Bayesian Methods for the calibration of the Light-Shift gate

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Abstract:

The Light-Shift (LS) gate is a robust implementation of a two-qubit entangling gate in trapped-ion devices, but it must be precisely calibrated to achieve a desired error rate [1]. Among the parameters it depends on is the power of the laser used to control the internal state of the ions, which lacks an efficient calibration routine. We devise a new calibration method using Bayesian optimization, and we demonstrate a speed up in the calibration time by a factor of more than 9. Moreover, this method is not restricted to the calibration of the laser power, nor to operations on trapped-ions.

Introduction. Quantum computing is potentially one of the most revolutionary technologies of this century, as it allows for exponential speed up relative to classical computers for some calculations [2]. In order to implement any desired calculation, a quantum computer must have a set of universal gates, which must include an entangling gate. Trapped ions were first suggested as a platform for the implementation of quantum operations in 1995 by Cirac and Zoller [3]. They can achieve decoherence times on the order of seconds, thus remaining one of the most promising candidates for scalable quantum computing [4]. In trapped-ion devices, the internal spin states of the ions are controlled using laser pulses on the order of microseconds to milliseconds. We can use such laser pulses to couple the spin states to the motional states of multiple ions, generating a spin-dependent force that can entangle them. The LS gate is one implementation of such operation, and in order for it to correctly entangle the ions, we need to set the laser power to an optimal value that can be analytically calculated from the system Hamiltonian. Still, we lack information about a few of the system parameters, so that we need to perform calibration routines every time we want to optimize the LS gate. This may represent a significant time cost, as the devices need to be recalibrated periodically.

Methods. Bayesian optimization consists of representing the possible values of the laser power W (or any other parameter) with a probability distribution and updating it after each measurement cycle according to Bayes formula in eq. (1):

$$\mathrm{P}(W \mid m) \propto \mathrm{P}(m \mid W)\, \mathrm{P}(W)$$

We calculate the likelihood P(m | W) by numerically integrating the system Hamiltonian and finding the resulting qubit populations for each value of the power detuning (see Fig. 1). At each step, we calculate what is the optimal number of LS gates that can be applied to narrow down the probability distribution the most, we perform a measurement cycle with that number, and update the distribution.

The algorithm was run on Jupyter notebooks, first using simulated measurement data in order to test its performance and limitations, then using data from actual measurements on trapped-ion devices from our partner group at Johannes Gutenberg-Universität Mainz.

Results and Discussion. Simulations of the algorithm demonstrated that the probability distribution keeps narrowing down indefinitely, as well as the absolute difference between the calculated value and the actual value (see Fig. 2). This is the case even when the depolarizing and SPAM error rates used by the algorithm to calculate the likelihoods are not the same as those used to generate the measurement data. In practice, this means that the algorithm can work on a real trapped-ion quantum computer even if we just have a rough idea of the error channels caused by other gates in the sequence or by uncorrectable errors in the LS gate. Moreover, there is somewhat a pattern in the choice of the number of LS gates that are applied at each step, which can be explored in possible future developments of the code: the optimizer always chooses to apply a single LS gate in the first step, and increases this number until it always apply the maximum number of LS gates available to it.

The results from experiments agreed very well with our expectations based on simulations. We chose to stop the optimization once the probability distribution reached the same standard deviation as the best calibration routines could achieve so far, around 0.01. This resulted in an average of 2.3 steps to achieve the same level of precision of the previous routines, which used 21 steps on average. We chose to minimize the number of steps instead of experimental shots since the communication between the quantum and classical device at each step was the most time consuming part of the calibration. We emphasize that, in order for the algorithm to work, we did not need to know the precise relation between the applied laser power and the resulting Rabi frequency, nor did it need to be a linear one, just a monotonically increasing relation is enough to guarantee the performance of the algorithm.

Conclusion:

We propose a Bayesian optimization protocol for the calibration of an entangling gate in trapped-ion quantum computers. We demonstrate its efficiency by speeding up the calibration process in a real quantum computer by a factor of more than 9. We reinforce that this algorithm can be easily expanded to include other gate calibration parameters that might be relevant, such as the sideband detuning or ion shuttling-induced phases. This protocol represents a significant advantage for experimental research on quantum computing, as it minimizes one of the most time-consuming operations that need to be done.

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