Efficient experimental verification of continuously-parameterized gate sets and analog quantum simulators

Ryan Shaffer,[1,3] Hang Ren,[1,3] Emiliia Dyrenkova,[2,3] Eli Megidish,[1,3] Joseph Broz,[1,3] Wei-Ting Chen,[1,3] Christopher G. Yale,[4] Daniel S. Lobser,[4] Ashlyn D. Burch,[4] Matthew N. Chow,[4,5,6] Melissa C. Revelle[4], Susan M. Clark,[4] Hartmut Häffner[1,3]

[1] Department of Physics, University of California, Berkeley, CA, USA
[2] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA, USA
[3] Challenge Institute for Quantum Computation, University of California, Berkeley, CA, USA
[4] Sandia National Laboratories, Albuquerque, NM, USA
[5] Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA
[6] Center for Quantum Information and Control, University of New Mexico, Albuquerque, NM, USA

We introduce the **randomized analog verification (RAV)** protocol for verification of quantum computers with continuously-parameterized gate sets, as well as for verification of analog quantum simulators. We show that RAV **requires fewer circuit repetitions** than cross-entropy benchmarking (XEB) to produce an equivalently precise estimate of the error rate. We demonstrate this **efficiency advantage** numerically and experimentally.

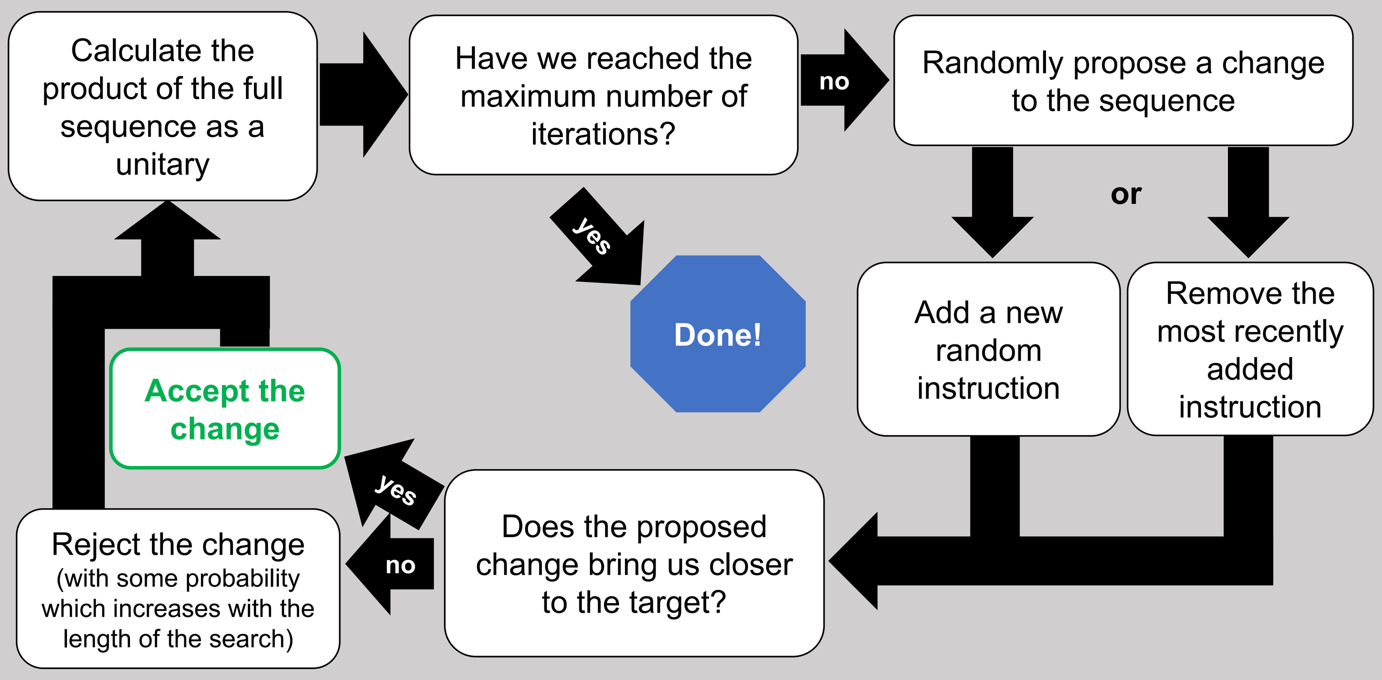
npj QI 7, 46 (2021)
arXiv 2205.13074

Verification of gate-based devices	Building blocks	Sequence generation	Measurement efficiency	Scalability	Parameterized gate support
Randomized benchmarking (RB) $\|0\rangle$ → Random n-qubit Clifford → Random n-qubit Clifford ••• Random n-qubit Clifford → Inversion n-qubit Clifford → $\|0\rangle$	Random n-qubit Cliffords	Efficient	Efficient	Infeasible for n >> 2	No
Cycle benchmarking (CB) $\|0\rangle$ → Pauli layer → Native n-qubit Clifford → Pauli twirl ••• Native n-qubit Clifford → Pauli twirl → Inversion layer of Paulis → $\|0\rangle$	Native n-qubit Cliffords, random single-qubit Cliffords	Efficient	Efficient	Scalable to large n (for n-qubit native gate)	No
Mirror RB $\|0\rangle$ → Random 1-, 2-qubit Clifford layer ••• Random 1-, 2-qubit Clifford layer → Twirled inverse ••• Twirled inverse → $\|0\rangle$	Random native single-qubit and two-qubit Cliffords	Efficient	Efficient	Scalable to large n	No
Cross-entropy benchmarking (XEB) $\|0\rangle$ → Random native gate layer → Random native gate layer ••• Random native gate layer → $\|\varphi\rangle$	Random native gates	Efficient	Inefficient	Infeasible for n >> 50	Yes
Randomized analog verification (RAV) $\|0\rangle$ → Random native gate layer → Random native gate layer ••• Random native gate layer → Approx. inversion sequence → $\|0\rangle$ (approx.)	**Random native gates**	**Inefficient**	**Efficient**	**Infeasible for n >> 10**	**Yes**

Verification of analog simulators	Error sensitivity	Hardware requirements	Scalability
Time-reversal benchmarking $\|0\rangle$ → $e^{-iH\tau}$ → $\|\psi\rangle$; $e^{+iH\tau}$	Incoherent noise	Implement time reversal of Hamiltonian	Scalable to large n
Cross-entropy benchmarking (XEB) $\|0\rangle$ → n random steps → $\|\varphi\rangle$	Coherent errors, incoherent noise	Implement programmable Hamiltonian terms	Infeasible for n >> 50
Randomized analog verification (RAV) $\|0\rangle$ → n random steps → $\|\varphi\rangle$ → inversion steps	**Coherent errors, incoherent noise**	**Implement programmable Hamiltonian terms**	**Infeasible for n >> 10**

Approximate compilation of RAV inversion sequence via STOQ

STOQ is a stochastic approximate compilation technique for compiling unitaries in terms of an arbitrary set of native gates, which may be fixed or parameterized.



Variance of RAV and XEB fidelity estimates

Fidelity estimates for a single circuit execution:

$$\hat{F}_{\mathrm{XEB}} = \frac{\sum_x P(x)Q(x) - \frac{1}{N}}{\sum_x P(x)^2 - \frac{1}{N}} \qquad \hat{F}_{\mathrm{RAV}} = \frac{Q(x_0) - \frac{1}{N}}{P(x_0) - \frac{1}{N}}$$

$P(x)$ = ideal probability of measuring x
$Q(x)$ = observed probability of measuring x
x_0 = expected RAV output state
$N = 2^n$ = dimension of n-qubit system

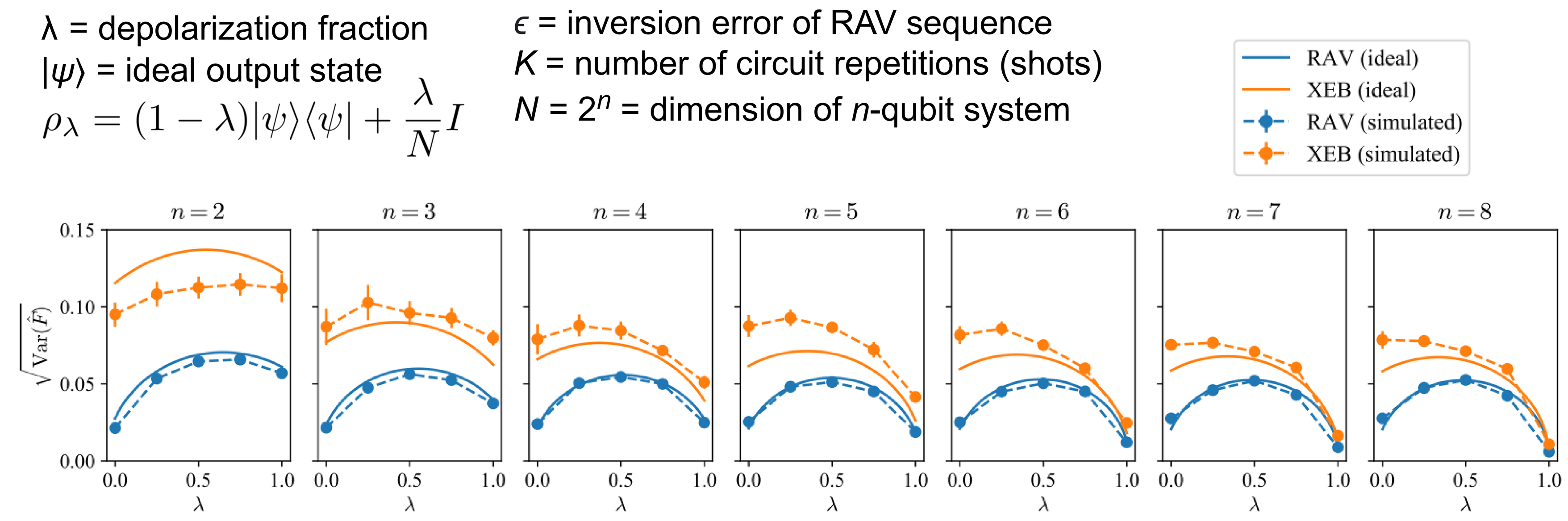
Measurement of RAV fidelity estimates is more efficient than XEB fidelity estimates, since only one output probability must be measured.

We demonstrate this by calculating the variance of the RAV and XEB fidelity estimates under varying amounts of depolarization:

$$\mathrm{Var}\left[\hat{F}_{\mathrm{RAV}}\right] \approx \frac{1}{K}\left(\frac{1}{(1-\epsilon)-\frac{1}{N}}\right)^2 \left[(1-\lambda)(1-\epsilon)+\frac{\lambda}{N}\right]\left[1-(1-\lambda)(1-\epsilon)-\frac{\lambda}{N}\right]$$

$$\mathrm{Var}\left[\hat{F}_{\mathrm{XEB}}\right] \approx \frac{1}{K}\left(\frac{N}{\frac{1}{2}N-1}\right)^2 \left[\frac{1}{2}\left(\frac{\lambda}{N}\right)\left(1-\frac{\lambda}{N}\right)+\frac{1}{3}(1-\lambda)\left(1-\frac{2\lambda}{N}\right)-\frac{1}{4}(1-\lambda)^2\right]$$

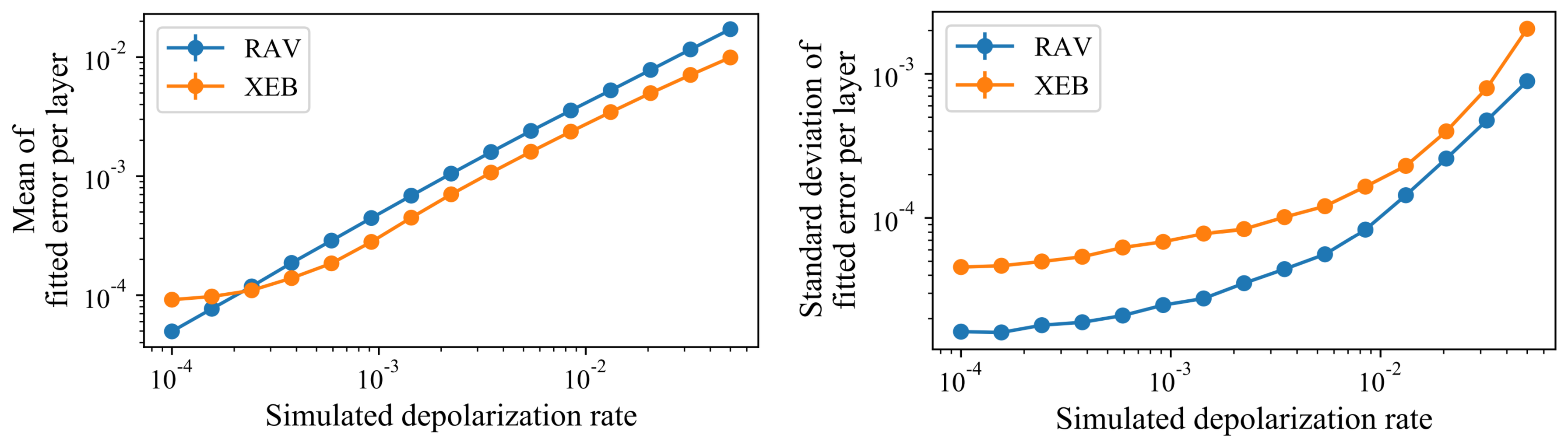
λ = depolarization fraction
$|\psi\rangle$ = ideal output state
$\rho_\lambda = (1-\lambda)|\psi\rangle\langle\psi| + \frac{\lambda}{N}I$
ϵ = inversion error of RAV sequence
K = number of circuit repetitions (shots)
$N = 2^n$ = dimension of n-qubit system



We observe that RAV fidelity estimates have a **smaller standard deviation** than XEB fidelity estimates in all cases, and especially for smaller qubit count n and smaller depolarization fraction λ.
This means that for a fixed number of shots K, RAV circuits will provide a fidelity estimate with **lower uncertainty** than XEB circuits.

Numerical demonstration

We simulated 50 RAV and 50 XEB sequences for a five-qubit system under varying depolarization rates. Statistics of the error estimates:



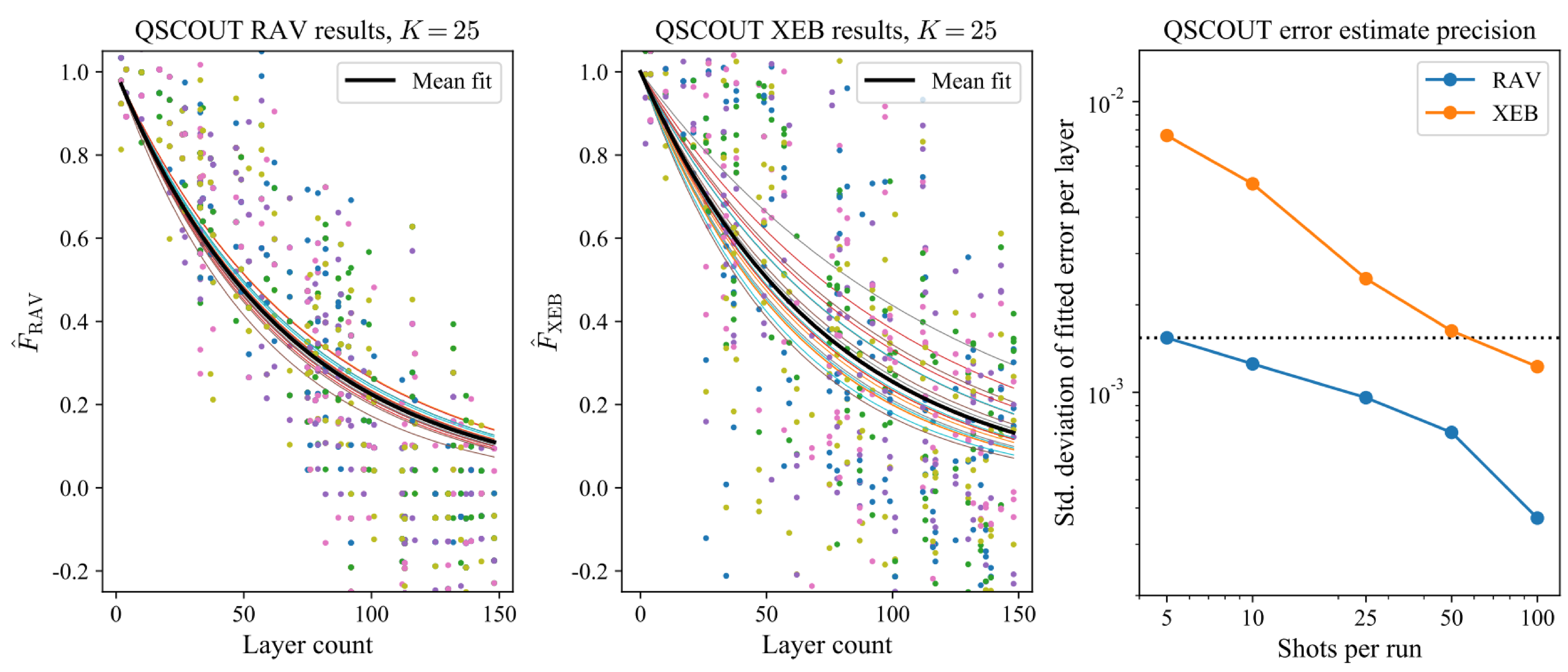
For this simulated five-qubit system, we observe that RAV error estimates have **significantly smaller (by a factor of 2 to 3)** standard deviation than XEB error estimates given the same number of circuit repetitions.

This suggests that RAV would require **4x-9x fewer shots than XEB** to obtain error estimates to some desired precision.

Experimental demonstration

QSCOUT

We tested 50 RAV and 50 XEB two-qubit sequences on a trapped-ion quantum processor at the Quantum Scientific Computing Open User Testbed (QSCOUT) operated by Sandia National Laboratories.



The RAV runs on QSCOUT produce error estimates with significantly smaller standard deviation (by a factor of 2.5 to 5) than those obtained from XEB runs. This suggests that RAV would require **6x-25x fewer shots than XEB** to produce an equivalently-precise error estimate.