

Coherent errors in a superconducting six-qubit network with beyond-nearest-neighbor connectivity

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Enhancing qubit connectivity in quantum processors is an important milestone for more efficient implementation of algorithms and novel error-correction protocols. While all-to-all connectivity has been demonstrated in quantum processors based on ion traps and neutral atoms, the exploration of enhanced connectivity in the superconducting qubit architecture has been a more recent endeavor. Here, we demonstrate the operation of a network comprising six superconducting transmon qubits with a novel, beyond-nearest-neighbor connectivity. We use a circular ring resonator with six qubits placed on the periphery at 60° spacing and capacitively coupled to it in a three-dimensional circuit-QED architecture. The ring resonator acts as a two-path coupler between each pair of qubits, and we present results demonstrating that each qubit has finite coupling to three other qubits with negligible coupling to the remaining two qubits. In this architecture, with fixed-frequency qubits and always-on coupling, we benchmark the single-qubit and two-qubit gates using randomized benchmarking. We find that our gate fidelities are strongly affected by the enhanced connectivity. We characterize the spread in qubit frequencies due to cross-Kerr terms and quantify its detrimental effect on the performance of single- and two-qubit gates. Finally, we analyze the effect of the spectator qubits using numerical simulations and propose a path toward optimizing this system and achieving >99% two-qubit gate fidelities across all connected qubit pairs.

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I. INTRODUCTION

Quantum information processing promises to efficiently solve a class of problems intractable for conventional computers [1]. Quantum mechanical phenomena such as superposition and entanglement are employed as computational resources, leading to the availability of a larger phase space during an algorithm [2]. Superconducting qubits have been one of the leading platforms [3] for realizing large-scale quantum processors. With recent demonstrations of quantum

advantage [4] and suppression of error rates beyond threshold using surface codes for quantum error correction [5] with nanosecond-scale gate times, they remain the most promising architecture for achieving fault-tolerant quantum processing units (QPUs).

While it is imperative to push the typical metrics outlining DiVincenzo's criteria [6] such as qubit coherence times, measurement and gate fidelities, and state initialization, achieving beyond-nearest-neighbor connectivity may turn crucial in pushing the performance of future large-scale QPUs to achieve large quantum volume [7]. A densely connected QPU allows efficient implementation of quantum algorithms [8]. Further, particular classes of quantum error-correcting codes demand processors with higher connectivity [9–11]. While beyond-nearest-neighbor connectivity has been natively possible in ion trap and neutral atom systems [8], it has only been engineered more recently in the superconducting qubit architecture [12–14]. Here, we study the operation of a six-qubit network implementing a novel, beyond-nearest-neighbor connectivity using a ring-resonator (RR) coupler [12] in the superconducting circuit architecture. This work extends prior ring-resonator demonstration [12] by demonstrating single- and two-qubit gates across the realized graph

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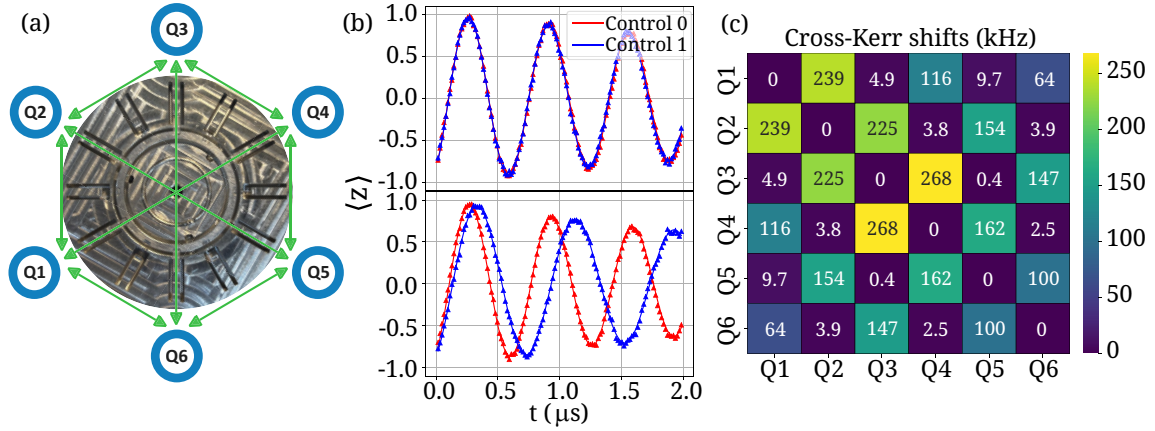


FIG. 1. (a) The connectivity of the six-qubit network achieved using the ring-resonator-based coupler. The connectivity graph is overlaid on the image of the six-qubit system achieved using 3D cQED and demonstrates beyond-nearest-neighbor coupling. (b) We distinguish connected and disconnected qubit pairs by measuring the cross-Kerr shift using a conditional Ramsey experiment. The top (bottom) plot shows the shift in frequency of Q3 when Q1 (Q4) is initialized in the excited state. (c) The cross-Kerr matrix establishes the connectivity of the six-qubit network. We see a difference in the order of magnitude of the measured values between connected and disconnected qubit pairs. We attribute the variability in the values to not functioning at precisely the special frequency of the RR and human error due to the manual placement of the transmon chips in the 3D cavity.

and analyzing gate-level errors under enhanced always-on connectivity.

We use the ring resonator as the coupling element between the six qubits and study the performance of single- and two-qubit gates using randomized benchmarking (RB) [15]. We use the fixed-frequency, always-on coupling architecture, with entangling gates generated using the cross-resonance (CR) [16,17] interaction. We first characterize the six-qubit network, measuring its typical parameters and demonstrating the novel connectivity. The always-on coupling with enhanced connectivity can bring additional error terms in the Hamiltonian of the full system [18]. The error terms in the Hamiltonian lead to frequency shifts dependent on the spectator qubit states, leading to an ambiguity in qubit frequency. This leads to off-resonant driving of qubits and, thus, coherent errors. Furthermore, the presence of more spectator qubits also adds additional constraints on the operational frequency landscape of the devices [13]. We investigate these errors by characterizing the spread in qubit frequencies and quantifying its detrimental effect on the performance of single- and two-qubit gates. Finally, we use numerical simulations to suggest a path to optimize performance and obtain sub-1% gate errors across all connected qubit pairs.

II. EXPERIMENT

The ring resonator is a circular transmission line that we use to mediate coupling between qubits. The qubits lie along the periphery of the RR and are capacitively coupled to it. We realize the ring-resonator coupler in three-dimensional (3D) circuit QED architecture using a rectangular coaxial geometry in a machined aluminum cavity [12]. There are 12 slots at angular spacings of 30° distributed along the periphery where qubit chips can be placed. All qubits have individual readout resonators, which are $\lambda/4$ resonators realized using a cantilever geometry. The fundamental mode of

the RR is 3.1 GHz. An image of the ring-resonator-based coupler is shown in Fig. 1(a) with the connectivity graph overlaid.

For this experiment, we place six transmon [19] qubits along the RR with 60° angular separation between adjacent qubits. As a consequence of the RR physics [12], the qubits separated by 60° and 180° are coupled to each other, and we refer to them as connected pairs. The qubits separated by 120° have negligible coupling, and we refer to them as disconnected pairs. This arrangement of the devices yields a network topology of a hexagon with all long diagonals, displayed in Fig. 1(a). The qubits have tantalum capacitor pads [20] with Al/AIO_x/Al Josephson junctions. The dimensions of the capacitor pads are optimized to achieve the desired anharmonicity and the interqubit, qubit-cavity couplings. We target the qubit frequencies around 4.7 GHz to achieve the desired interferometric effects due to the RR, and the qubit-qubit detunings and anharmonicity in the CR compatible regime [17]. The readout resonators have a fundamental frequency close to 7.3 GHz and a linewidth around 5 MHz. We work in the dispersive regime, with the dispersive shifts in 200–300 kHz.

Each resonator has its own output line with a low-noise high-electron-mobility transistor based amplifier but no parametric amplifiers. In order to improve the signal-to-noise ratio of the measurements, we enhance the phase shift by exchanging the $|1\rangle$ and $|2\rangle$ state populations before the measurement pulse [21]. We use three LO sources (R&S SGS100A—6 GHz) for generating qubit control signals and three LO sources (R&S SGS100A—12.75 GHz) for generating readout signals. Three Quantum Machines' OPX+ units are used to create the control and measurement pulse envelopes and for digital demodulation of readout signals. We use IQ mixers from Marki for modulating qubit and readout pulses, and Minicircuits' three-port mixers for demodulating the readout signals to baseband. A summary of the system characteriza-

TABLE I. Summary of the transmon parameters and coherence properties for the six-qubit system.

	Freq. (GHz)	Anh. (MHz)	T_1 (μ s)	T_2^* (μ s)	T_2 (μ s)
Q1	5.031 04	−271	44	35	40
Q2	4.926 72	−269	30	21	42
Q3	5.036 48	−268	25	11	27
Q4	4.969 60	−269	37	28	30
Q5	4.8378	−280	1.6	2.2	2
Q6	4.924 66	−271	57	26	28

tion is given in Table I. The frequencies of the devices are measured to be in the 4.8–5 GHz range. While they are not precisely at the desired values, the frequencies are sufficiently close to 4.7 GHz to preserve the expected connectivity, with the drawback of slightly nonuniform coupling values for the connected pairs. The disconnected pairs display a finite coupling, which is at least one order of magnitude lower than that of the connected pairs. We achieve T_1 , T_2 times $\sim 30 \mu$ s across all qubits, except one noisy device.

We establish the network's connectivity by measuring the cross-Kerr shift between all pairs of qubits. This shift is the magnitude of the $Z \otimes Z$ component of the two-qubit effective Hamiltonian [17] of two coupled transmons with transverse coupling J and detuning Δ . For $J \ll \Delta$, the leading order $Z \otimes Z$ term is proportional to J^2 , and thus the cross-Kerr shift can be used to estimate the coupling J . An estimate of the interqubit couplings can be found in Sec. I of the Supplemental Material [22]. As shown in Fig. 1(c), the measured cross-Kerr shifts confirm the expected connectivity of the six-qubit network. This network achieves beyond-nearest-neighbor couplings, with each qubit coupled to three other qubits ($\pm 60^\circ$, 180°). The coupling with the two remaining qubits ($\pm 120^\circ$) is weak but nonzero due to the qubit frequencies not having optimal values in relation to the RR mode frequencies.

We characterize the effect of the enhanced connectivity on the frequency spread for each qubit. We measure the frequency of the qubits using a Ramsey protocol while initializing the spectator qubits in all computational basis states. In this case, we measure eight different frequencies corresponding to the eight basis states of the three connected spectator qubits. Figure 2(a) shows the set of Ramsey fringes showcasing the spread in the qubit frequency. We observe the fringes separating into families representing the total excitation number of the three qubits. The spread in each qubit's frequency as a consequence of cross-Kerr shifts due to the connected spectator qubits ranges from 0.3 to 0.6 MHz as shown in Fig. 2(b). Using these data, we estimate the interqubit couplings to be ≈ 2.5 –4 MHz. This spread in frequency degrades the QPU performance as the qubits cannot be driven on resonance, leading to dephasing effects during qubit operations.

In order to quantify the coherent error, we tune up the single-qubit gates across the six qubits and compare the RB fidelities for two cases. We first calibrate the gates by driving the qubit at the frequency f_0 , corresponding to all other qubits being in their ground states. We then measure the single-qubit

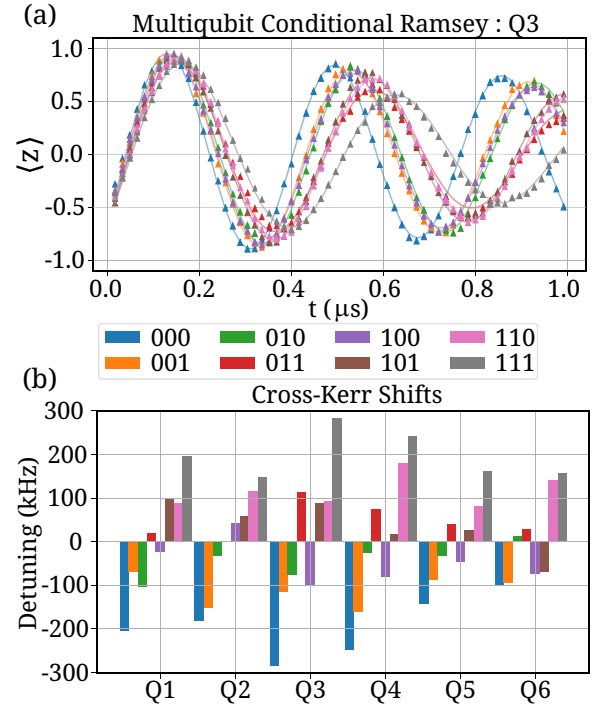


FIG. 2. Measuring the spread in frequency of a qubit due to the enhanced connectivity. (a) We directly measure the spread by performing a Ramsey experiment on one qubit while initializing the three connected qubits in the eight possible computational states. We observe the fringes separating into families representing the total excitation number of the three qubits. (b) The qubits are operated at the mean frequency of this full spread. The bar plots represent the deviation from the mean frequency for every computational state of the three connected qubits.

RB fidelity while maintaining all other qubits in the ground state. We achieve the best performance for single-qubit gates for this case. We then repeat the calibration across all qubits, but now driving at the frequency f_{mean} , the mean of the frequency spread measured using the multiqubit conditional Ramsey experiment. We then perform RB on all six qubits simultaneously, with different random sequences chosen for every qubit. The RB protocol running simultaneously on all the qubits ensures that the spectator states are randomized and correspond to the largest ambiguity in the qubit frequency. We observe a systematic degradation in the performance of the single-qubit gates. Figure 3(a) shows the corresponding data for Q3; we measure an RB fidelity of 99.8% (red trace) when driven individually at f_0 , which reduces to 99.3% (blue trace) when driven at f_{mean} , with RB simultaneously performed on all other qubits. We measure similar numbers when we choose smaller networks of five (green trace) and four (yellow trace) qubits, as the number of connected qubits being driven simultaneously is invariant. The RB fidelity degrades as the simultaneous operation corresponds to the maximum spread in qubit frequencies, leading to off-resonant driving and accumulation of dephasing errors. Figure 3(b) shows the gate infidelity measured using individual RB on Q3 as a function of detuning from the optimal driving frequency. The measured infidelity is consistent with the degradation observed in RB

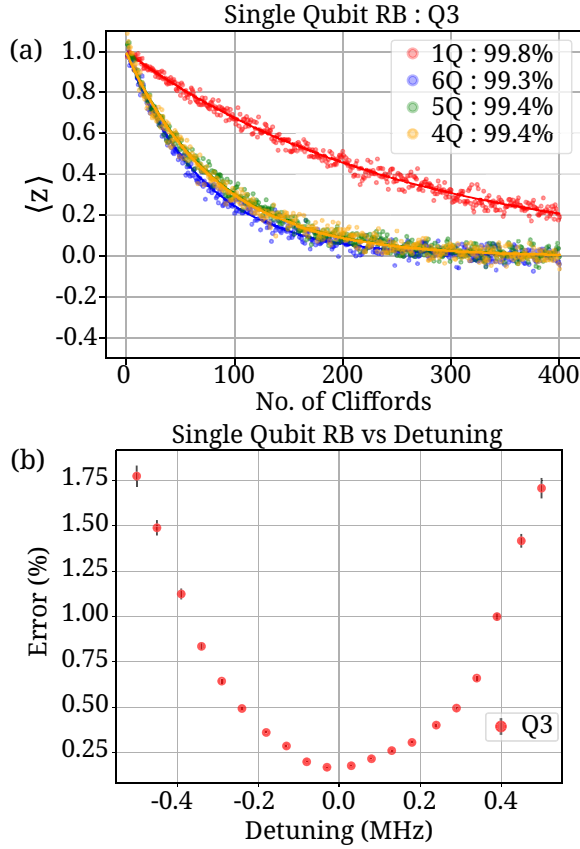


FIG. 3. Degradation in the performance of single-qubit gates. (a) We quantify the coherent error added to single-qubit gates due to driving at the mean frequency of the measured frequency spread using RB. This plot compares the single-qubit RB fidelities for Q3 measured in different scenarios. The red curve represents the RB experiment while keeping all other qubits in the ground state and driving Q3 on resonance. The other curves represent the RB data for network sizes of 6 (all qubits), 5 (Q1, Q2, Q3, Q4, Q6), and 4 (Q2, Q3, Q4, Q6). We randomize the states of the remaining qubits in the network using the simultaneous RB experiment with all qubits driven at their respective mean frequencies. (b) Individual RB degradation with off-resonant driving. The coherent error measured is consistent with the degradation of performance measured using simultaneous RB while driving at mean frequency.

when driving at f_{mean} and randomization of the states of all other qubits. All single-qubit pulses are optimized using the Derivative Removal by Adiabatic Gate (DRAG) [26] protocol.

We then proceed to benchmark the two-qubit entangling gates. Since we are working in the fixed-frequency always-on coupling architecture, we exploit the CR effect [16,27,28] to generate a controlled-not gate. The CR effect is realized between two coupled qubits, labeled control and target qubits, by driving the control qubit at the frequency of the target qubit. This drive generates a rotation of the target qubit state, with the direction of the rotation determined by the control qubit state, thus enabling the creation of entangled states. By appropriately tuning the phase of the CR drive, the $Z \otimes X$ component of the two-qubit effective Hamiltonian can be amplified, leading to a conditional rotation of the target qubit state. In addition, we use an echo sequence to cancel the

TABLE II. CR poles in a control-target-spectator system. State $|ijk\rangle|n\rangle$ represents the control, target, spectator, and drive field fock states, respectively.

Resonant transition	Matching condition
$ 110\rangle n\rangle \leftrightarrow 200\rangle n\rangle$	$\Delta_{ct} = -\alpha_t$
$ 010\rangle n\rangle \leftrightarrow 100\rangle n\rangle$	$\Delta_{ct} = 0$ MHz
$ 000\rangle n\rangle \leftrightarrow 200\rangle n-2\rangle$	$\Delta_{ct} = -\alpha_c/2$
$ 101\rangle n\rangle \leftrightarrow 002\rangle n\rangle$	$\Delta_{st} = \alpha_t$
$ 110\rangle n\rangle \leftrightarrow 020\rangle n\rangle$	$\Delta_{st} = \Delta_{ct} + \alpha_c$
$ 100\rangle n\rangle \leftrightarrow 001\rangle n\rangle$	$\Delta_{st} = 0$ MHz
$ 100\rangle n\rangle \leftrightarrow 010\rangle n\rangle$	$\Delta_{st} = \Delta_{ct}$

evolution due to the $Z \otimes I$ and $I \otimes X$ components. Finally, we choose the gate time such that the final target qubit states corresponding to the two control qubit states are maximally separated. The typical CR gate time for our experiments is 300 ns.

We first tune up the CNOT gate on the connected pairs of qubits (two-qubit bonds) while restricting the other qubits to the ground state. We determine the optimal driving frequency for performing single-qubit gates on this system by measuring the cross-Kerr shift between the two qubits. As the CR drive needs to have a precise phase relationship with the target qubit drive, this uniquely determines the CR drive frequency. We benchmark the performance of the cnot gate using interleaved RB. We then repeat the calibrations, choosing f_{mean} as the choice for the single qubit and CR drives, as the target qubit frequency spread is broader when the remaining qubits assume arbitrary states. We choose the Q3–Q4 bond for this study because it is well separated from the dominant CR pole conditions (stated in Table II) in our device.

This suboptimal choice of CR drive shows up as an enhanced $I \otimes Z$ strength in the two-qubit effective Hamiltonian of the bond leading to phase errors in the entangling operation. This results in a significantly worse RB fidelity of the cnot gate. The data for the Q3–Q4 bond are shown in Fig. 4. The top plot shows interleaved RB traces for the cnot gate tuned up using the optimal drive frequency for the two-qubit bond with other qubit states restricted to their ground states. These data for the other bonds can be found in Table II and Fig. 6 of the Supplemental Material [22]. We measure a fidelity of $96.2\% \pm 0.7\%$ for Q3–Q4, which degrades to $93.2\% \pm 0.8\%$ when we choose f_{mean} as the CR drive and target drive frequency.

III. SIMULATIONS

Given the coherence properties of Q3 and Q4, the coherence limit [29] for a 300 ns gate time assuming an ideal two-qubit system is about 98.8% (RB fidelity). We observe a significant underperformance of the CR gate compared to that value, even when choosing the bond's ideal drive frequency, indicating the presence of coherent errors in the system. For ideal CR performance, the control-target detuning (Δ_{ct}) needs to be in a regime where the $Z \otimes X$ rate is large compared to the $Z \otimes Z$ rate [17,28]. Furthermore, the detuning (Δ_{ct}) and anharmonicity ($-\alpha_c$) should be chosen to avoid the poles at $\Delta_{ct} = -\alpha_c$ and $\Delta_{ct} = -\alpha_c/2$ to prevent leakage out of the

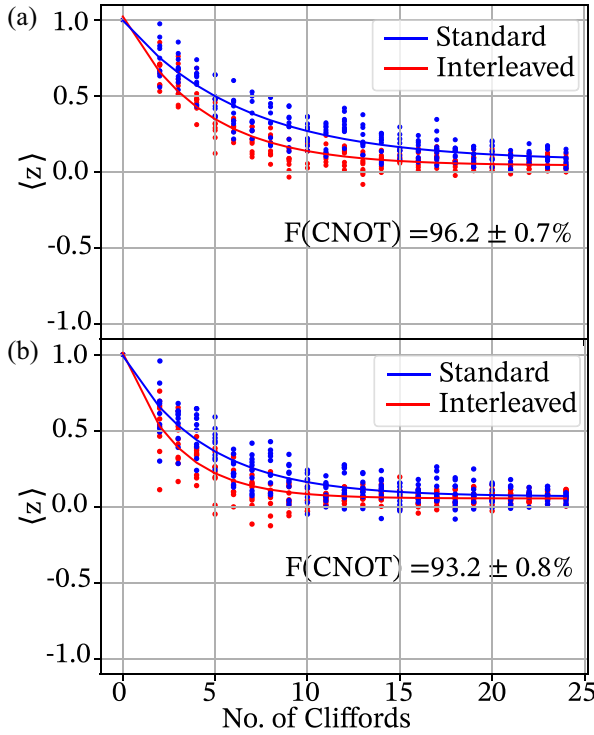


FIG. 4. Comparison of performance of cnot gate on Q3–Q4 (control Q3, target Q4) when optimized for that two-qubit bond vs the full six-qubit network using interleaved RB. We tune up a cnot gate by driving the CR interaction. The frequency of the CR drive needs to be identical to the single-qubit drive of the target qubit to define a precise phase relationship. (a) We measure a cnot RB fidelity of $96.2\% \pm 0.7\%$ when choosing the optimal drive frequency for the given two-qubit bond and (b) $93.2\% \pm 0.8\%$ when choosing the optimal drive frequency for the full six-qubit network. The degradation in the performance of cnot is attributed to the amplification of the $I \otimes Z$ term in the two-qubit CR Hamiltonian due to the suboptimal choice of the drive frequency.

computational subspace. The restrictions on the control-target detuning get more stringent when spectator qubits are added to the picture [30]. A summary of the list of CR poles is given in Table II. Δ_{ct} refers to the control-target detuning and Δ_{st} refers to the spectator-target detuning. We attribute the enhanced coherent errors to the frequency collisions in the six-qubit system. Qubits Q1 and Q3 are detuned by about 5 MHz, and qubits Q2 and Q6 are detuned by about 2 MHz. These collisions correspond to the last two resonances mentioned in the list of poles. Considering these poles, we construct a frequency set for the six-qubit system and compare its performance to the experimental set using QuTiP [31,32] simulations. Our approach extends the method in Tripathi *et al.* [33]. We model the system of N -coupled qubits with a drive field on the k th qubit (control), using the following Hamiltonian:

$$\hat{H}_{\text{sys}} = \hat{H}_q + \hat{H}_c + \hat{H}_d, \quad (1)$$

$$\hat{H}_q = \sum_{i=1}^N (\omega_i - \omega_d) \hat{a}_i^\dagger \hat{a}_i + \alpha_i (\hat{a}_i^\dagger \hat{a}_i) (\hat{a}_i^\dagger \hat{a}_i - \hat{I}), \quad (2)$$

$$\hat{H}_c = \sum_{i=1}^N \sum_{j=1}^N J_{ij} (\hat{a}_i^\dagger \hat{a}_j + \hat{a}_j^\dagger \hat{a}_i), \quad (3)$$

$$\hat{H}_d = \epsilon(t) \hat{a}_k + \epsilon^*(t) \hat{a}_k^\dagger, \quad (4)$$

where ω_i , α_i are the frequency and anharmonicity of the i th qubit, J_{ij} is the coupling between qubits i , j , and $\epsilon(t)$ is the time-dependent function that represents the shape of the CR pulse applied on the control qubit. We chose a flattop pulse with cosine rise and fall for our simulations. The coupling matrix encodes the connectivity achieved using the RR-based coupler with a uniform coupling strength of 3 MHz across all connected pairs and zero coupling between the disconnected pairs. We define the Hamiltonian in the frame rotating at the drive frequency ω_d .

We choose a two-qubit bond and perform CR simulations for every permutation of two spectator qubits from the remaining four qubits. This approach allows us to distill the effect of every spectator qubit and confirm the effect of frequency collisions in the system. We compute the fidelity of the CR gate using the following expression [33]:

$$F_{MU} = \frac{\text{Tr}(M^\dagger M)}{d(d+1)} + \frac{|\text{Tr}(M^\dagger U)|^2}{d(d+1)} \quad (5)$$

Here, M is the propagator calculated using the time-dependent simulations truncated to the computational subspace, U is the ideal CR unitary, and d ($= 2^4$ in this case) is the dimension of the computational subspace. The first term quantifies the unitarity of M , capturing the leakage out of the computational subspace. The second term quantifies the distance of M from the ideal unitary U in the computational subspace. The CR gate fidelity is computed as a function of the drive strength for all the spectator permutations. We perform this exercise for all two-qubit bonds for the two frequency sets: experimental and modified. Here, we construct the modified frequency set by tweaking the experimental set to avoid the unwanted resonance conditions in Table II by at least 25 MHz. The modified frequency set is provided in Table I in Sec. II of the Supplemental Material [22].

Figure 5 compares the CR gate errors across the bonds for the two frequency sets. In order to compare the performance, we pick the CR gate error versus drive amplitude curve for the most problematic spectator set and then pick the lowest error in the trace. We observe roughly an order of magnitude improvement in the error rates across all the bonds in the modified frequency set. Furthermore, the individual traces corresponding to various spectator permutations confirm that the experimental frequency set suffers heavily due to the frequency collisions between Q1–Q3 and Q2–Q6. We perform four-transmon simulations to isolate the impact of specific spectator-qubit pairs on the gate dynamics. A comparison with full six-transmon simulations is provided in Fig. 2 of the Supplemental Material [22]. The simulation results suggest that the six-qubit system realized in our experiment can be optimized to achieve sub-1% CR gate errors across all bonds. A discussion of the robustness of these results to realistic frequency mistargeting is provided in Sec. II of the

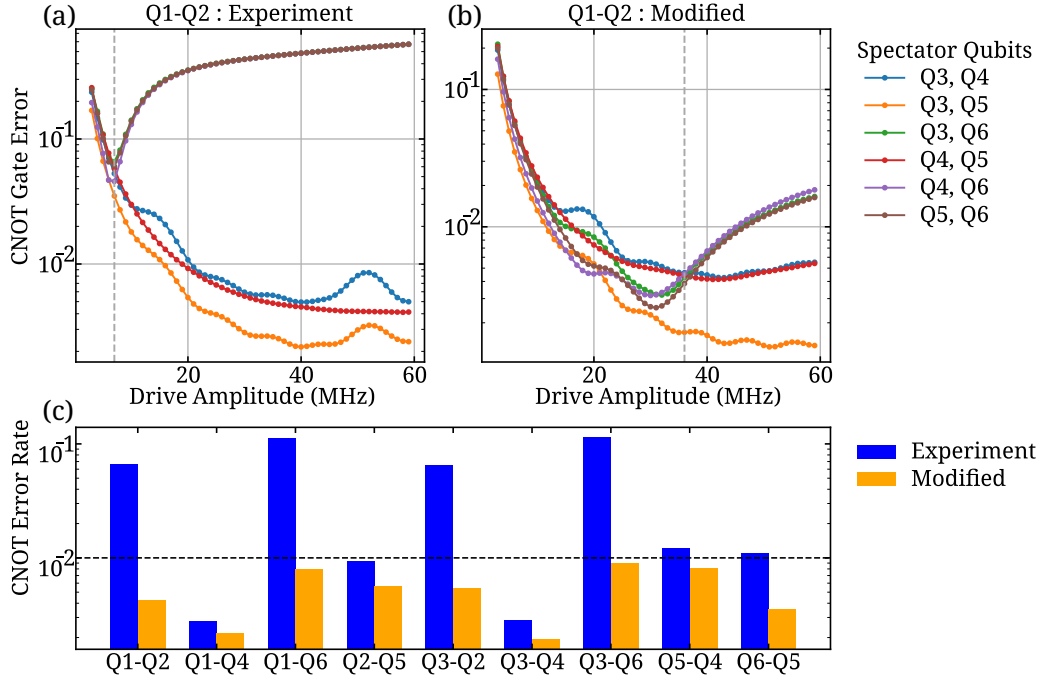


FIG. 5. Comparison of CR gate errors across the two-qubit bonds in the experimental frequency set vs the modified frequency set avoiding CR poles using QuTiP simulations. The gate error is computed as a function of the drive strength while including permutations of two spectator qubits. This approach confirms that the two-qubit gates in the experimental frequency configuration suffer due to the frequency collisions between Q1–Q3 and Q2–Q6. The CR gate error vs drive amplitude traces for the Q1–Q2 bond corresponding to the experimental and modified frequency sets are provided in panels (a) and (b), respectively. In order to compare the performance, we pick the CR gate error vs drive amplitude curve for the most problematic spectator set and then pick the lowest error in the trace, marked by the dashed vertical line. (c) The simulation results suggest that the six-qubit system achieved in the experiment can be optimized to realize sub-1% two-qubit errors across all bonds.

Supplemental Material [22]. The simulation results also point to a strong dependence of the coherent errors on the CR drive strength in a multiqubit system. While one might naively expect the shortest possible gate to be optimal due to minimal exposure to decoherence effects, the results point to a careful optimization of the gate time due to the presence of dynamical resonances.

IV. DISCUSSION

In conclusion, we characterized a six-qubit network with a novel, beyond-nearest-neighbor always-on connectivity achieved using a ring-resonator-based coupler in a 3D cQED architecture. We establish the connectivity using pairwise conditional Ramsey measurements and demonstrate single- and two-qubit gates across the network. We observe that the enhanced, always-on connectivity brings quantum-control challenges due to additional error terms in the Hamiltonian. We characterize the cross-Kerr terms in the six-qubit network, demonstrating the larger spread in qubit frequencies during arbitrary operation of the whole network. We also quantify the reduction in single- and two-qubit RB fidelity due to the cross-Kerr shifts exerted by connected spectator qubits. Furthermore, we quantify the coherent errors incurred due to frequency collisions in the six-qubit system and compare them to a modified frequency set using QuTiP simulations. We conclude that sub-1% two-qubit gate errors can be achieved across all bonds in the six-qubit system with optimal frequency targeting. With improved device fabrication tech-

niques, we aim to achieve optimal frequency detunings across all qubits in future devices, thereby significantly enhancing QPU performance. The simulations also suggest that the behavior remains robust under realistic fabrication variability, with only modest shifts in resonant features for frequency perturbations within typical transmon fabrication tolerances.

Optimal control methods can be employed to further suppress coherent errors in our system. Recent experimental work on transmon platforms [34–38] has shown that, in the perturbative regime, pulse engineering and calibration can substantially suppress spectator-induced cross-Kerr effects and push gate performance close to coherence limits, suggesting that always-on cross-Kerr interactions may not be a fundamental barrier to high-fidelity operation. Further, we can leverage the two-dimensional cQED architecture [39,40] to implement tunable couplers between the transmon qubits and the RR for dense, on-demand connectivity. We emphasize that these additions do not negate the core advantages of the RR architecture: we retain its geometric simplicity and compact routing, while the tunable elements can be used selectively to activate interactions when required. With these improvements, we envision this system as a potential candidate for transitioning to densely connected quantum processors.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [41].

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