — [3]Department of Mathematical Foundations of Computer Sciences, IMI, Bulgarian Academy of Sciences

For limited scenarios, depending on projector rank and system size, optimal measurement schemes for efficient quantum state tomography (QST) are known. In the case of errorless non-degenerate measurements, using mutually unbiased bases yields the optimal QST scheme [1]. However, in the general case, the optimal measurement scheme for efficient QST is not known and, may need to be numerically approximated. Here, we investigate the effect of noise on the optimal QST measurement sets using two noise models: the depolarizing channel, and over- and under-rotation in two-qubit gates [2]. Furthermore, we apply reinforcement learning for optimizing the effective times each quantum gate is switched on in a set of gate sequences which – combined with an elementary projective measurement – realizes a QST quorum. We extend the model by including errors from single-qubit gates and allow for longer gate sequences than necessary for realizing arbitrary measurements aiming at higher noise resilience overall.

[1] Wootters, Fields, Ann. Phys. 191, 363 (1989)
[2] Ivanova-Rohling, Rohling, Burkard, arXiv:2203.05677

QI 3.5 Mon 16:15 H8

Verifying arbitrary entangled state with homogeneous local measurements — •Ye-Chao Liu[1,2], Yinfei Li[2], Jiangwei Shang[2], and Xiangdong Zhang[2] — [1]Universität Siegen, Siegen, Germany — [2]Beijing Institute of Technology, Beijing, China

Quantum state verification is the task that uses only local measurements to judge whether one unknown state is the pure state that we desire. Recently, with the rapid growth in the size of manipulated quantum systems, such a fundamental task attracts more and more attention due to the weakness of the standard tomography method in the efficiency, and many entangled states can be verified efficiently or even optimally. However, how to design a verification protocol for an arbitrary entangled state is still an open problem. In this paper, we present a systematic framework to solve the problem by considering the locality of what we call choice-independent measurement protocols, whose operators can be achieved directly when it is homogeneous. Taking several kinds of entangled states as examples, we demonstrate the concrete processes and results of the design method under the most common Pauli projections. Moreover, our framework can tackle the local protocol design of other tasks, like entanglement witness, which is also an important problem. Finally, all these tasks can be converted into corresponding parameter estimation tasks, whose local protocols can be always easily achieved by our methods.

15 min. break

QI 3.6 Mon 16:45 H8

Dynamical Uncertainty Propagation with Noisy Quantum Parameters — •Felix Motzoi[1], Mogens Dalgaard[2], and Carrie Weidner[3] — [1]Forschungszentrum Juelich — [2]Aarhus University — [3]Bristol University

Many quantum technologies rely on high-precision dynamics, which raises the question of how these are influenced by the experimental uncertainties that are always present in real-life settings. A standard approach in the literature to assess this is Monte Carlo sampling, which suffers from two major drawbacks. First, it is computationally expensive. Second, it does not reveal the effect that each individual uncertainty parameter has on the state of the system. In this talk, we evade both these drawbacks by incorporating propagation of uncertainty directly into simulations of quantum dynamics, thereby obtaining a method that is orders of magnitude faster than Monte Carlo simulations and directly provides information on how each uncertainty parameter influences the system dynamics. Additionally, we compare our method to experimental results obtained using the IBM quantum computers.

Dalgaard et al., Phys. Rev. Lett. 128, 150503 (2022)

QI 3.7 Mon 17:00 H8

Error mitigation - handling noisy quantum hardware — •Kathrin König and Thomas Wellens — Fraunhofer IAF, Freiburg, Germany

Currently available quantum computing hardware suffers from errors due to environmental influences, nearest-neighbour interactions and imperfect gate operations. To achieve robust quantum computing, there are techniques like error mitigation by zero-noise extrapolation [1]. To reduce the impact of gate errors on observable expectation values, arbitrary noise can also be converted into stochastic Pauli errors by so called noise tailoring [2]. We elaborate on the implementation of error mitigation on a superconducting quantum computer and its impact on the computation of expectation values.

[1] He, A. et al., *Zero-noise extrapolation for quantum-gate error mitigation with identity insertions*, Phys. Rev. A 102, 012426 (2020)

[2] Wallman, J. J.; Emerson. J., *Noise tailoring for scalable quantum computation via randomized compiling*, Phys.Rev. A 94, 052325 (2016)

QI 3.8 Mon 17:15 H8

Break-even point of the quantum repetition code — Áron Rozgonyi and •Gábor Széchenyi — Eötvös University, Budapest

Repetition code is not a real quantum error correction code in the sense, that it cannot protect the logical information against any Pauli error. However, for simplicity repetition code is widely investigated theoretically and used for benchmarking state-of-the-art quantum devices. In our work, we analyze the efficiency of the phase-flip code as a quantum memory in presence of relaxation and dephasing. We take into account noisy two-qubit gates suffering from depolarizing and coherent error. We determine the parameter regime, where the repetition code performs better than an idle qubit.

QI 3.9 Mon 17:30 H8

Benchmarking quantum error correcting codes on near-term devices — •Regina Finsterhoelzl and Guido Burkard — Department of Physics, University of Konstanz

We evaluate the performance of small error-correcting codes which we implement on hardware platforms of very different connectivity and coherence: On a superconducting processor and on a spintronic quantum register consisting of a color center in diamond. Taking the hardware-specific errors and connectivity into account, we investigate the dependence of the resulting logical error rate on the platform features such as the native gates, the native connectivity, gate times, and coherence times. Using a standard error model parametrized for the given hardware, we simulate the performance and benchmark these predictions with experimental results when running the code on a real quantum device. The results indicate that for small codes, the hexagonal layout of the superconducting processor proves advantageous, yet for larger codes with multi-qubit controlled operations, the star-like connectivity of the color centers enables lower error rates.

QI 3.10 Mon 17:45 H8

Quantum Lifelong Learning — •Lukas Sigl[1,2], Tatjana Wilk[2], Anna Donhauser[3,2], Stefan Küchemann[3,2], Bernhard Kraus[1], Jan von Delft[3,2], Jochen Kuhn[3,2], and Alexander Holleitner[1,2] — [1]TU Munich, Germany — [2]MCQST, Germany — [3]LMU Munich, Germany

Quantum technologies comprise rapidly growing scientific fields with great potential for applications in industry. The current challenge for Germany and Europe is to educate a sufficiently large number of students in quantum technologies and to transfer knowledge as well as technological expertise from the research laboratories to the industrial sector.[1] A key role is played by the specialists and executives of the high-tech industry, who have to recognize and implement the specific potential of quantum technologies for the respective company. We present our Munich project Quantum LifeLong Learning (QL3), a targeted education and training program of the Munich universities in the field of quantum technologies according to a university certificate and ECTS system with the target group of specialists and executives in industry. We acknowledge financial support by the Bundesministerium für Bildung und Forschung (BMBF) of Germany.

References: 1. C.D. Aiello, et al. Achieving a quantum smart workforce. Quantum Science and Technology 6, 030501 (2021)