Leakage reduction in fast superconduting qubit gates via optimal control: Overview

D. Tien

VNU University of Science

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Introduction

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- Open-loop optimal control theory (gradient/newton-descent) offers means for states and gates realization with high fidelity.
- However, this method produces less accurate results in comparision to ion traps and NMR systems.
- As a results, pulse shaping for supercond. qubits requires closed-loop optimal control (finite, continuous space), i.e., direct optimization of the experimental system.

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Backend comparison

Experiments are carried out on a transmon-type fixed-frequency superconducting qubit. Some numbers:

- transition frequency $\omega_{01}/2\pi = 5.11722$ GHz;
- anharmonicity $\Delta/2pi = -315.28$ MHz;
- $T_1 = 105\mu$s and $T_2 = 39\mu$s.

Better than armonk ($\sim$us). Not as good as jakarta.

Realization of X and Y pulses

Drive IF signal consists of two control components,

$$\Omega = \Omega(t)\exp\{i(\omega_{ssb}t + \phi)\}, \tag{1}$$

which is up-converted to the qubit frequency ω_{ij} and synthesized by AWG. Thus real-time control over phase, frequency, and amplitude. In a frame rotating at the qubit frequency, the transmon Hamiltonian is given by

$$\frac{\hat{H}^R}{\hbar} = \Delta|2\rangle\langle 2| + \frac{\tilde{\Omega}_x(t)}{2}\sum_{j=1}^{2}\hat{\sigma}^x_{j,j-1} + \frac{\tilde{\Omega}_y(t)}{2}\sum_{j=1}^{2}\hat{\sigma}^y_{j,j-1}, \tag{2}$$

where $\Omega_{x,y}$ are the drive's IQ-components. Choosing appropriate ϕ and θ results in realization of arbitrary X and Y pulses.

DRAG first-order correction

Since transmons have low anharmonicity, DRAG is employed to suppress leakage out of the computation subspace. To the first-order correction, a Gaussian shaped pulse $\Omega_x(t) = A\exp\{-t^2/(2\sigma^2)\}$ with amplitude A and width σ, is corrected by

$$\Omega_{DRAG}(t) = \Omega_x(t) + i\frac{\beta}{\Delta}\frac{d\Omega_x(t)}{dt}, \tag{3}$$

where the imaginary component eliminates the spectral weight of the pulse at $|1\rangle \leftrightarrow |2\rangle$ transition.

DRAG second-order correction

DRAG pulses fail to produce high fidelity state transition when gate duration is lower than $10/\Delta$[1]. To overcome this, higher-order correction terms $\delta_n = a_n + ib_n$ have to be added. This results in a list of piecewise-constant control amplitudes

$$\Omega_n = \Omega_{DRAG}(n\Delta t) + \delta_n. \tag{4}$$

The time discretization Δt is naturally given by the sampling rate of the AWG generating the pulse envelope. Optimization parameters are amplitude corrections a_n and b_n to the n-th sample of $\Omega_{x,y}$.

[1] $\Delta/2\pi = -315.28$ MHz

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Pulse parameter optimization

- Pulse parameters are optimized using the covariance matrix adaptation-evolution strategy (CMA-ES) algorithm. Briefly, $\mathcal{S}^k$ (λ sets) are generated, with $k = 1, \ldots, \lambda$ each characterized by the parametrization of the pulse shape. Each's shape-candidate is evaluated by a cost function, which generates a new set of candidate shapes.
- Randomized benchmarking as cost function (m Clifford gates, K sequences). Clifford gates are constructed by composing $\pm X/2$ and $\pm Y/2$ pulses (!?) based on $\mathcal{S}^k$.

Fidelity estimates of optimized short pulses

1. First round using CMA-ES to calibrate DRAG pulses, $\mathcal{S} = \{A, \beta, \omega_{ssb}\}$.
2. Next round extending $\mathcal{S}$ to include higher correction orders, namely a_j and b_j.

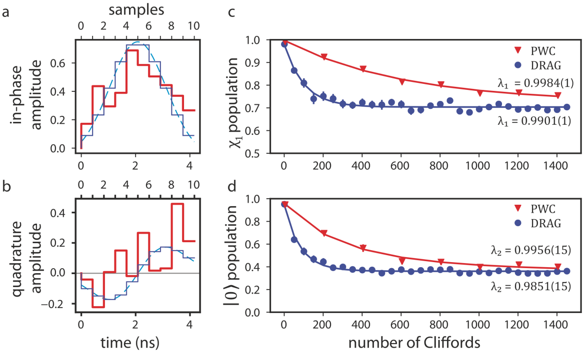

Figure: Optimized DRAG pulse.