Simulation of real world superconducting quantum information processing devices

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Abstract

- *Superconducting circuits (transmon qubit devices) are contestants in the race to build a universal quantum computer. This poster presents one way to study these systems numerically (for about 15 to 20 qubits) on a supercomputer without making approximations to the model Hamiltonian. In the near future we will use the corresponding simulation code to simulate real world devices which are currently built within the OpenSuperQ project.*

Methodology: Product Formula Algorithm

- *The so-called product formula algorithm [1] enables us to solve the time dependent Schrödinger equation in such a way that the error with respect to the exact solution is controllable by the time step parameter* τ.

- *The first order product formula algorithm has a local error which is bounded by* $\mathcal{O}(\tau^2)$, *the error for the second order algorithm is bounded by* $\mathcal{O}(\tau^3)$, *more generally the n-th order algorithm has an error which is bounded by* $\mathcal{O}(\tau^{n+1})$.

- *Note that if the error, introduced by the truncation (see model), is greater than the product formula approach error, the error scaling is not valid any more.*

Model: Superconducting Circuits

- *The model Hamiltonian* $H(t) = H_{Tr.}(t) + H_{Res.}(t) + H_{Int.}$ *consists of a transmon or SQUID term*

$$H_{Tr.}(t) = \sum_{i \in \mathcal{I}} E_{C_i}(\hat{n}_i - n_{Ex_i}(t))^2 - E_{J_{i,1}} cos(\hat{\varphi}_i)) \; - E_{J_{i,2}} cos(\hat{\varphi}_i \pm \varphi_{Ex_i}(t)),$$

with the capacitive energies E_{C_i} *and junction energies* $E_{J_{i,1}}$ *and* $E_{J_{i,2}}$. *The function* $\varphi_{Ex_i}(t)$ *enables us to perform quantum gate operations by means of a high speed flux line. Similarly, the function* $n_{Ex_i}(t)$ *allows us to perform quantum gate operations by using a voltage source.*

- *The second term*

$$H_{Res.}(t) = \sum_{j \in \mathcal{J}} \Omega_j \hat{a}_j^\dagger \hat{a}_j + \Omega_j \epsilon_j(t)(\hat{a}_j + \hat{a}_j^\dagger),$$

describes the resonators, with eigenfrequencies Ω_j *as well as the measurement process itself by means of the time dependence part [2]* $\Omega_j \epsilon_j(t)(\hat{a}_j + \hat{a}_j^\dagger)$.

- *The last term describes a dipole coupling between the different subsystems*

$$\begin{aligned} H_{Int.} = & \sum_{(i,j) \in \mathcal{I} \times \mathcal{J}} G_{i,j} \hat{n}_i (\hat{a}_j + \hat{a}_j^\dagger) \\ & + \sum_{(j,j') \in \mathcal{J} \times \mathcal{J}} \lambda_{j,j'} (\hat{a}_j + \hat{a}_j^\dagger)(\hat{a}_{j'} + \hat{a}_{j'}^\dagger) + \sum_{(i,i') \in \mathcal{I} \times \mathcal{I}} \Lambda_{i,i'} \hat{n}_i \hat{n}_{i'}. \end{aligned}$$

The parameters $G_{i,j}$ *describe the qubit-resonator interaction,* $\lambda_{j,j'}$ *determine the resonator-resonator interaction and* $\Lambda_{i,i'}$ *the qubit-qubit interaction.*

- *Our goal is to keep the truncation error low. Therefore we usually use the four lowest eigenstates* $|m\rangle$ *of the transmon subsystems as well as the four lowest eigenstates* $|k\rangle$ *of the resonators as a basis* $\mathcal{B} = \{|m\rangle \otimes |k\rangle\}_{m,k}$ *for the simulations.*

Engineering issues: Leakage, Crosstalk and Enviorment

- *Due to the fact that we use the four lowest eigenstates of the transmon term as basis for the time development, we are able to describe and study the leakage effects.*

- *Additionally, since we do not approximate the interaction term, as it is done in most other studies [2], we are able to describe and study crosstalk in more detail. Crosstalk is associated with undesirable qubit-qubit interaction.*

- *The method we use also allows us to extend the current model Hamiltonian to one which describes different environments, e.g. two level defects [3] or quasiparticles [4]. Hopefully this will allow us to study engineering issues beyond leakage and crosstalk.*

Results: The Same Control Pulse And Three Different Approximations

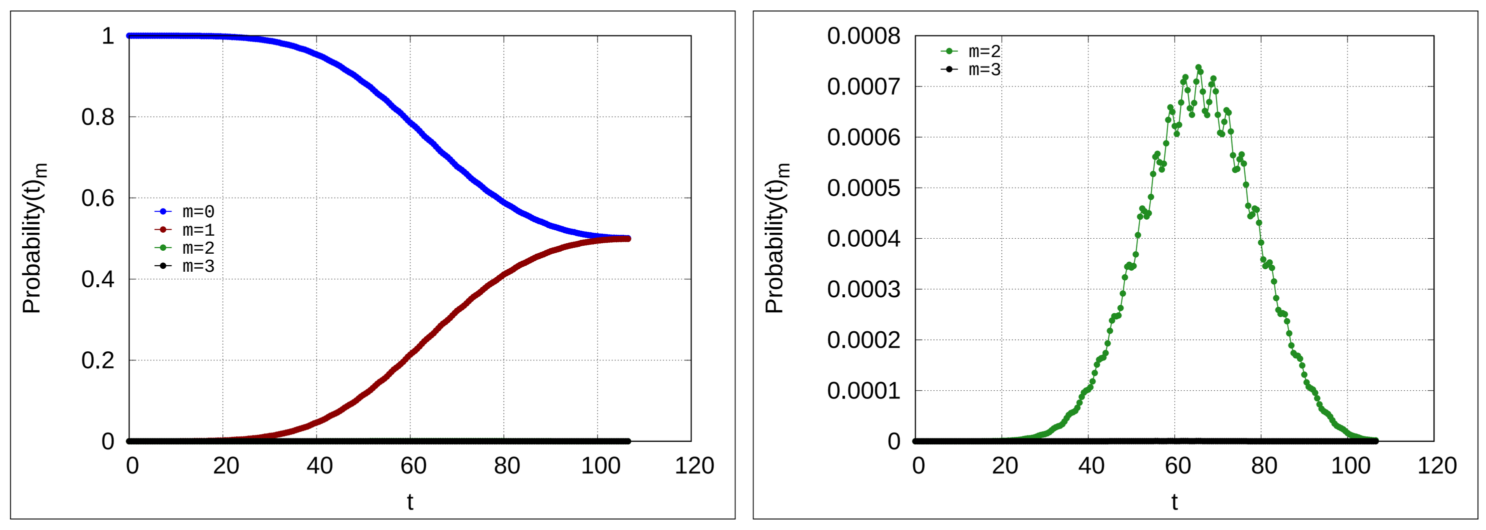

Figure: Transmon qubit Hamiltonian is truncated at φ^2.

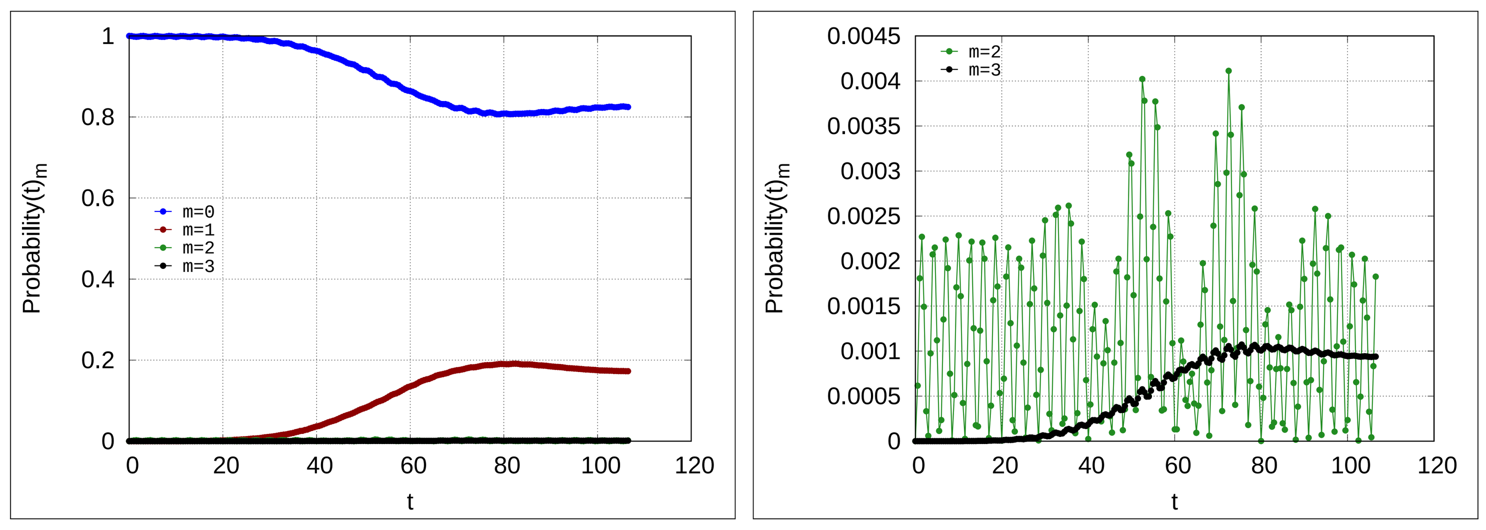

Figure: Transmon qubit Hamiltonian is truncated at φ^4.

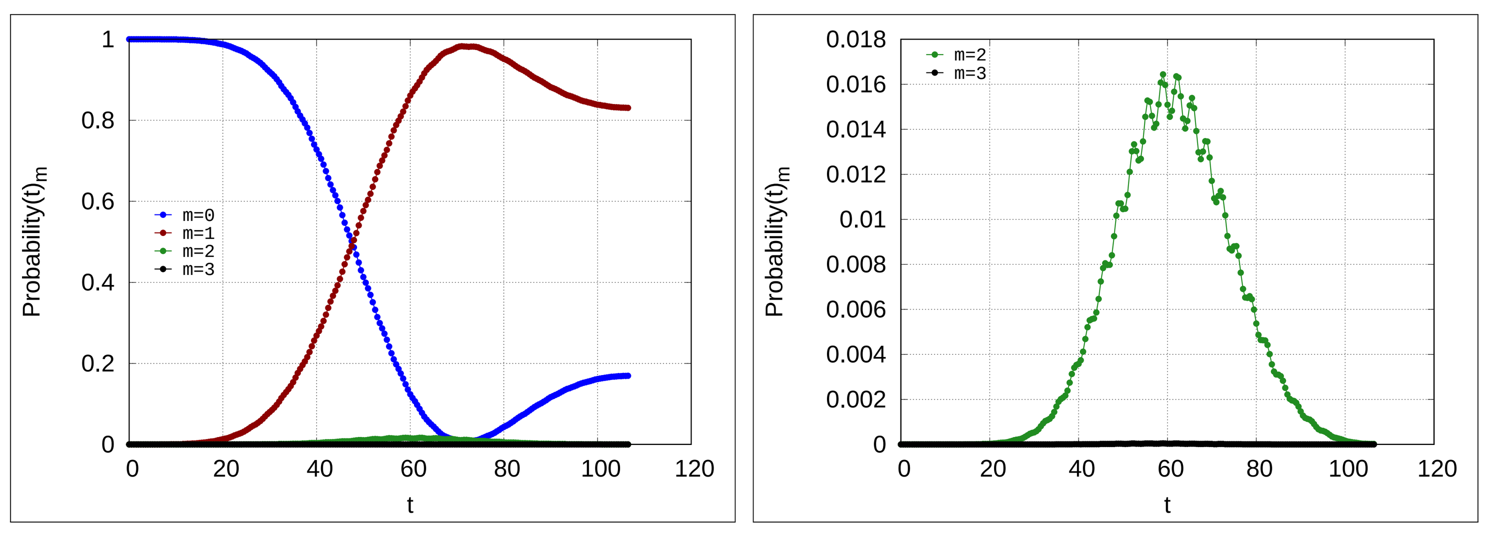

Figure: Transmon qubit Hamiltonian without any approximation.

References

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