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Final Report for Grant W911NF-14-1-0124 from IBM
Prepared by: David McKay

Notice: The definitive technical resource on this grant is a file "QCVV_Report_Year6.pdf" which was delivered to ARO at the conclusion of this grant. The ARO site does not allow this to be upload as the final report and so I am making this document as a summary. However, please refer to that document which is available from TR or myself (dcmckay@us.ibm.com).

Abstract:

As quantum circuits grow larger we must contend with two critical issues, the combinatorial increase in the number of gate configurations and the exponential increase of the state space. The first issue means that gates must operate in the presence of other qubits (spectators) and/or in parallel with other gates. One aspect of this project is to better understand these errors in multi-qubit settings, prioritize and remove them. The second issue, exponential scaling, means that it becomes intractable to fully characterize multi-qubit devices. Therefore, the challenge is to find new approximate methods and metrics for characterization. Randomized benchmarking is one such method, however, it only gives information for one specific metric (the average Clifford error). This project involves proposing and implementing additional methods based on the specific axis we want to benchmark the device.

Findings:

New Approaches to Randomized Benchmarking: In this program we looked in detail at extending randomized benchmarking protocols and we made great strides in this effort. In terms of standard RB we demonstrated the first (and only) three-qubit RB (1712.06550), we quantified leakage (1704.03081) and validating virtual gates (1612.00858).

We also developed several new RB protocols, such as correlated randomized benchmarking (2003.02354), iterative RB (1504.06597), and non-Clifford RB (1510.02720, 2007.08532)

Holistic Benchmarks: One of the pressing problems in large device systems is how to quantify errors in a scalable way. While RB was poised to be this method there are several difficulties with how it scales in terms of decomposing the Cliffords into native gates. As part of this program we developed several new holistic benchmarking techniques, such as the widely used quantum volume (1811.12926) and GHZ states (1905.05720). At the end of the program we were working on a binned output characterization that was completed in QCISS.

Noise Characterization and Improvements: Another major finding of the program was how to use the characterization methods developed to improve device performance so that we could investigate even lower errors down the stack. In particular we looked at methods to reduce and characterize crosstalk and better understand the fundamental physics of our systems at a Hamiltonian level.

List of Publications:

This is a list of publications from the grant. Some of these involved major funding from the QCVV program and some just involved earlier device funding.

Publication Title	Authors	Journal	Arxiv	Year	Contribution
Correlated Randomized Benchmarking	David C. McKay, Andrew W. Cross, Christopher J. Wood, Jay M. Gambetta		2003.02354	2020	A - Major funding from QCVV
Mitigating measurement errors in multi-qubit experiments	Sergey Bravyi, Sarah Sheldon, Abhinav Kandala, David C. Mckay, Jay M. Gambetta		2006.14044	2020	A - Major funding from QCVV
Verifying Multipartite Entangled GHZ States via Multiple Quantum Coherences	Ken X. Wei, Isaac Lauer, Srikanth Srinivasan, Neereja Sundaresan, Douglas T. McClure, David Toyli, David C. McKay, Jay M. Gambetta, Sarah Sheldon	Phys. Rev. A 101, 032343	1905.05720	2020	A - Major funding from QCVV
Effective Hamiltonian models of the cross-resonance gate	Easwar Magesan, Jay M. Gambetta	Phys. Rev. A 101, 052308	1804.04073	2020	A - Major funding from QCVV
First-principles analysis of cross-resonance gate operation	Moein Malekakhlagh, Easwar Magesan, David C. McKay		2005.00133	2020	A - Major funding from QCVV
Three-Qubit Randomized Benchmarking	David C. McKay, Sarah Sheldon, John A. Smolin, Jerry M. Chow, and Jay M. Gambetta	Phys. Rev. Lett. 122, 200502	1712.06550	2019	A - Major funding from QCVV
Validating quantum computers using randomized model circuits	Andrew W. Cross, Lev S. Bishop, Sarah Sheldon, Paul D. Nation, Jay M. Gambetta	Phys. Rev. A 100, 032328	1811.12926	2019	A - Major funding from QCVV

Quantification and Characterization of Leakage Errors	Christopher J. Wood, Jay M. Gambetta	Phys. Rev. A 97, 032306	1704.03081	2018	A - Major funding from QCVV
Experimental demonstration of fault-tolerant state preparation with superconducting qubits	Maika Takita, Andrew W. Cross, A. D. Córcoles, Jerry M. Chow, Jay M. Gambetta	Phys. Rev. Lett. 119, 180501	1705.09259	2017	A - Major funding from QCVV
Efficient Z-Gates for Quantum Computing	David C. McKay, Christopher J. Wood, Sarah Sheldon, Jerry M. Chow, Jay M. Gambetta	Phys. Rev. A 96, 022330	1612.00858	2017	A - Major funding from QCVV
Characterizing errors on qubit operations via iterative randomized benchmarking	Sarah Sheldon, Lev S. Bishop, Easwar Magesan, Stefan Filipp, Jerry M. Chow, Jay M. Gambetta	Phys. Rev. A 93, 012301	1504.06597	2016	A - Major funding from QCVV
Scalable randomized benchmarking of non-Clifford gates	Andrew W. Cross, Easwar Magesan, Lev S. Bishop, John A. Smolin, Jay M. Gambetta	npj Quantum Information 2,16012	1510.02720	2016	A - Major funding from QCVV
A universal gate for fixed-frequency qubits via a tunable bus	David C. McKay, Stefan Filipp, Antonio Mezzacapo, Easwar Magesan, Jerry M. Chow, Jay M. Gambetta	Phys. Rev. Applied 6, 064007	1604.03076	2016	A - Major funding from QCVV
Procedure for systematically tuning up crosstalk in the cross resonance gate	Sarah Sheldon, Easwar Magesan, Jerry M. Chow, Jay M. Gambetta	Phys. Rev. A 93, 060302	1603.04821	2016	A - Major funding from QCVV
Machine learning for discriminating quantum measurement trajectories and improving readout	Easwar Magesan, Jay M. Gambetta, A.D. Córcoles, Jerry M. Chow	Phys. Rev. Lett. 114, 200501	1411.4994	2015	A - Major funding from QCVV

Leakage Suppression in the Toric Code	Martin Suchara, Andrew W. Cross, Jay M. Gambetta	Quant. Inf. Comp. Vol. 15, No. 11/12, pp. 997-1016	1410.8562	2015	A - Major funding from QCVV
Experimental implementation of non-Clifford interleaved randomized benchmarking with a controlled-S gate	Shelly Garion, Naoki Kanazawa, Haggai Landa, David C. McKay, Sarah Sheldon, Andrew W. Cross, Christopher J. Wood		2007.08532	2020	B - Minor funding from QCVV
Suppression of Unwanted ZZ Interactions in a Hybrid Two-Qubit System	Jaseung Ku, Xuexin Xu, Markus Brink, David C. McKay, Jared B. Hertzberg, Mohammad H. Ansari, B.L.T. Plourde		2003.02775	2020	B - Minor funding from QCVV
Reducing unitary and spectator errors in cross resonance with optimized rotary echoes	Neereja Sundaresan, Isaac Lauer, Emily Pritchett, Easwar Magesan, Petar Jurcevic, Jay M. Gambetta		2007.02925	2020	B - Minor funding from QCVV
Characterization of hidden modes in networks of superconducting qubits	Sarah Sheldon, Martin Sandberg, Hanhee Paik, Baleegh Abdo, Jerry M. Chow, Matthias Steffen, Jay M. Gambetta	Appl. Phys. Lett. 111, 222601	1703.04501	2017	B - Minor funding from QCVV
Leakage reduction in fast superconducting qubit gates via optimal control	Max Werninghaus, Daniel J. Egger, Federico Roy, Shai Machnes, Frank K. Wilhelm, Stefan Filipp		2003.05952	2020	C - Device Funding Only

Benchmarking the noise sensitivity of different parametric two-qubit gates in a single superconducting quantum computing platform	M. Ganzhorn, G. Salis, D. J. Egger, A. Fuhrer, M. Mergenthaler, C. Müller, P. Müller, S. Paredes, M. Pechal, M. Werninghaus, S. Filipp		2005.05696	2020	C - Device Funding Only
Entanglement generation in superconducting qubits using holonomic operations	Daniel J. Egger, Marc Ganzhorn, Gian Salis, Andreas Fuhrer, Peter Mueller, Panagiotis Kl. Barkoutsos, Nikolaj Moll, Ivano Tavernelli, Stefan Filipp	Phys. Rev. Applied 11, 014017	1804.04900	2019	C - Device Funding Only
Adiabatic quantum simulations with driven superconducting qubits	Marco Roth, Nikolaj Moll, Gian Salis, Marc Ganzhorn, Daniel J. Egger, Stefan Filipp, Sebastian Schmidt	Phys. Rev. A 99, 022323	1808.04666	2019	C - Device Funding Only
Gate-efficient simulation of molecular eigenstates on a quantum computer	Marc Ganzhorn, Daniel J. Egger, Panagiotis Kl. Barkoutsos, Pauline Ollitrault, Gian Salis, Nikolaj Moll, Andreas Fuhrer, Peter Mueller, Stefan Woerner, Ivano Tavernelli, Stefan Filipp	Phys. Rev. Applied 11, 044092	1809.05057	2019	C - Device Funding Only
Pulsed reset protocol for fixed-frequency superconducting qubits	Daniel J. Egger, Max Werninghaus, Marc Ganzhorn, Gian Salis, Andreas Fuhrer, Peter Mueller, Stefan Filipp	Phys. Rev. Applied 10, 044030	1802.08980	2018	C - Device Funding Only

Analysis of parametrically driven exchange-type (iSWAP) and two-photon (bSWAP) interactions between superconducting qubits	Marco Roth, Marc Ganzhorn, Nikolaj Moll, Stefan Filipp, Gian Salis, Sebastian Schmidt	Phys. Rev. A 96, 062323	1708.02090	2017	C - Device Funding Only