Pulse Optimization for Mediated Entangling Gates on a Neutral Atom Quantum Processor

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Neutral Atoms as Qubits

Neutral Atoms have emerged as a promising quantum information platform due to their well-characterized energy levels, long coherence times, and relative ease of scalability. Neutral atom quantum computing utilizes the nuclear spin of neutral atoms, such as Strontium and Ytterbium, to construct qubits. Utilizing laser pulses, atoms are excited to highly energized states called a Rydberg state, $|r\rangle$, in which their electrons orbit the nucleus at a high principal quantum number, n.

In neutral atoms, qubits are defined using hyperfine split nuclear spin states, denoted $|0\rangle$ and $|1\rangle$, with both global and individually addressed lasers used to implement single qubit gates . To implement entangling two qubit gates, a laser is used to drive a transition from $|1\rangle$ to $|r\rangle$. Entanglement is possible due to a blockade effect called the Rydberg Blockade (r_B) where the excitation of one atom can prevent the excitation of nearby atoms within a certain radius.

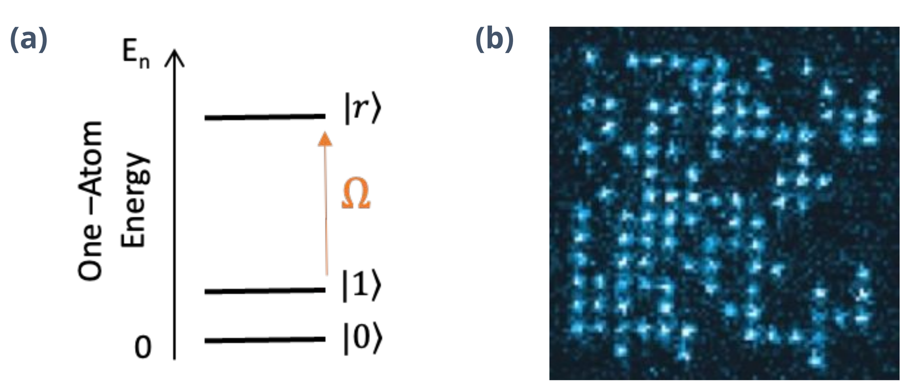

Fig 1: (a) A resonant laser with strength Ω drives the $|1\rangle$state to Rydberg state $|r\rangle$transition. (b) Optical Tweezer array of >100 Sr^{57} atoms.

Motivation for wire gate design

By driving nearby atoms within the Rydberg blockade regime, a two-qubit controlled phase gate (CZ) may be implemented; however, the use of these spatially extended Rydberg states impose constraints on speed and parallelization of entangling gates.

One way to alleviate this issue is to move the atoms further apart and place mediating "wires" of ancilla atoms between adjacent rows of atoms being used as data qubits. The ancilla atoms ensure that the rydberg radii of the data qubits do not overlap while allowing for entanglement between data qubits mediated through the ancilla atoms. This enables greater parallelization of entanglement operations.

Constructing a time-optimal pulse that implements a high-fidelity, mediated entangling gate between two data qubits is a challenging task. Our goal with this project is to use numerical simulation to determine ideal parameters for such a pulse sequence and characterize its robustness to a variety of noise sources

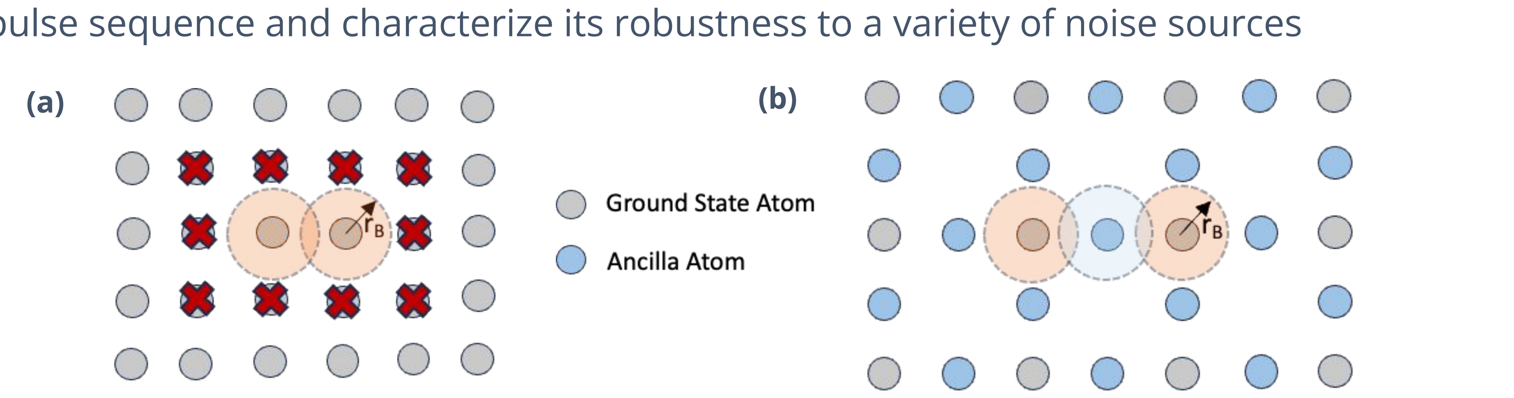

Fig 2: Tweezer arrays without (a) and with (b) ancilla atoms between qubits. Dotted orange circles represent ground state qubits made resonant to their rydberg state. In (a), red crosses correspond to atoms barred from excitation due to the nearby Rydberg blockade.

Methods & Proof of Concept

We simulated our systems using the following general form for the Hamiltonian implemented using the QCTRL Boulder Opal optimization suite:

$$H(t) = \Omega(t) H_{\text{drive}} + \Delta(t) H_{\text{detune}}$$

Where H_{drive} couples the qubit subspace to the Rydberg states, H_{detune} encodes the laser detuning, and $\Omega(t)$ and $\Delta(t)$ are the temporal profiles of the laser amplitude and detuning respectively. Finding an optimal pulse sequence entails optimizing the functional form of $\Omega(t)$ and $\Delta(t)$ such that the resulting unitary evolution yields a CZ gate on the data qubit subspace.

To validate our optimization scheme, we implemented a direct CZ gate on two atoms using the Levine-Pilcher (LP) gate [3]. In this simplified system we optimized over the pulse amplitude, pulse detuning, and phase jump between the two pulse segments. We found that QCTRL successfully reproduces the population dynamics expected from the LP gate with a fidelity greater than 99.999%.

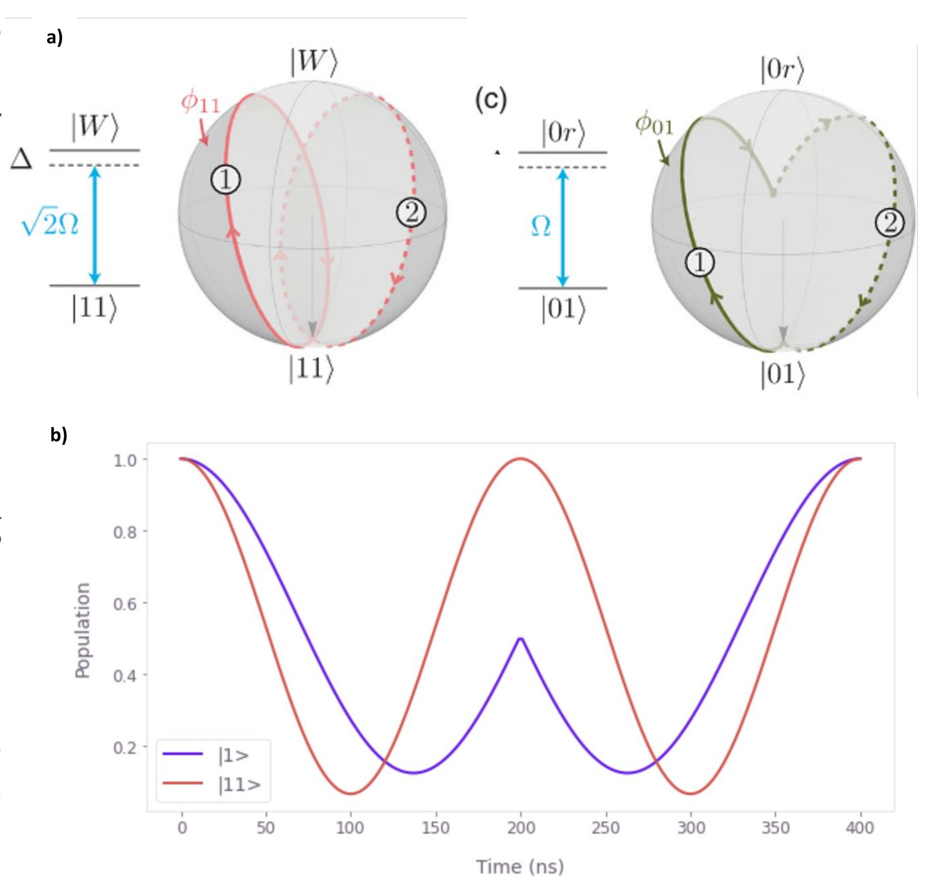

Fig 3: a) Dynamics of the LP gate on the bloch spheres for the {|11⟩,|W⟩=|1r⟩+|r1⟩} and {|01⟩,|0r⟩} subspaces. Taken from [3].
b) Population dynamics from the two atom CZ gate optimized using QCTRL.

CCZ Results

We utilized our optimization scheme to implement two different CCZ pulses. The first was optimized assuming infinite blockade strength and zero next-nearest-neighbor interactions. For this pulse, we optimized over the pulse amplitude, pulse detuning, phase jump between the two pulse segments, phase offset, and pulse duration. We then repeated this procedure accounting for finite blockade strength and nonzero next-nearest-neighbor interactions. In this case, we additionally optimized over the atom separation distance in the array.

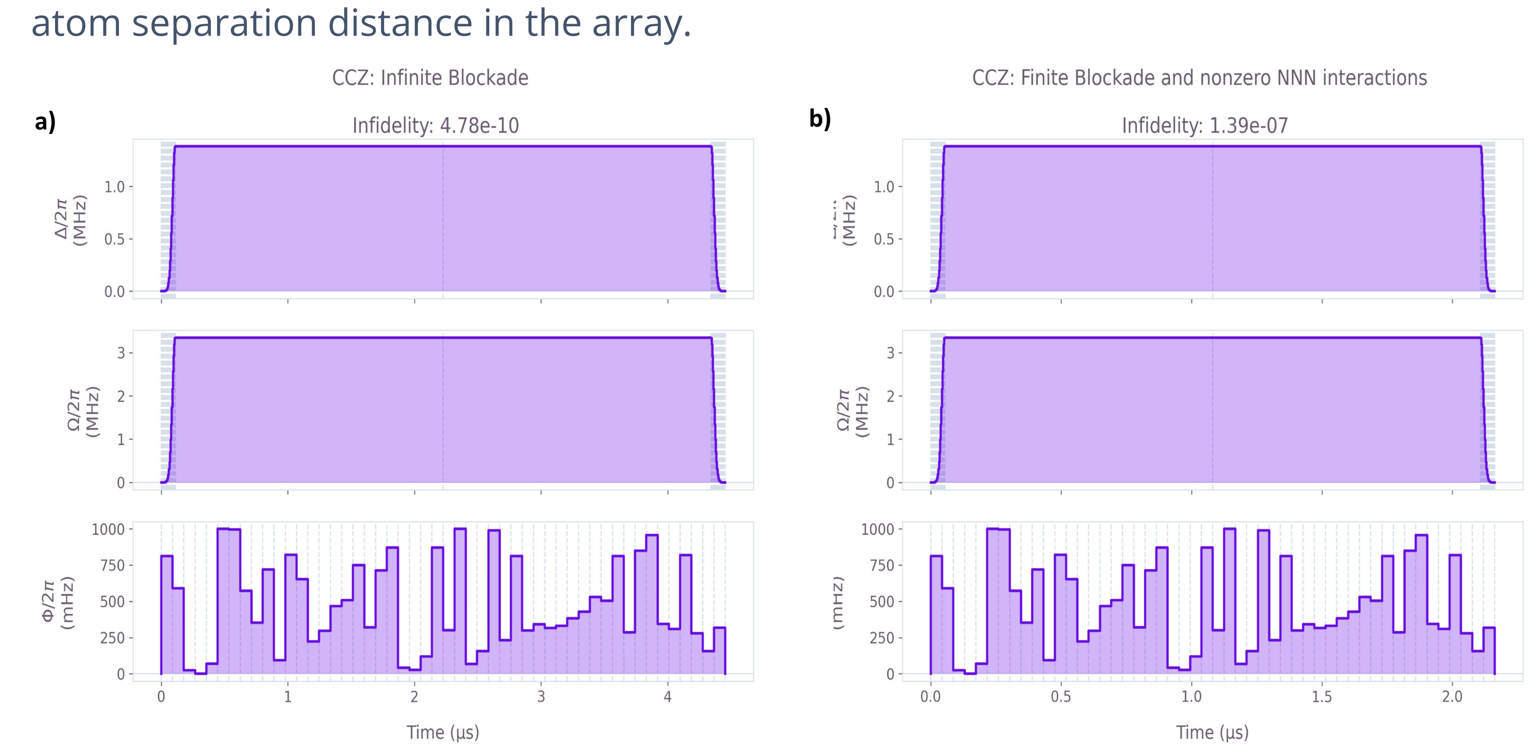

Fig 5: Optimized CCZ pulse profiles for systems with: a) infinite blockade strength and zero next-nearest-interactions and b) finite blockade strength and nonzero next-nearest-neighbor interactions

Detuning Robustness

To better characterize how our optimized gate would perform in a realistic noise environment we simulated how a fixed offset in the optimized laser amplitude and detuning affected the gate fidelity for both the optimized two qubit LP gate and the three qubit CCZ gate.

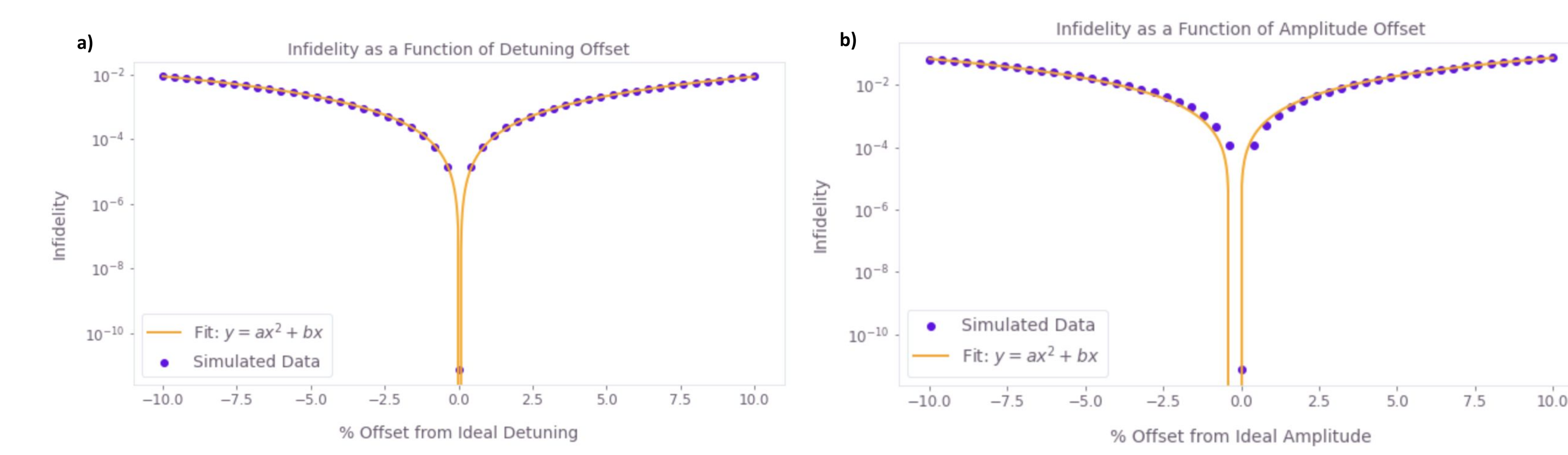

Fig 5: a) Log scaled infidelity as a function of offset from ideal detuning and b) infidelity as a function of offset from ideal laser amplitude . The change in infidelity with detuning offset is well captured by a quadratic fit while the change infidelity with amplitude is not as well captured but the quadratic model still provides a reasonable fit at larger offsets. The gate seems to be an order of magnitude more sensitive to deviations in laser amplitude than in deviations to detuning.

CCZ Atom Distance Robustness

To characterize the tolerance of the CCZ pulse optimized with finite blockade strength and next-nearest-neighbor interactions to variations in atom separation, we also simulated how different offsets in the ideal atom separation distance would affect the fidelity.

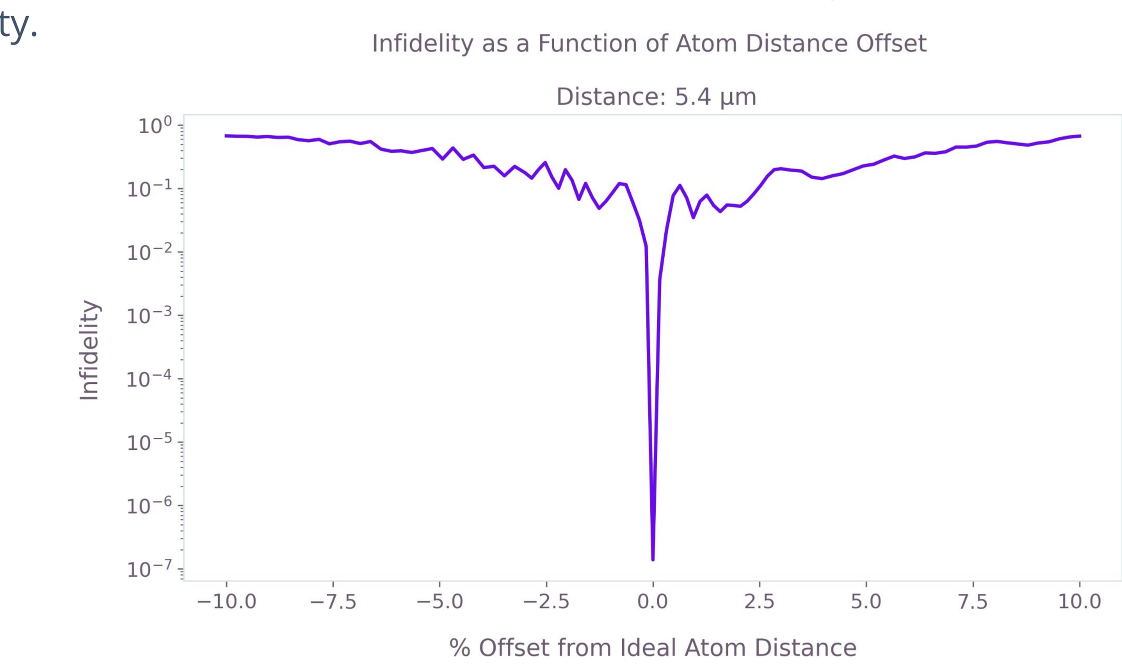

Fig 6: Log scaled infidelity as a function of offset from ideal atom separation distance.

Future Work and Acknowledgments

- Incorporate noise models that model atom loss and generalized dephasing noise into robustness analysis
- Analytically derive a temporal profile that implements the desired mediated interaction
- Examine robustness when classical stochastic noise is incorporated into the simulated laser pulse

We thank Jeffrey Epstein, Frederic Hummel, Prof. Deep Gupta, and Brant Bowers for their support throughout the completion of this project.

ELECTRICAL & COMPUTER ENGINEERING
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