

# Summary of the quantumsim paper [1]

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December 5, 2018

## 1 Error model parameters

Table 1: Main error model parameters for simulation

Parameter	Symbol	Value	Explanation and notes
Qubit relaxation time	$T_1$	30 $\mu s$	Only affects qubits in the excited state. Consistent set of values: [20 - 100 $\mu s$ ]
Qubit dephasing time (white noise)	$T_\phi$	60 $\mu s$	Consistent set of values would be $2T_1$ or $\infty$ (all white noise dephasing eliminated)
Decay time	$T_2$	30 $\mu s$	$\frac{1}{T_2} = \frac{1}{T_\phi} + \frac{1}{2T_1}$
Single-qubit gate time	$T_{g,1Q}$	20 ns	
Two-qubit gate time	$T_{g,2Q}$	40 ns	
Measurement time	$\tau_m$	300 ns	
Depletion time	$\tau_d$	300 ns	?
Fast Measurement time	$\tau_m^{\text{fast}}$	100 ns	
Fast Depletion time	$\tau_d^{\text{fast}}$	100 ns	?
Readout infidelity	$\epsilon_{RO}$	5 (-3)	
Physical qubit Fidelity	$\mathcal{F}_{phys}(t)$	-	$\mathcal{F}_{phys}(t) = \frac{1}{6} \left( 1 + e^{-\frac{t}{T_1}} \right) + \frac{1}{3} \left( 1 + e^{-t \left( \frac{1}{2T_1} + \frac{1}{T_\phi} \right)} \right)$
Physical qubit error rate	$\epsilon_{phys}$	-	$\epsilon_{phys} = -\tau_{circuit} \frac{d\mathcal{F}_{phys}(t)}{dt}  _{t=0} = \frac{\tau_{circuit}}{3T_1} + \frac{\tau_{circuit}}{3T_\phi}$
In-axis rotation error	$p_{axis}$	1 (-4)	? Decay corresponding to shrinking along the y axis because of the single-qubit gates depolarizing noise
In-plane rotation error	$p_{plane}$	5 (-4)	? Decay corresponding to shrinking along the x and z axis because of the single-qubit gates depolarizing noise

## 2 Error models

In the quantumsim module, all gates are applied in the Pauli transfer matrix representation:

$$(R_\Lambda)_{ij} = \frac{1}{2} \text{Tr}(\sigma_i \Lambda \sigma_j)$$

where  $\sigma_i$  are the Pauli operators:  $\sigma_0 = I$ ,  $\sigma_1 = X$ ,  $\sigma_2 = Y$ ,  $\sigma_3 = Z$

### 2.1 Qubit Idling

While idling for a time  $t$ , a transmon in  $|1\rangle$  or in superposition could relax to  $|0\rangle$  or acquire random quantum phase shifts due to  $1/f$  noise sources (flux noise) or others. The dephasing effect only appears in a superposition state.

### 2.1.1 Amplitude-phase damping model

$$R_{\Lambda_{T_1}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \sqrt{1-p_1} & 0 & 0 \\ 0 & 0 & \sqrt{1-p_1} & 0 \\ p_1 & 0 & 0 & 1-p_1 \end{bmatrix}$$

$$R_{\Lambda_{T_\phi}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \sqrt{1-p_\phi} & 0 & 0 \\ 0 & 0 & \sqrt{1-p_\phi} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

with  $p_1 = 1 - e^{-\frac{t}{T_1}}$  and  $p_\phi = 1 - e^{-\frac{t}{T_\phi}}$  that are the probabilities for relaxation and pure dephasing, respectively.

### 2.1.2 Qubit idling

Idling for a duration  $t$ :

$$R_{AP(t)} = R_{\Lambda_{T_1}} R_{\Lambda_{T_\phi}}$$

## 2.2 Single-qubit $R_y(\pi/2)$ rotations

"Single-qubit gates [...] errors can mostly be attributed to Markovian noise. [...] we thus model these errors as Markovian".

"Single-qubit rotations are modeled by sandwiching an instantaneous Pauli transfer matrix, representing the rotation, with periods of duration  $\frac{\tau_{g,1Q}}{2}$  of amplitude and phase damping. This allows to model the gate for different  $T_1$  and  $T_\phi$  [...] However, [...] actual gates are more accurately described when adding a [...] depolarizing noise to the instantaneous part. In the Bloch sphere, this decay corresponds to shrinking toward the origin, with factor  $1 - p_{axis}$  along the y axis and  $1 - p_{plane}$  along the x- and z-axes":

$$R_{R_y(\pi/2)} = R_{AP(\frac{\tau_{g,1Q}}{2})} R'_{R_y(\pi/2)} R_{dep} R_{AP(\frac{\tau_{g,1Q}}{2})}$$

where

$$R_{dep} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-p_{plane} & 0 & 0 \\ 0 & 0 & 1-p_{axis} & 0 \\ 0 & 0 & 0 & 1-p_{plane} \end{bmatrix}$$

and  $R'_{R_y(\pi/2)}$  is the Pauli transfer matrix describing the theoretical  $\pi/2$  rotation along the y axis.

## 2.3 CZ gates

"The C-Z gate is achieved by flux pulsing a transmon into the  $|11\rangle \leftrightarrow |02\rangle$  avoided crossing with another, where the 2 denotes the second-excited state of the fluxed transmon. Holding the transmons here for  $\tau_{g,2Q}$  causes the probability amplitudes of  $|01\rangle$  and  $|11\rangle$  to acquire phases[...]

Our full (but simplistic) model of the CZ gate consists of an instantaneous CZ gate with single-qubit phase error  $\delta_{\phi_{1Q}}$  and two-qubit phase error  $\delta_{\phi_{2Q}} = \frac{\delta_{\phi_{1Q}}}{2}$ , sandwiched by idling intervals of duration  $\frac{\tau_{g,2Q}}{2}$ ."

## 2.4 Measurement

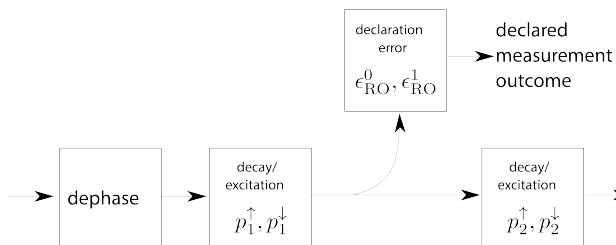


Figure 1: The model for measurements consists of a dephasing of the qubit followed by a period of decay and excitation with probability  $p_{\uparrow/\downarrow}^{(1)}$ . At this point, the qubit state is sampled. The sampling result is subject to a declaration error  $\epsilon_{RO}$ , and the qubit state is subject to further decay or excitation with probabilities  $p_{\uparrow/\downarrow}^{(2)}$  before the end of the measurement block

The initial dephasing step in the measurement model (Fig. 1) occurs due to the photon decay effect.

"We find that the readout errors  $\epsilon_{RO}^{(i)}$  are almost independent of the qubit state  $|i\rangle$ , and so we describe them with a single readout error parameter  $\epsilon_{RO}$ ". The outcome-independent declaration error of  $\epsilon_{RO} = \epsilon_{RO}^1 = \epsilon_{RO}^0 = 0.15\%$  is extracted from experiments.

They ignore effects leading to measurement-induced mixing and non-linearity of the readout resonator, as well as residual photon numbers.

## 2.5 Photon decay

In the presence of photons in a readout resonator, the coupled qubit is affected suffering a  $p_{\phi, photon}$  dephasing. This dephasing is present whenever the coupled qubit is brought into superposition before the readout resonator has returned to the vacuum state following the last measurement. This dephasing is then implemented via the same Pauli transfer matrix as  $R_{\Lambda_{T_\phi}}$ .

## 2.6 Flux Noise

During a quantum algorithm, "transmons are repeatedly moved in frequency away from their sweetspot using flux pulses, either to implement a C-Z gate or to avoid one. Away from the sweetspot, transmons become first-order sensitive to flux noise, which causes an additional random phase shift."

"As this noise typically has a  $1/f$  power spectrum, the largest contribution comes from low-frequency components that are essentially static for a single run, but fluctuating between different runs." "Shifting the transmon from its sweetspot  $f_{q,max}$  to a lower frequency  $f_q(t)$  makes it first-order sensitive to flux noise".

"In our simulation, we approximate the effect of this noise through ensemble averaging, with quasi-static phase error added to a transmon whenever it is flux pulsed."

As one could see in the figures 4 and 5 from the Supplemental information, a little over-rotation caused by inaccurate calibration of the flux pulse in a single- or two-qubit gate translates in a huge increase of the  $\epsilon_L$ .

## 3 The quantumsim simulation package

"Quantumsim performs calculations on density matrices utilizing a graphics processing unit in a standard desktop computer [...]"

One-qubit and two- qubit gates are applied to the density matrix as completely positive, trace preserving maps represented by Pauli transfer matrices. When a gate involving a « new » qubit must be performed, the density matrix of the system is dynamically enlarged to include that one [...]"

Qubit measurements are simulated as projective and following the Born rule, with projection probabilities given by the squared overlap of the input state with the measurement basis states. In order to capture empirical measurement errors, we implement a black-box measurement model by sandwiching the measurement between idling processes. After measuring some qubit they remove that qubit from the density matrix.

## 4 Optimization of logical error rates

## 5 Projected improvement with advances in quantum hardware

- Memory figure of merit ( $\gamma_m = \frac{\epsilon_{phys}}{\epsilon_L}$ ). How close are  $\epsilon_{phys}$  and  $\epsilon_L$ . Metric to check how good the error correction is.
- Computational performance ( $\gamma_c = \frac{\epsilon_{phys}\tau_{g,1Q}}{\epsilon_L\tau_{cycle}}$ ), where, at  $\gamma_c = 1$  the computational break-even point is defined.
- A value of  $T_1 > 80\mu s$  for planar transmons is emerging.

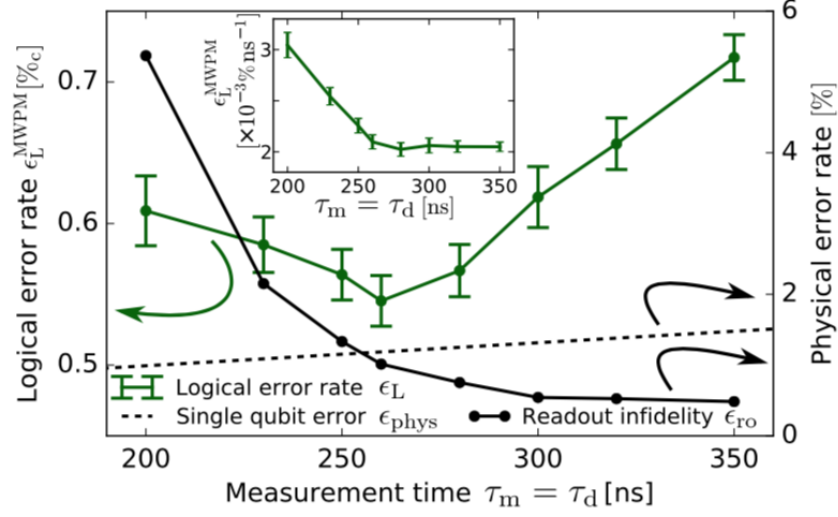


Figure 2: Measure time optimization based on the SC-17 logical error rate. Optimal  $\tau_m = 280$  ns

## 6 Other observations

The following statements are fairly general:

- "Small quasi-static qubit errors are suppressed by the repeated measurements"
- If either the ancilla error rate ( $\epsilon_{anc}$ ) or the  $\epsilon_{RO}$  are bigger than  $\epsilon_{phys}$
- "Optimal cycle parameters for logical error rates per cycle and per unit time are not the same. This implies that logical qubits functioning as quantum memory should be treated differently to those being used for computation"

## 7 Effects not taking into account

They use a simple model for the CZ errors. They neglect leakage (previous experiments have reduced leakage probability per CZ to  $\approx 0.3\%$ ) Of course this simplification is also in **quantumsim**.

## 8 Doubts

- What is the depletion time?
- I do not understand the Inset in Fig. 2
- What is the difference between qubits used for quantum memory and quantum computation? In our case we consider both at the same time, isn't it?
- Why do we consider that the measurement time is 300 ns instead of 280 ns, that is the optimum time for logical qubit error rate?
- Study the optimum times for each gates to minimize the physical qubit error rate

- At some point  $T_\phi = \infty$  is mentioned. Is it possible to clean all the dephasing white-noise.
- Is the Y rotation gates the only ones affected by the dephasing noise?
- ~~What is the flux noise?~~ → "Shifting the transmon from its sweetspot  $f_{q,max}$  to a lower frequency  $f_q(t)$  makes it first-order sensitive to flux noise"
- What are the quasi-static qubit errors?
- Does the  $R_{dep}$  parameter mean that the polarizing model is included?
- ~~Is the  $p_{\phi,photon}$  summed to the  $p_\phi$  in the  $R_{\Lambda T_\phi}$  or how is it done?~~ → is the dephase at the beginning of the measurement model (Fig. 1)
- What is an adiabatic gate?
- I do not understand anything in the measurement.
  - What is  $\epsilon_i^{m,o}$ ,  $a$  and  $b$
  - Are the ignored effects during measurements important for us? Do not think so.
- Quantsim is able to work not taking into account the surface code, isn't it?
- Surface code is good for Quantum Memory. Which code is good for Quantum Computation?
- Is this error model the one that they use in quantsim?
- "Ancillas are measured at the end of each cycle, and thus not entangled with the rest of the system". Is this due to the circuit they are using or quantsim works like that in general

## 9 Ideas

### 9.1 Maximum depth given a $\epsilon_{phys}$

Depth:	$d$
Cycle time (minimum operation time):	$T_{cycle}$
Circuit time:	$\tau_{circuit} = d \times T_{cycle}$
Physical qubit error rate:	$\epsilon_{phys} = \frac{d \times T_{cycle}}{3} \frac{T_\phi + T_1}{T_\phi T_1}$

Given a maximum error rate for the qubits ( $\epsilon_{phys}^\uparrow$ ) as an upper bound, the maximum depth of the circuit would be:

$$d^\uparrow = \frac{3\epsilon_{phys}^\uparrow}{T_{cycle}} \frac{T_\phi T_1}{T_\phi + T_1}$$

## References

- [1] T. E. O'Brien, B. Tarasinski, and L. DiCarlo. Density-matrix simulation of small surface codes under current and projected experimental noise. *npj Quantum Information*, 3(1), Sep 2017.