Device challenges for near term superconducting quantum processors: frequency collisions

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Abstract**—** The outstanding progress in experimental quantum computing with superconducting Josephson-junction based qubits over the past few decades has pushed coherence times many orders of magnitude above that of the first measured. We are also in the midst of scaling towards complex architectures of multi-qubit processors where maintaining very low gate error rates at the limits supported by coherence times is extremely important. Here we will review some of the critical materials and device challenges for superconducting qubits from the perspective of improved coherence and improved error rates. In particular we will focus on the problem of frequency allocations in order to target multi-qubit lattices for fixed-frequency microwave-based gates.

I. Introduction

In quantum processors employing fixed-frequency superconducting Josephson-junction-based transmon qubits [1] and all-microwave cross-resonance two-qubit gates [2-3], 'frequency collisions' and 'frequency crowding' are a distinct challenge to attaining low gate error rates. The problem arises due to nearest-neighbor or next-nearest-neighbor qubits which are degenerate in one or another excitation energy. Josephson junctions for transmon qubits are typically patterned lithographically out of Al/AlOx/Al. Fabrication defines the critical current of the junction and in turn the frequency of the transmon qubit.

The cross-resonance gate is an all-microwave entangling gate between a control qubit and a target qubit. It involves a defined fixed coupling between two qubits, where a ZX interaction (generator of a controlled NOT, CNOT, gate) is activated by driving the control qubit at the transition frequency of the target qubit. The strength of the drive and the frequency detuning between the qubits affect the total CNOT gate time and effectiveness. In particular, the transmon is a weakly anharmonic qubit, meaning there are higher energy levels that are not too far away from the ground to first excited state energy. Such levels can also cause collisions that can be detrimental to the cross-resonance gate performance.

Therefore, as processors scale up in the number of qubits, allowed cross-resonance gates depend upon accuracy of fabricated Josephson junctions and where the frequencies of the qubits come out. The rest of this paper will describe the types of problems that can arise with respect to frequency collisions and we show a Monte Carlo modeling method to demonstrate the yield of devices with usable qubit frequencies.

II. Types of Gate Collisions

The transmon cross-resonance frequency collision conditions are not simply limited to qubits that participate together in a CR gate, but extends to non-nearest neighbors as well. Considering transmon qubits of frequency f and anharmonicity δ, we know of six degeneracy conditions that degrade gate fidelities and one that leads to unfavorably slow gate rates: $f_j = f_k$ (any two qubits j, k sharing a coupling), $f_j = f_k - \delta/2$ (gate pair of control j, target k qubits), $f_j = f_k - \delta$ (any two qubits j, k sharing a coupling), $f_j > f_k - \delta$ (gate pair of control j, target k will exhibit `slow gate' behavior), $f_i = f_k$ (two target qubits i, k sharing a control j), $f_i = f_k - \delta$ (two target qubits i, k sharing a control j) and $2f_j + \delta = f_k + f_i$ (gate pair of control qubit j & target qubit k; spectator qubit i is coupled to control j). To ensure high gate fidelities in our devices, we must avoid any of these conditions. Assuming all qubits are transmons with frequencies on the order 5 GHz and anharmonicity δ ~ -340 MHz, we can assume an exclusion region of at least +/- 5 MHz around each condition. Exact bounds remain under study both experimentally and using effective-Hamiltonian modeling.

III. Frequency Arrangement Strategies and Monte Carlo Modeling

How can we be confident to meet these constraints in a lattice of 17 (e.g. for a distance 3 rotated surface code) or more qubits? A useful metric is the standard deviation σ_f in precisely setting the qubit frequency. One tactic to avoid frequency crowding would be to design all of the qubits in the lattice to be identical, and rely on the random scatter σ_f to avoid 'frequency collisions.' Another idea would be to arrange the lattice into a regular pattern of qubit frequencies. Figure 1 shows likely arrangements. For instance, a pattern of five frequencies should prevent any two adjacent qubits from sharing a frequency [4]. We can model the behavior in a Monte Carlo manner, as diagrammed in Figure 3: assign a mean frequency to each position in the pattern, populate the lattice with random frequencies from distributions σ_f around each mean, count the collisions, and repeat the process more than 10^3 times. The yield is the fraction of cases having no collisions. In Figures 4 and 5 we see that in order to achieve a useful yield (more than a few %) in a 16 or 17 qubit lattices we will have to use a 5-frequency pattern with σ_f well below 50 MHz. To produce a useful yield in a 49-qubit lattice will require a 5-frequency pattern with σ_f well below 20 MHz.

The connectivity of the lattice also has a measurable effect. For instance, figure 4 shows that in a 17-qubit device, for most values of σ_f, using a square-lattice layout will improve yield ~ 2x over a skew-symmetric lattice.

Statistical models can guide our designs for scaled-up qubit lattices if we know the fabrication precision σ_f,. We expect the ground-state to first excited state qubit frequency difference to follow $f01 \sim (8\ E_J\ E_C)^{0.5}$ with Josephson energy E_J given by $E_J \sim I_c/2$ and Josephson junction critical current I_c related to junction resistance R_n by the Ambegaokar-Baratoff relation $I_c \sim \Delta/2eR_n$, while charging energy E_c derives from qubit capacitance C as $E_c = e^2/2C$. This implies that we can learn about the statistics of our qubit frequencies from measurements of junction resistances.

We will present correlations of room temperature resistance measurements with actual measured qubit frequencies and give a guide towards achievable device yields for larger qubit lattices.

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REFERENCES

[1] Jens Koch et al., "Charge-insensitive qubit design derived from the Cooper pair box" *Physical Review A*, 76, 042319, 2007.

[2] Chad Rigetti and Michel Devoret, "Fully microwave-tunable universal gates in superconducting qubits with linear couplings and fixed transition frequencies" *Phyiscal Review B,* 81, 134507, 2010.

[3] Jerry M. Chow et al., "Simple All-Microwave Entangling Gate for Fixed-Frequency Superconducting Qubits" *Physical Review Letters*, 107, 080502, 2011 .

[4] Jay M. Gambetta, Jerry M. Chow, Matthias Steffen, Building logical qubits in a superconducting quantum computing system". *npj Quantum Information*, 3, 2, 2017.

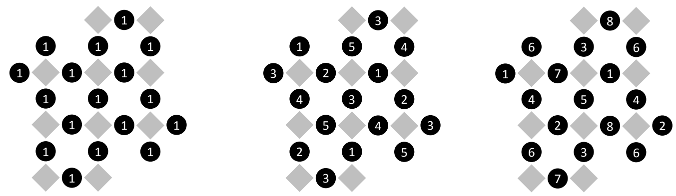

FIG. 1: Possible frequency patterns for 17Q skew-symmetric lattice. Qubits are indicated by solid circles, coupling buses by gray squares. Left: One frequency. Rely on random scatter to avoid collisions. Middle: Two frequencies. Right: Five frequencies. No two qubits on the same bus has the same frequency

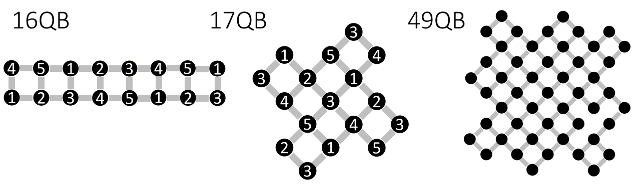

FIG. 2: Square lattices of three sizes. Five-frequency patterns illustrated in two cases.

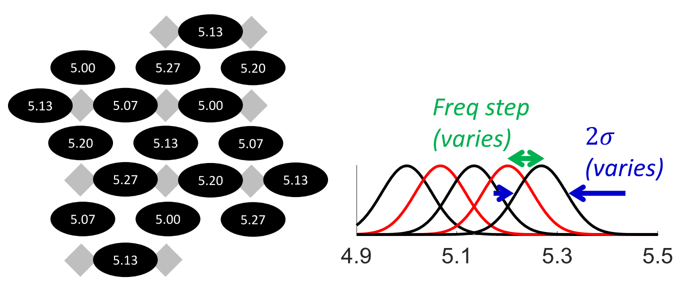

FIG. 3: Example of frequency collision statistical model. Five-frequency pattern. Lattice is populated from random distributions about five mean frequencies. We vary the frequency step between means (67 MHz in this example) as well as the width of the distributions. Left: Mean frequencies, Right: Distributions

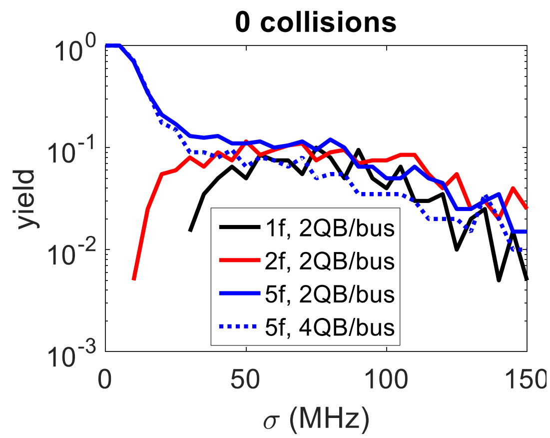

FIG. 4: Predicted yield of 17-qubit chips having no frequency crowding. Lattice connected either in skew-symmetric (4Q/bus) or square (2Q/bus) manner. Three possible patterns of qubit frequencies

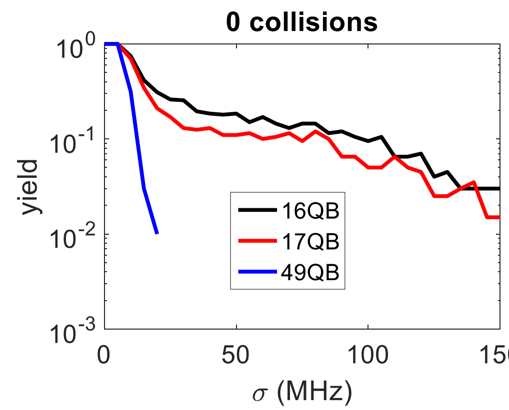

FIG. 5: Predicted yield of chips having no frequency crowding. Monte Carlo model predicts yield of square qubit lattices shown in FIG. 2, as a function of σ