UNIVERSITÀ DEGLI STUDI DI MILANO

FACOLTÀ DI SCIENZE E TECNOLOGIE

Master degree in Physics

Development of an open-source calibration framework for superconducting qubits

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Notes on quantum computing

1.1 Qubits

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1.2.1 Density matrix

1.3 Quantum operations

A quantum operation is a mathematical transformation that describes how a quantum state changes as a consequence of a physical process. Formally, it is a map $\mathcal{E}$ that transforms a quantum state described by a density operator $\hat{\rho}$ into another state described by a new density operator $\hat{\rho}'$:

$$\mathcal{E}(\rho) = \rho'. \tag{1.1}$$

The simplest example of a quantum operation is the evolution of a quantum state $\hat{\rho}$ of a closed quantum system, under a unitary operator $\hat{U}$, which can be written as $\mathcal{E} \equiv \hat{U}\hat{\rho}\hat{U}^\dagger$.

Depolarizing chennel A depolarizing channel describes a process in which the current state of the n-qubit system ρ, is replaced by $\frac{\mathbb{I}}{2^n}$, with probability d. This process can be represented with a quantum map as follows:

$$\mathcal{E}_{dc}(\rho) = d\frac{\mathbb{I}}{2^n} + (1-d)\rho \tag{1.2}$$

1.4 Superconducting qubits

Chapter 2

Qibo

Chapter 3

Results

Tutti i risultati che sono presentati nel seguito sono stati ottenuti utilizzando il software di `Qibolab`per l'interazione con gli strumenti del laboratorio e `Qibocal`per il controllo delle operazioni sui qubit. L'hardware è un chip ... di QunatumWare. Durante il lavoro condotto per questo progetto di tesi entrambe le libereria, sia Qibocal che Qibolab undergo update and release, for this reason the first part of this work was realized using `Qibocal`v0.1 and `Qibolab`v0.1 while the second part of the work, dato che puntava anche allo sviluppo di routine ch epotessero essere utili per la calibrazione dei qubit è stato realizzato direttamente con `Qibocal`v0.2 e `Qibolab`v0.2.

3.1 RB fidelity optimization

3.1.1 Randomized Benchmarking

A strong limitation to the realization of quantum computing technologies is the loss of coherence that happens as a consequence of the application of many sequential quantum gates to to the quibts. A possible approach to characterize gate error is the quantum process tomography which allows the experimenter to establish the behaviour of a quantum gates; the main drawback of this approach is that process tomography can be very time consumig since its time complexity scales exponentially with the number of qubits involved [1] and the result is affected by state preparation and measurements (SPAM) errors.

To overcome these limitations, randomized benchmarking (RB) was introduced and is currently widely used to quantify the avarage error rate for a set of quantum gates. The main idea is that the error obtained from the combined action of random unitary gates drawn from a uniform distribution with respect to the Haar measure [2] and applied in sequence to the qubit will avarage out to behave like a depolarizing channel [3]. This last consideration simplifies the characterization of noise because it removes dependence on specific error structures and allows fidelity to be extracted through a simple exponential decay. It was later shown that simplifies this procedure by restricting the unitaries to gates in the Clifford group [1] and by not requiring that the sequence is strictly self-inverting [4].

The fundamental principle of RB is the application of sequences of randomly selected quantum gates from the Clifford group $\mathcal{C}$ followed by an inversion gate which, in absence of noise, return the system to its initial state. For real systems, where noise is present, the observed survival probability provides an estimate of the avarage gate fidelity. The standard RB protocols consist of the following steps:

1. Initialize the system in ground state $|0\rangle$
2. For each sequence-length m build a sequence of m randomly drawn Clifford gates $C_1, C_2, ..., C_m$
3. Determine the inverse gate $C_{m+1} = (C_m \circ ... \circ C_1)^{-1}$
4. Measure $C_{m+1} \circ C_m \circ ... \circ C_1 |0\rangle$

This process must be repeated for multiple sequence of the same length and with varying length.

As mentioned before, randomization with Clifford gates behave as a depolarizing channel 1.2 with depolarization probability d. We can compute the expectation value for the system to be in the initial state $|0\rangle$, after the application of the gate sequence described in 3.1.1 as

$$P(m) = Ae^{-m/\lambda} + B, \tag{3.1}$$

[1] unitary rotations mapping the group of Puali operators in itself

where A and B model the noise, m is the sequence length (or equivalently the number of random Clifford gates applied before inversion) and λ is related to the avarage gate fidelity.

The avarage error per Clifford gate $\epsilon_{Clifford}$ is given by

$$\epsilon_{Clifford} = 1 - F, \tag{3.2}$$

where F is the avarage gate fidelity (correct?). Sobstituting in 3.2 the formula for F we obtain

$$\epsilon_{Clifford} = \frac{d}{2^n - 1} = \frac{1-p}{1-2^{-n}}, \tag{3.3}$$

which shows how the avarage error per Clifford gate is directly connected to the exponential decay rate.

Randomized Benchmarking

For the results we present in the following the technique used slightly differs from the one described in section 3.1.1,

3.1.2 Optimization methods

I primi metodi che abbiamo provato per l'ottimizzazione dei parametri sono quelli standard implementati nella libreria `Scipy` [5] evitando metodi gradient-based considerato il landscape potenzialmente complicato della funzione RB. Il primo metodo utilizzato è stato Nelder-Mead [6] dato che in letteratura ara già stato riportato il suo utilizzo per obiettivi simili [7].

`Optuna` [8]

`CMA-ES` [9]

3.2 RX90 calibration

3.3 Flux pulse correction

3.3.1 Notes on signal analysis

3.3.2 Cryoscope

The experiment that we describe in this section was first introduced in [10], the goal is to determine predistortions that needs to be applied to a flux pulse signal so that the qubit receives the flux pulse as intended by the experimenter.

3.3.3 Filter determination

IIR

FIR

for description and notes on `CMA-ES` see section 3.1.2

Output filters in QM

Chapter 4

Conclusions

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