Fully pulse-controlled gate operations on always coupled qubit chains

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Motivation

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- Motivated by superconducting flux qubits
- Strong, direct coupling $\Rightarrow$ fast multi-qubit gates
- Challenge: switching off coupling when not needed
- Crazy idea: keep qubits permanently coupled, use dynamical decoupling

Content

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The qubit chain model

Implementing the two-qubit CNS gate with decoupling

Performing an entangling gate sequence

The qubit chain Hamiltonian

- N-qubit chain with nearest-neighbor couplings and pulse generator:

$$
\begin{aligned}
H = & \frac{1}{2} \sum_{i=1}^{N} \left[\epsilon_i Z^{(i)} + f_i(t) \left(X^{(i)} \cos \varphi_i(t) - Y^{(i)} \sin \varphi_i(t) \right) \right] \\
& - \frac{g}{2} \sum_{i=1}^{N-1} \left[X^{(i)} X^{(i+1)} + Y^{(i)} Y^{(i+1)} \right]
\end{aligned}
$$

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The two-qubit CNS gate

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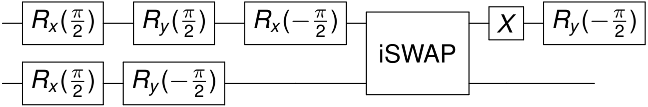
- iSWAP [1] gate resulting from XX-type interaction after $T = \pi/(2g)$:

$$U_{\text{iSWAP}} = \exp\left[iT\frac{g}{2}\left(X^{(i)}X^{(i+1)} + Y^{(i)}Y^{(i+1)}\right)\right] = \begin{pmatrix} 1 & & & \\ & 0 & i & \\ & i & 0 & \\ & & & 1 \end{pmatrix}$$

- Combine with single-qubit gates to construct CNS (CNOT+SWAP) gate:



[1] N. Schuch and J. Siewert, Phys. Rev. A. **67**, 032301 (2003)

Single-qubit rotations

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- Rotations $R_x(\phi) = \exp(-iX\phi/2)$, $R_y(\phi) = \exp(-iY\phi/2)$
- Make use of the pulse generator:

$$H^{(i)}_{\text{pulse}}(t) = \frac{f_i(t)}{2}\left(X^{(i)}\cos\varphi_i(t) - Y^{(i)}\sin\varphi_i(t)\right)$$

- Rectangular pulse: $f_i(t) = f$ during pulse duration
- $T = \phi/f$
- Special cases: $X = R_x(\pi)$, $Y = R_y(\pi)$

Isolating a single qubit from the chain

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- Single qubit annihilator scheme: alternating X and Y pulses

$$\begin{aligned} U(4\tau) &= Y\exp(-iH\tau)X\exp(-iH\tau)Y\exp(-iH\tau)X\exp(-iH\tau) \\ &= \exp(-iYHY\tau)\exp(-iZHZ\tau)\exp(-iXHX\tau)\exp(-iH\tau) \\ &\equiv \exp(-i\overline{H}4\tau) \end{aligned}$$

- Lowest-order decoupling

$$\overline{H}^{(0)} = \frac{1}{4}\sum_{A\in\{\mathbb{1},X,Y,Z\}} AHA = 0$$

Selective decoupling on the qubit chain

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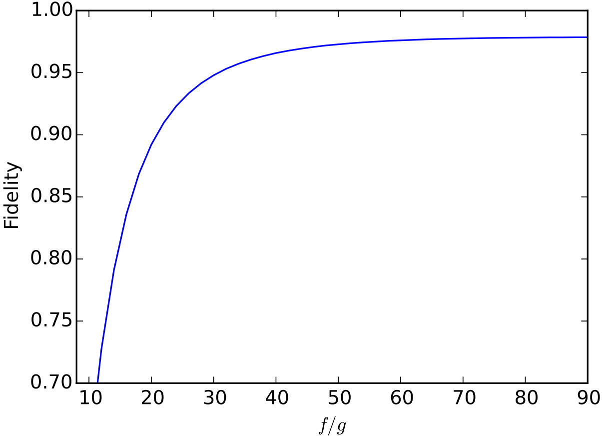
- Alternating $X \otimes X$ and $Y \otimes Y$ pulses preserve coupling between qubits
- Alternating $X \otimes Y$ and $Y \otimes X$ pulses eliminates coupling
- $\Rightarrow$ Combine as needed to preserve couplings for two-qubit gates and isolate remaining qubits
- E.g. parallel gates on qubits 2-3 and 4-5:

$$p_1 = X \otimes Y \otimes Y \otimes X \otimes X \otimes Y$$
$$p_2 = Y \otimes X \otimes X \otimes Y \otimes Y \otimes X$$
$$p_3 = p_1$$
$$p_4 = p_2$$

- Actual pulses not instantaneous $\Rightarrow$ performance depends on f

Numerical results for a single CNS gate



Numerical results for a single CNS gate

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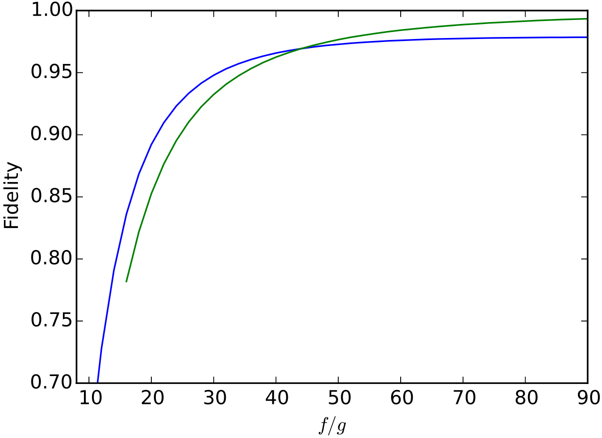

Physical limits for the pulse amplitude

Realistic f/g ratios?

- Strong flux qubit coupling: $g \approx 500\,\text{MHz}$
- Problem: A pulse amplitude of several GHz may excite higher states
- $f = 20g$ might be possible
- Idea: pulse shaping
- Alternative: reduce g

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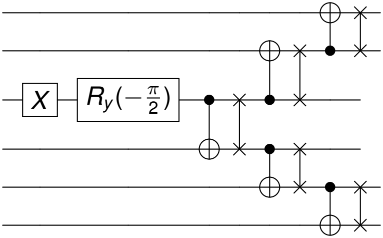
Entangling the qubits

Sequence of CNS gates to entangle all qubits in the state $|\mathrm{GHZ}\rangle = \frac{|0\rangle^{\otimes N} + |1\rangle^{\otimes N}}{\sqrt{2}}$:



Numerical results for GHZ state fidelity

N	$f = 40g$	$f = 60g$	$f = 80g$
3	0.969	0.974	0.985
4	0.927	0.949	0.969
5	0.894	0.932	0.958
6	0.860	0.915	0.948
7	0.821	0.896	0.935
8	0.796	0.876	0.922

Protection from other errors

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- By construction, annihilator scheme on each qubit
- $\Rightarrow$ Offers limited protection against environmental influences
- E.g. engineering deficiencies: $\epsilon_i \neq \epsilon_j$ degrades gate fidelity:
- Decoupling protects against small discrepancies

GHZ state fidelity with $\epsilon_i \neq \epsilon_j$

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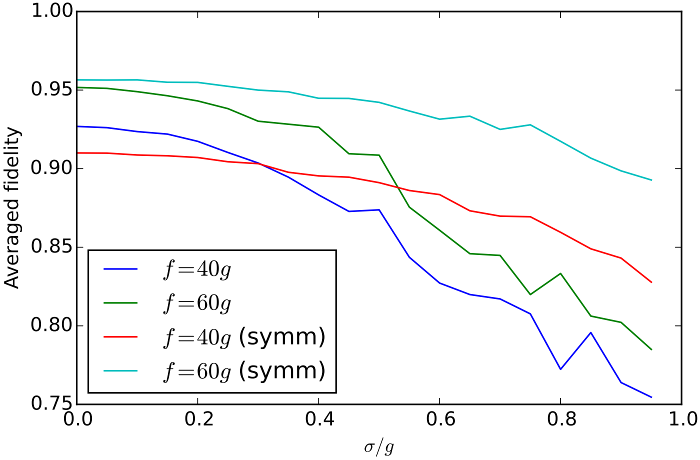

Summary

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- Linear chain of permanently coupled qubits
- Use decoupling to suppress couplings as needed
- Decoupling pulses X, Y implemented by pulse generator which also implements single-qubit gates
- $\Rightarrow$ Quantum gate sequences controlled entirely through local pulses
- Also: all qubits are protected to first order against environmental influences and diagonal disorder
- But: require very strong pulses, $f/g = 80$ desirable

Thank you!