

Quantum circuit debugging and sensitivity analysis via local inversions

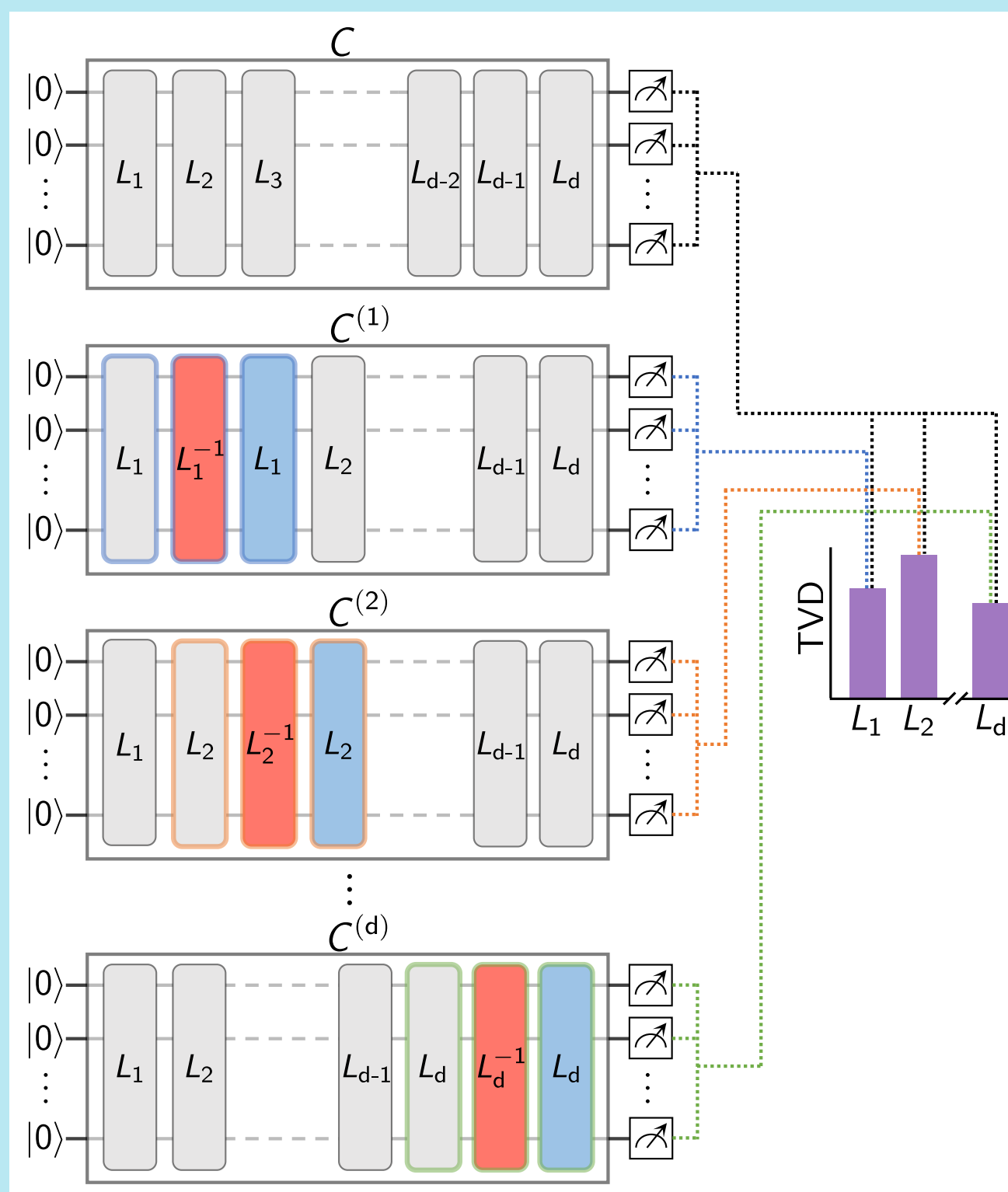
Fernando A. Calderon-Vargas¹, Timothy Proctor², Kenneth Rudinger², Mohan Sarovar¹

¹Quantum Algorithms and Applications Collaboratory, Sandia National Laboratories, Livermore, CA

²Quantum Performance Laboratory, Sandia National Laboratories, Albuquerque, NM and Livermore, CA

Overview

- We present a practical and scalable circuit debugging technique that **identifies which circuit layers most influence the circuit output and discovers time-dependent error modes such as degradation of gates as the circuit progresses.**
- Our work is one of the first to address the notion of *in-situ* debugging, where information about quantum information processor (QIP) operation is collected while a quantum program is being executed rather than through off-line calibration or characterization information.

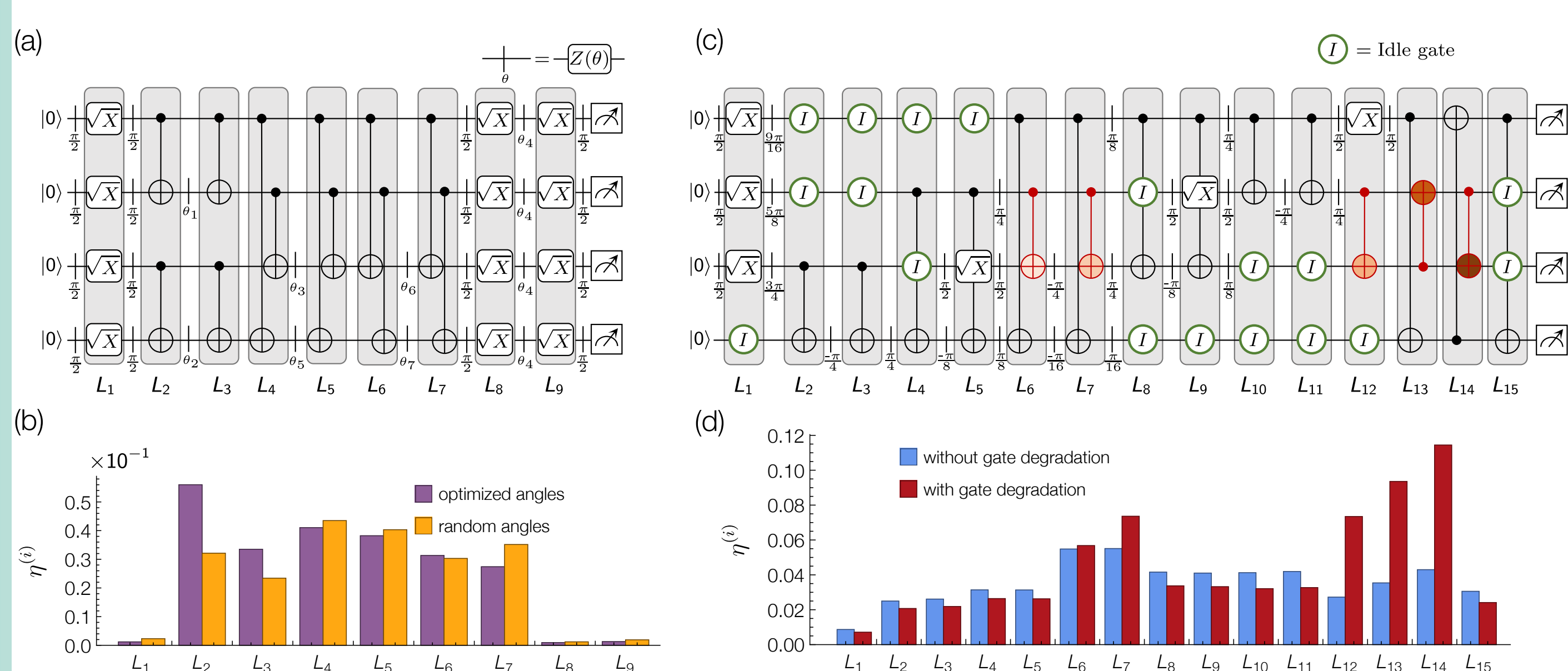


Method

- We write a d -layer circuit as: $C = L_d L_{d-1} \dots L_2 L_1$.
- We define the i -inverse of the circuit as $C^{(i)} = L_d \dots L_{i+1} [L_i L_{i-1}^{-1} L_i] L_{i-1} \dots L_1$, which we view as a local perturbation of the circuit.
- With the probability distribution over measurement outcomes, $p(k|C)$ ($k \in B^n$ and B^n is the set of all length- n bitstrings), we assess how such local perturbations affect the circuit outcomes by computing the distance, $d[p(\cdot|C), p(\cdot|C^{(i)})]$, between the original and perturbed output distributions.
- We use the total variation distance (TVD) for the distance measure

$$\eta^{(i)} \equiv d_{\text{TVD}}[p(\cdot|C), p(\cdot|C^{(i)})] = \frac{1}{2} \sum_k |p(k|C) - p(k|C^{(i)})|.$$

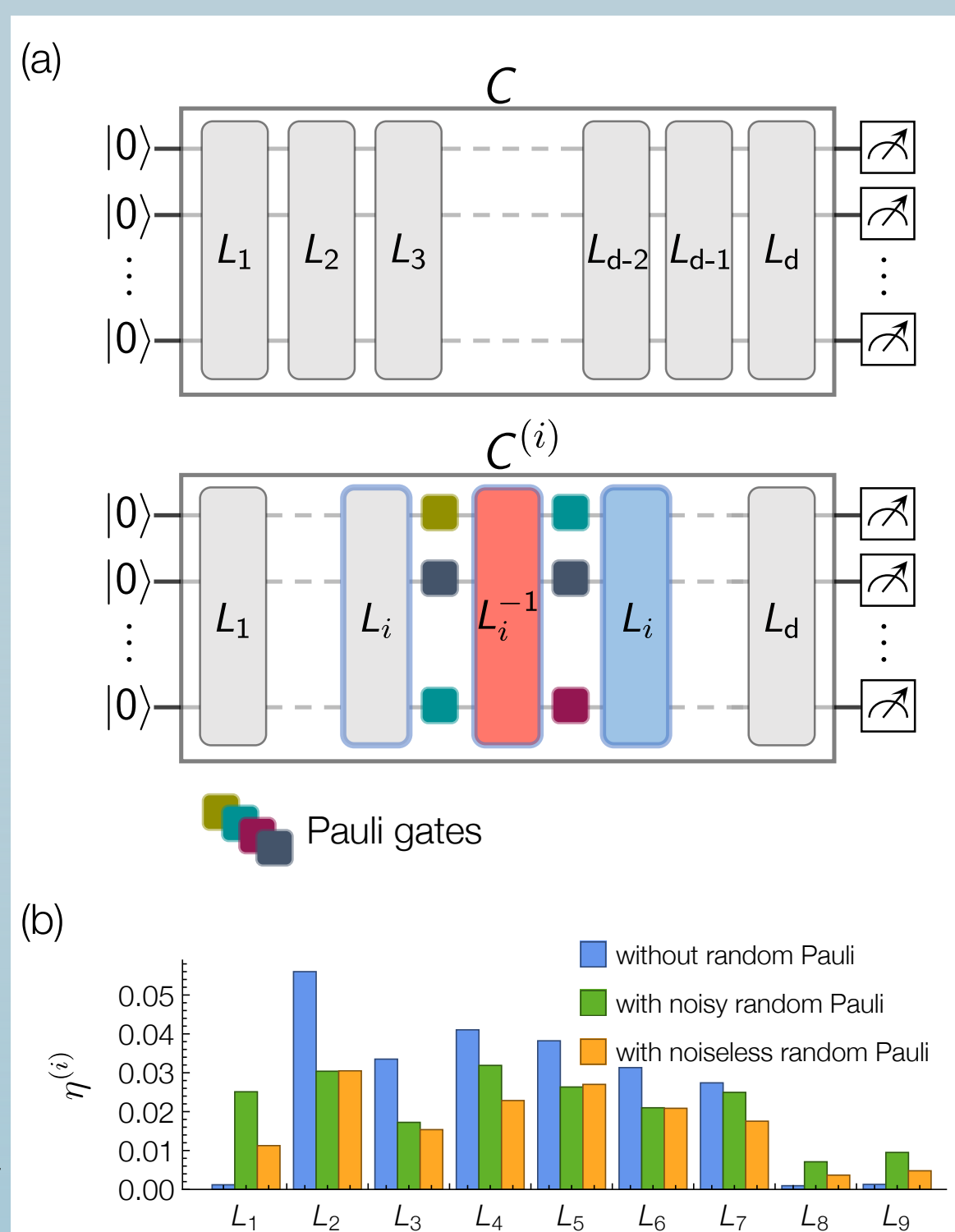
Numerical simulations



- We simulated a noisy 4-qubit circuit (a) implementing the QAOA on a Max-Cut problem and a noisy 4-qubit circuit (c) implementing the QFT.
- We show that the **effect perturbations in each layer** have on the circuit output distribution **also depends on the circuit structure**. In (a, b), we consider two sets of angles (labeled *random* and *optimized*) for the circuit's noiseless Z -rotations. Even though the difference in magnitude between the *optimized* and *random* angles is small, it is enough to modify which layers affect the output distribution the most.
- We demonstrate how our local inversion **technique can be used to detect gates with temporally varying noise (e.g., degrading gates)**. In (c, d), we add incremental noise to the two-qubit gates in layers 6, 7, 12, 13, 14, which is clearly identified by an increasing TVD for later layers.

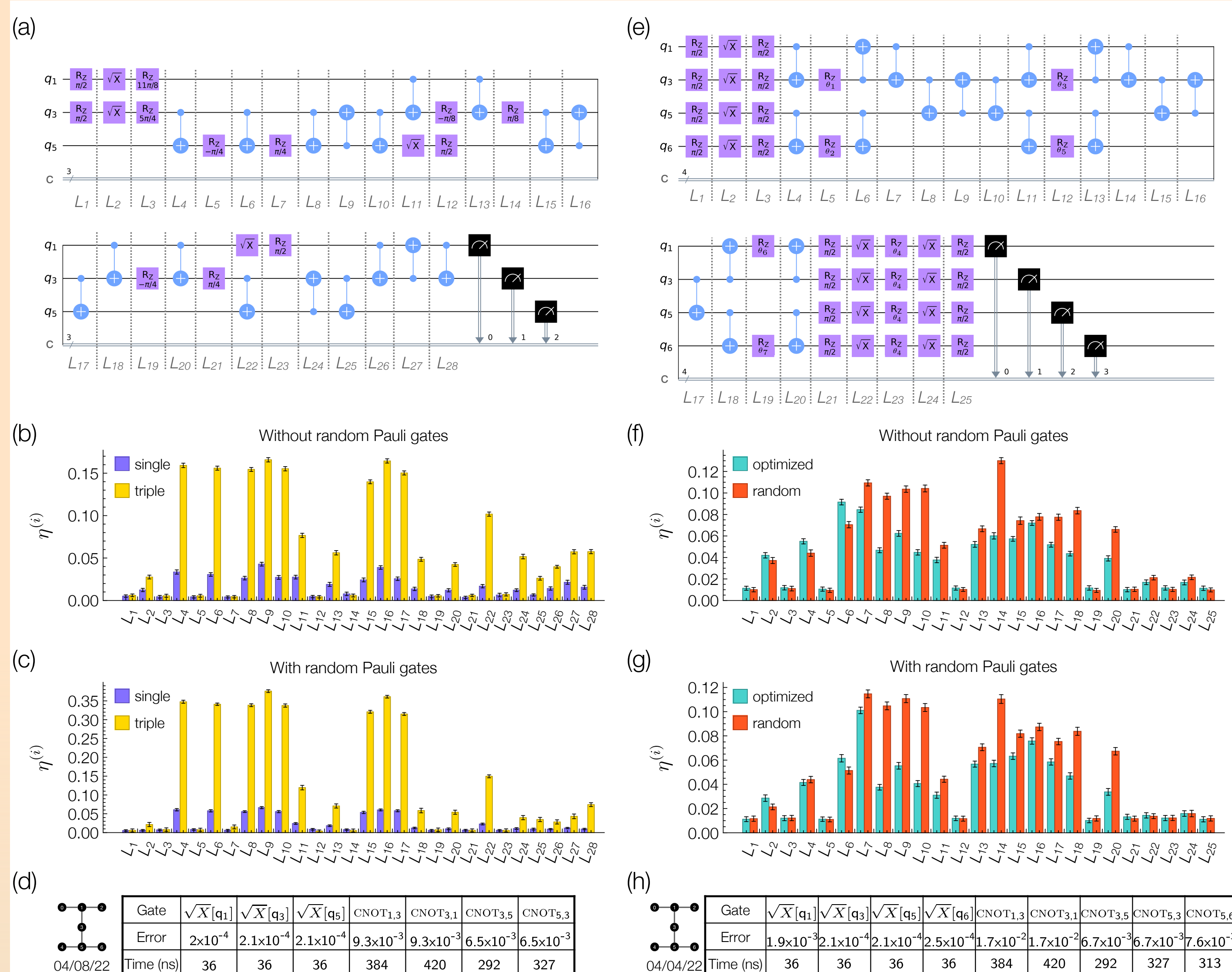
Technique refinements

- Multiple inversions** of a layer:
 $C^{(i)} = L_d \dots L_{i+1} L_i [L_i^{-1} L_i]^m L_{i-1} \dots L_1$.
The effect of doing this is to **amplify the perturbation** from the target layer on the circuit output.
- We **introduce random single-qubit Pauli gates** before and after the inverse of each layer (a):
 $C^{(i)} = L_d \dots L_i \left[\prod_{\ell=1}^m \mathcal{P}_\ell L_i^{-1} \tilde{\mathcal{P}}_\ell L_i \right] \dots L_1$.
The average over many such Pauli "twirls" **removes any unwanted self-cancellation of coherent noise**.
- In (b), we show that, with random Pauli gates, either noisy or perfect, the local inversion technique correctly identifies the effect of the layers (1, 8, 9) with coherent noise.



Experimental demonstration

- On the IBM QIP ibmq_jakarta, we implemented a 3-qubit QFT circuit (a) and a 4-qubit QAOA for Mac-Cut circuit (e) using two different sets of Z -rotation angles (labeled *random* and *optimized*).
- For the QFT circuit, we obtained experimental results using single and triple local inversion ($m = 1$ and $m = 3$, respectively) for circuits without (b) and with random Pauli gates (c).
 - In all cases, the largest TVDs correspond to layers with a single CNOT between qubits 3 and 5, which is not the noisiest nor the longest gate according to the table in (d).
- For the QAOA circuit, we show TVDs between the original and the i -inverted circuits without (f) and with (g) random Pauli layers inserted during the inversion. We show here only the results for triple layer inversion ($m = 3$) for conciseness.
 - Depending on the QAOA angles used (*optimized* or *random*), the dominant layers can be different.
 - With the exception of layer 6, none of the layers with two CNOT gates (the two noisiest gates according to the table in (h)) are among the layers with largest TVD.



Reference: Calderon-Vargas, F. A., Proctor, T., Rudinger, K., & Sarovar, M., *Quantum circuit debugging and sensitivity analysis via local inversions*. arXiv preprint arXiv:2204.06056 (2022).