Microscopic parametrizations for gate set tomography under coloured phase noise

P. Viñas[1] and A. Bermudez[1]

[1]*Instituto de Física Teórica UAM-CSIC, Universidad Autónoma de Madrid, Cantoblanco, 28049, Madrid, Spain*

Gate set tomography (GST) allows for a self-consistent characterization of noisy quantum information processors (QIPs). The standard device-agnostic approach treats the QIPs as black boxes that are only constrained by the laws of physics, attaining full generality at a considerable resource cost: numerous circuits built from the gate set must be run in order to amplify each of the gate set parameters. In this work, we show that a microscopic parametrization of quantum gates under phase noise, which builds on recent experiments for the quantum dynamical map of trapped-ion gates, reduces these resources and thus enables a more efficient version of GST. By making use of the formalism of filter functions over the noise spectral density, we discuss the minimal parametrizations of the gate set that include the effect of finite correlation times and non-Markovian quantum evolutions during the individual gates. We compare of the estimated gate sets obtained by our method and fully-general GST, discussing the achieved accuracies in terms of established metrics, as well as showcasing the advantages of the parametrized approach in terms of the sampling complexity for specific examples.

Unlocking the full potential of quantum information processors (QIPs) is a multifaceted challenge. The development of efficient techniques for the characterization of undesired interactions – or noise – in QIPs, is of particular relevance, for it allows to develop improved strategies to counter its undesired effects in noise mitigation and error correction schemes. In pursuit of this goal, the community working in quantum characterization, verification, and validation (QCVV) has devised methodologies for a precise prediction of the actual faulty operations in the noisy QIPs. Here we are interested in those belonging to the family of quantum tomography techniques.

In quantum process tomography (QPT), the focus lies on a quantum channel $\rho \mapsto \mathscr{E}(\rho)$, where $\mathscr{E} \in \mathsf{C}(\mathscr{H}) \subset \mathsf{L}(\mathscr{H})$ is a completely-positive and trace-preserving linear operator that describes a physically-admissible operation on a quantum system transforming input to output states.

GST was introduced to overcome a fundamental shortcoming of QPT, its dependence on state preparation and measurement (SPAM) errors. Even if QPT has become a reference tool that is now used in several QIP platforms, it suffers from a self-consistency issue: it assumes that the set of initial states and measurements are error free. In reality, these states and measurements are usually obtained by acting with a set of gates $\{G_i\}$ from a single fiducial state ρ_0 and a measurement M_0. The gates are implemented similarly to the one we aim at characterizing, and will thus contribute with a SPAM error that is of the same of order as the one that afflicts the characterized gate. GST eliminates the need of an independent SPAM calibration, solving the problem by providing a complete self-consistent characterization that treats the whole QIP device as a black box. However, to attain this full generality, it requires at least $N_{GST} = N_G \times 4^N(4^N - 1) + 2^{3N} - 1$ parameters for an N-qubit system. These free parameters need from an equivalent amount of independent circuits to be executed. In addition to this exponential scaling, the number of samples required to achieve a target precision ε increases as $N_{\text{shots}} \sim 1/\varepsilon^2$. This indeed limits the applicability of GST.

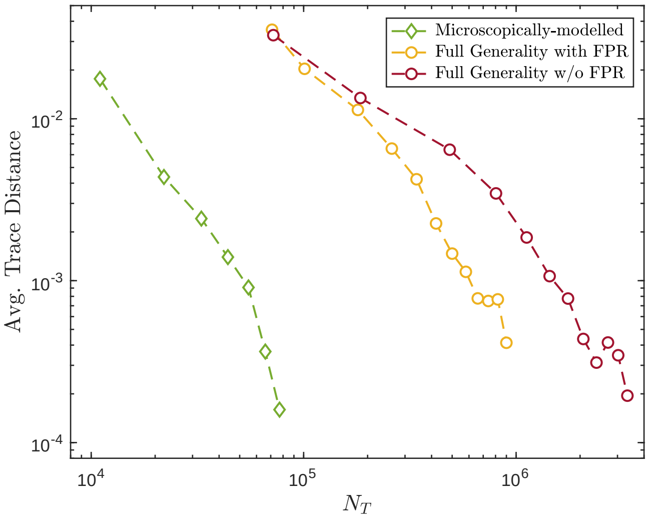

FIG. 1. **Comparison with fully general GST:** we present the average trace distance of the estimated gate set with respect to the one used to generate simulated data. We display it as a function of the total number of shots used N_T. In the plot, our microscopically-motivated implementation is depicted in green with diamond markers, while fully general GST implementations are shown in other colors. Specifically, the yellow and magenta plots represent general GST estimations with and without fiducial pair reduction, respectively. We fix the number of shots per circuit, in this case $N_{\text{b,s}} = 1e3$. The total number of shots N_T varies by considering increasingly deeper circuits, ranging in the interval $p_g \in \{2^i\}_{g=0}^{11}$. It is notable that our tailored approach achieves much better estimation accuracies at a fixed N_T.

In this work, instead of using a device-agnostic approach, we advocate for a microscopically-motivated parametrization of the above gate set with a specific setup in mind: QIPs that are mainly limited by coloured phase noise, such as high-precision trapped-ion QIPs. As shown in our work, the parameters of the gate set can be related to integrals of the noise spectral density under different filters that depend on how one drives the gates, reducing considerably the number of parameters that is required to model the gate set in full generality and thus the number of experiments needed (Fig. 1). We also find other benefits with respect to the general GST framework, such as the absence of gauge redundancy in our results and the reduction in complexity to find an amplificationally complete set of circuits.