Operations in superconducting qubits: Measurements - Niels Bultink

In this lecture I will explain how we can perform measurement of superconducting qubits.

At the end of every quantum algorithm, the computation result has to be obtained by performing measurement of the qubits. And, as dictated by the laws of quantum mechanics, any superposition states are projected into well-defined zeros and ones.

A transmon qubit, as depicted here, can be measured via a readout resonator that is coupled to it. The resonance frequency of the resonator is quite far away from the qubit transition frequency, on the order of GHz. However, due to the coupling, there is a shift in the resonator's frequency depending on the qubit state. This shift is evidenced here by the measured resonator transmission dips of the qubit in the ground state and the excited state.

This shift is typically on the order of a few megahertz, three orders of magnitude smaller than the detuning. We can observe this shift (and thereby the qubit state) by injecting the resonator with a pulse near the resonator frequency.

The pulse, as shown here, is reflected by the resonator. Here, we show the output voltage as a function of time for the qubit in the ground state and the excited state, which clearly look different. Hence, we are able to distinguish and measure the two different qubit states.

The traces I've just shown you, look very clean and distinguishable as they are averaged over thousands of measurements.

However, for most real quantum protocols, we require to discern the qubit state in a just single run. But to avoid disturbing our precious quantum system, we can only use readout pulses that consist of a couple of photons. At these power levels, in the order of just a few femto Watts, we are struggling to distinguish the different quantum states as the signal is hampered by quantum noise, as depicted here.

To quantify how well qubit measurement is performing in the presence of this noise, we record the integrated voltage of thousands of individual traces. By plotting these individual shots in the histograms, we extract the fidelity of the measurement.

The fidelity expresses the probability that the measurement returns the right outcome averaged over the two possible qubit input states. Epsilon01 expresses the probability for erroneously getting outcome 1 for a ground state input and Epsilon10 vice versa. In this case, aided by the world's lowest noise, superconducting amplifiers we can achieve a fidelity close to 98%.

I've just shown you the readout of one qubit. Of course, a full quantum computer consists of many quantum bits and these quantum bits all have to be read out at the same time. To allow this simultaneous readout, we couple each qubit to its own readout resonator and choose the lengths of the resonators such that they resonate all at a distinct frequency. Just like the different strings in a piano.

By next sending down a pulse that is the sum of multiple components, in this case two, each tuned to its own readout resonator, we can probe multiple readout resonators at the same time. Each component will only be picked up by the targeted resonator. In the analysis of the output signals, we again separate the two different frequency components.

Here, we show the readout results for qubit 1 for each of the four possible two-qubit basis states, indicating that the signal practically only depends on the state of the targeted qubit, separating 00 and 10 from 00 and 11.

Dually, we here show the readout results for the other qubit, which separate 00 and 10 from 00 and 11.

You might now be able to imagine how this readout scheme can be extended to measure ever increasing numbers of qubits. Here, we depicted a seventeen-qubit device where we play the simultaneous readout trick using seventeen readout resonators divided over three different input and output lines.

This might sound to you like a finished story. However, there are many improvements to be made still to get to a fully scalable quantum computer. Exemplary topics that are currently being addressed in research, and which might also be attractive for additional reading are:

Advanced readout pulse shaping to quickly populate and depopulate the readout resonators to speed up the readout. Second, superconducting amplifiers to suppress noise in the readout amplification chain and methods to quantify their performance. And lastly we work on advanced readout topologies. In this case, using multiple cascaded readout resonators per qubit, to increase the flux of photons and further speed up the readout.