Operations in superconducting qubits: Two-qubit gates - Adriaan Rol

Interactions between qubits are controlled using two-qubit gates. In transmon qubits the two-qubit gate that is used to form the universal gate set is the conditional-phase gate, also known as a CPhase- or CZ- gate. Applying a conditional-phase gate to two qubits causes the target qubit to acquire \pi radians of phase based on the state of the control qubit.

As an example let us consider two qubits, a control qubit, qC starting in either the ground or the excited state, and a target qubit, qT starting the in |+> state. When the control qubit is in the ground state and we apply the C-Phase gate there is no effect on the target qubit, however, when the control qubit is in the excited state the target qubit will acquire \pi radians of phase.

In transmon qubits, the C-Phase gate is implemented by tuning in and out of resonance with an interaction in the two-excitation manifold.

To understand how to perform such a C-Phase gate, we will look at

- what mediates the interaction;
- how qubits can be tuned in and out of resonance with an interaction and why this causes the qubits to accumulate phase;
- how to use this interaction to perform a C-Phase gate while minimizing leakage out of the computational subspace, and finally;
- what the experimental challenges are when implementing high fidelity gates.

In superconducting transmon qubits two-qubit gates are based on a transversal qubit-qubit coupling. This coupling is mediated through a coupling resonator. Because the interaction is mediated by a coupling resonator, it is possible to couple physically separated qubits, making room for other components on the chip, such as readout resonators.

To be able to tune in and out of resonance with interaction the transition frequency of a transmon qubit must be controlled.

By applying a current to the flux-bias line, the amount of flux through the SQUID loop of the transmon changes, making it is possible to control the qubit's frequency.

When a pulse is applied to the flux-bias line, the qubit is detuned from it's operating frequency for the duration of the pulse, while the qubit is detuned, phase accumulates.

To understand how this flux control can be used to perform a C-Phase gate, let us take a look at the level diagram of two transmon-qubits as a function of the flux through the target qubit.

In this level diagram, the subscripts denote the number of excitations in the control- and target-qubit respectively.

The interaction that is used to perform a C-Phase gate is an avoided crossing between the |11> and |02> state.

The amount of phase that the target qubit picks up is most evident when the |11> and |01> level diagrams are overlaid, by expressing them in terms of detuning with respect to their maximum energy.

It can be seen that the detuning of the target qubit is different based on the state of the target qubit. This difference is marked in red over here.

By detuning the qubit into the red region, it is possible to make the target qubit acquire a phase conditional on the state of the control qubit.

However, the interaction we are using is an interaction between the |11> and |02> state. As the |02> state is not part of the computational subspace, we want to avoid any energy transfer to this state.

This is typically done using a special pulse-shape known as a fast-adiabatic pulse that minimizes the leakage. This pulse shape can be expressed as a Fourier series in the frame of the interaction, which, with the knowledge of the system parameters can be converted first into a frequency and then into a voltage to be applied to the flux-bias line. Because the conditional phase and the leakage depend on the exact trajectory of the qubit, flux-pulsing-based two-qubit gates are highly sensitive to distortions of the pulse shape.

Distortions can be caused by electrical components in the signal path between the waveform generator and the qubit such as filters and cables but even the on-chip response causes distortions to the signal the qubit experiences.

These effects are typically corrected by pre-distorting the waveform “x” with a filter designed to invert the distortions, turning it into “x-tilde”, so that the qubit experiences, not a pulse “y”, but a pulse “y-tilde” that is equal to the intended waveform.

The key challenge in flux-pulsing based CZ gates is to correct for these distortions. This requires characterizing the distortions that the qubit experiences when cooled down and correcting these with sufficiently high precision. At the same time, efforts are under way to become more resilient against these effects, both by exploring new pulsing shaping techniques and through innovations in hardware.