High-Fidelity Control of Superconducting Qubits Using Direct Microwave Synthesis in Higher Nyquist Zones

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Control electronics for superconducting quantum processors have strict requirements for accurate command of the sensitive quantum states of their qubits. Hinging on the purity of ultra-phase-stable oscillators to upconvert very-low-noise baseband pulses, conventional control systems can become prohibitively complex and expensive when scaling to larger quantum devices, especially as high sampling rates become desirable for fine-grained pulse shaping. Few-GHz radio-frequency digital-to-analog converters (RF DACs) present a more economical avenue for high-fidelity control while simultaneously providing greater command over the spectrum of the synthesized signal. Modern RF DACs with extra-wide bandwidths are able to directly synthesize tones above their sampling rates, thereby keeping the system clock rate at a level compatible with modern digital logic systems while still being able to generate high-frequency pulses with arbitrary profiles. We have incorporated custom superconducting qubit control logic into off-the-shelf hardware capable of low-noise pulse synthesis up to 7.5 GHz using an RF DAC clocked at 5 GHz. Our approach enables highly linear and stable microwave synthesis over a wide bandwidth, giving rise to resource-efficient control and the potential for reducing the required number of cables entering the cryogenic environment. We characterize the performance of the hardware using a five-transmon superconducting device and demonstrate consistently reduced two-qubit gate error (as low as 1.8%) accompanied by superior control chain linearity compared to traditional configurations. The exceptional flexibility and stability further establish a foundation for scalable quantum control beyond intermediate-scale devices.

I. INTRODUCTION

Quantum computing is widely regarded as a promising technology for solving classically intractable problems in fields ranging from chemistry [1] to cryptography [2]. Superconducting qubits have emerged as a viable candidate for a physical realization of a quantum computer [3][4], as they are able to be fabricated using well-developed techniques from the semiconductor industry and are controlled using standard microwave electronics. However, state-of-the-art qubits are quite “noisy” compared to the error rates required for quantum algorithms to be carried out with high fidelity [5]; this can be mitigated by combining many noisy qubits into fewer reduced-noise logical qubits through quantum error correction [6][7]. Additionally, certain algorithms combat noise by directly utilizing higher numbers of qubits, such as variational quantum optimizers [8]. These techniques can rapidly increase the number of qubits that a quantum algorithm requires, and the electronics that enable these interactions grow increasingly complex and expensive [9].

The microwave electronics that comprise a control system for superconducting qubits must have extremely low electrical noise so as not to reduce coherence [10]. This requirement is even more critical when driving all-microwave two-qubit gates [11][12][13], in which one instrument channel may need to remain phase coherent with the rotating reference frames of multiple qubits, making tight phase locking between channels essential. With conventional control hardware requiring as many as four arbitrary waveform generator channels per qubit (two dual-quadrature complex pairs) [4], orchestrating and calibrating tens or hundreds of instrument channels becomes a daunting task as the density of quantum hardware increases.

It is often difficult to predict how much power must be synthesized at room temperature to drive any individual qubit before characterizing it, even before attempting to reduce gate time to optimize higher-depth quantum algorithms. Shorter gates require higher amplitude [14], underscoring the need for a control system to be capable of pulse synthesis over a wide dynamic range with minimal distortion. Furthermore, all-microwave two-qubit gates can require as much as 10 times the amplitude of single-qubit gates (see Section IV). Although modern mixers used in upconversion systems can behave approximately linearly over a moderate voltage range [15], the true output diverges from this approximation at high input power (determined by the manufacturer). Avoiding the result-
ing harmonics is often achieved by either using mixers with higher power ratings or by using lower input powers and increasing amplification at the output; however, the former solution often requires specialized components with limited bandwidths, and the latter solution requires additional low-noise amplifiers which also distort high-power signals. Additionally, attenuating the input signal degrades the signal-to-noise ratio at the output (as well as the usable vertical resolution of the pulse synthesizer if passive attenuation is not used) and other mixer nonlinearities such as LO leakage and imperfect sideband suppression are amplified [16]. Furthermore, the electrical properties of mixers tend to vary due to manufacturing tolerances and environmental effects, and therefore periodic calibration must be performed to sufficiently suppress the microwave carrier and unwanted image tones [17]. Performing these calibrations requires additional hardware to probe the desired outputs and places additional overhead on long-running experiments.

The commercial availability of radio-frequency digital-to-analog converters (RF DACs) with multi-GHz sampling rates presents a promising alternative to traditional microwave pulse synthesis for superconducting qubits in terms of channel count, spurious emissions, noise performance, and distortion. While AWGs operating as high as 65 GHz have been shown to be capable of controlling a superconducting qubit [18], such instrumentation is not economical for widespread integration. While the sampling rates of more affordable and available DACs are slightly below typical qubit and resonator frequencies (near 6 GHz), the analog bandwidths can allow for synthesis in higher Nyquist zones.

Having a wide-bandwidth control instrument can also greatly simplify the process of implementing modern techniques for improving fidelity in quantum circuits such as optimal control [19][20][21], parametric gates [22][23][24], and entanglement stabilization protocols [25]. Additionally, certain quantum error correction codes require driving multiple modes of a cavity [26][27], which could be performed using a single wide-bandwidth channel in lieu of combining multiple channels, thereby reducing the implementation cost of these schemes.

In this manuscript, we demonstrate the capability of an RF DAC operating in higher Nyquist zones to synthesize shorter, lower-error, all-microwave two-qubit gates than those generated by a state-of-the-art upconversion system. We demonstrate control and readout of a qubit using a single instrument channel and show superior linearity over a wide dynamic range compared to the upconversion system.

II. THEORY

To consider how a DAC is able to synthesize signals above its sampling rate, we consider an analytical treatment of the DAC as a device which accepts numerical data (“samples”) through a digital interface and converts them into a corresponding voltage. It is assumed that there is a linear relationship between the numerical value of a sample and the corresponding analog output, and that samples are converted at a constant rate $f_s$ [28]. When samples are generated by computing the value of an analytical function $x(t)$, the output of the DAC may be expressed as:

![Figure 1](image-url)
The reconstruction waveform \( r(t) \) manifests itself as a frequency-dependent attenuation, but careful choice of \( r(t) \) can be used to maximize power in preferred Nyquist zones. Three common functions for \( r(t) \) include non-return-to-zero (NRZ), return-to-zero (RZ), and mix-mode/RF-mode (Fig. 1b), each with their own attenuation profile (Fig. 1c). Analytical expressions and their derivations are provided in Appendix A. The NRZ waveform is the most common and is often the only choice available in low-frequency DACs. Also referred to as a zero-order hold, this reconstruction waveform represents the DAC presenting a sample at its output and holding that value constant until the next sample [28]. More advanced DACs can update their outputs between samples, such as driving the output to zero or inverting the output. When this occurs exactly halfway between samples, the former describes RZ mode and the latter describes mix mode. Although this requires the analog core of the DAC to have a higher sampling rate, mathematically this is treated as a series of impulses at the original sampling rate with non-constant behavior between samples. Because our hardware uses DACs with sampling rates near qubit and resonator frequencies, the second and third Nyquist zones are the desired bands for signal synthesis, and choosing mix mode yields the highest power in this range.

\[
v(t) = \left[ x(t) \sum_{k=-\infty}^{\infty} \delta(t - kT) \right] \ast r(t), \quad (1)
\]

\[
V(\omega) = R(\omega) \left[ X(\omega) \ast \sum_{n=-\infty}^{\infty} \delta(\omega T - 2\pi n) \right], \quad (2)
\]

where capital-letter functions denote the Fourier transform of the corresponding time-domain function (a derivation of this expression is provided in Appendix A). The summation represents a series of peaks at all integer multiples of the sampling frequency, and the convolution of \( X(\omega) \) with these peaks creates copies of the spectrum of the original signal at each of these peaks (Fig. 1a). If \( X(\omega) \) has a bandwidth greater than \( f_s/2 \), these copies will overlap, resulting in aliasing. Consecutive bands of width \( f_s/2 \) are referred to as Nyquist zones, with the first Nyquist zone spanning DC to \( f_s/2 \), the second Nyquist zone spanning \( f_s/2 \) to \( f_s \), and so on. Hence, when a signal is confined to a single Nyquist zone, sampling the signal places a copy of the signal’s spectrum in each odd Nyquist zone and an inverted copy in the even Nyquist zones [28].

Figure 2. (a) Internal block diagram of direct RF synthesis system. Blue lines indicate paths carrying dual-quadrature digital information, and orange paths indicate analog signals. RS232 is exposed on the front panel for communication with the embedded processor. The processor configures numerically-controlled oscillators (NCOs) and reconstruction waveforms in the RF DACs by writing to digital registers using a serial peripheral interface (SPI). The onboard phase-locked loop (PLL) exposes an input for a reference clock from which the RF DAC and FPGA clocks are derived. The FPGA logic implements two sequencers which read instructions and waveforms from memory, numerically modulate baseband tones, and stream the complex data to the RF DACs over JESD204B. Instructions and waveforms are written to memory over Ethernet, which is also used to configure the sequencers. (b) Implementation of single-channel control and readout of a superconducting qubit in a dilution refrigerator (complete wiring used for experiments available in Appendix C). (c) Dual-channel control and readout hardware configuration used for experiments with two-qubit gates (complete wiring available in Appendix B).
III. HARDWARE

We implement direct microwave synthesis using a combination of off-the-shelf hardware and custom field-programmable gate array (FPGA) logic (Fig. 2a). We employ the VadaTech AMC599 [29], which contains a Xilinx XCKU115 UltraScale FPGA [30] and two Analog Devices AD9164 DACs [31] clocked at 5 GHz in an advanced mezzanine card (AMC) form factor module. We note that the actual data stream of the DAC is limited to 2.5 GSa/s due to the use of complex data, but because the update rate of the DAC is still 5 GHz, this does not affect the location of the Nyquist zones. Because the data is complex, tones may be generated directly as upper or lower sidebands of a carrier produced by an NCO internal to the DAC; when this NCO is centered in a Nyquist zone, a signal bandwidth of 2.5 GHz is achieved. Multiple AMC599 modules are loaded into a VadaTech VT848 1U AMC chassis [32].

The FPGA logic commanding the DACs iterates upon our previous work developing specialized instrumentation for superconducting qubit experiments [33]. Unique functionality in the system includes a sequencer for advanced control flow, waveform engines with multiple numerically-controlled oscillators (NCOs) for coherent control between densely-connected qubits, and marker engines for triggering external instruments. An embedded processor configures clocking, DACs, and external communication interfaces.

To demonstrate the efficiency of the RF DAC, individual control and readout is achieved with a single channel per qubit. This is made possible by the architecture of our superconducting device, in which all qubits are driven through their transmission line readout resonators. With only a single externally-coupled feedline per qubit, the RF DAC offers an efficient alternative to conventional upconversion systems requiring two dual-quadrature baseband signals to be upconverted with IQ mixers driven by separate microwave sources. An analog front-end for the RF DAC is constructed as shown in Fig. 2c (full wiring shown in Appendix C). The DAC output is split and selectively filtered; this allows for extraction of the readout pulse for heterodyne downconversion and for additional attenuation without sacrificing dynamic range. Multiple amplifiers are employed to provide enough power to apply gates and to drive the LO port of the downconversion mixer. The control and readout paths are then recombined before entering the cryogenic environment.

IV. RESULTS

We compare the performance of the RF DAC to a traditional control scheme by conducting experiments on a device with five fixed-frequency transmon qubits [7] located at the base of a dilution refrigerator operating at 10 mK. Our upconversion control system uses the BBN second-generation Arbitrary Pulse Sequencer (APS2) [33] to generate dual-quadrature signals at 1.2 GSa/s. Control pulses are then upconverted with a single channel of a Holzworth HS9003A microwave source shared between all qubits, whereas measurement pulses are upconverted using separate sources (Vaanix Lab Bricks) for each qubit. All instruments are phase-locked using a Stanford Research Systems FS725 Rubidium Frequency Standard. Device details and a complete diagram of the upconversion system are provided in Appendix B.

We first calibrate the $X_{\pi/2}$ rotation gate comprised of a Gaussian pulse with DRAG [34][35] for one qubit on the device using both control systems. Because the RF DAC and upconversion system operate at different clock rates, pulse lengths must differ by a small amount; single-qubit gates are calibrated at 50 ns when using upconversion and at 48 ns when using direct RF synthesis.

To confirm that the RF DAC does not degrade relevant qubit performance metrics, we measure the characteristic decay time $T_{2e}$ of a spin echo experiment and single-qubit error per Clifford (as measured by randomized benchmarking [36]) and find comparable values to those obtained when using upconversion (Fig. 3). In particular, the lack of any additional dephasing indicates that the integrated phase noise of the RF DAC over the coherence time of the qubit is comparable to that of an upconversion system that utilizes an ultra-low-phase-noise local oscillator [10].

Next, we compare the performance and stability of the
RF DAC when driving two-qubit gates to that of the upconversion system. Our device uses all-microwave two-qubit echoed cross-resonance (CR) gates between qubits directly coupled through a bus resonator [11][37][38]. The gate is comprised of two flat-top Gaussian pulses driven at the target qubit frequency through the control channel, along with an $X_\pi$ rotation on the control qubit to cancel undesired terms the cross-resonance Hamiltonian. We compute two-qubit gate error as the mean of the target and control error per two-qubit Clifford measured using two-qubit randomized benchmarking (RB) [39], and we choose to use the qubit pair with the lowest two-qubit error rate on the device.

To reduce the number of external components required, for experiments with CR gates we assemble an analog front-end using separate DACs for control and readout as shown in Fig. 2b (full wiring is presented in Appendix B). We then sweep the length of the CR pulse, and for each pulse length, the gate is calibrated and 30 sequences of two-qubit RB are used to characterize the quality of the calibration. Between 8 and 11 repetitions of this process are performed at each pulse length to avoid local minima in gate error due to small variations in calibration parameters.

The RF DAC is able to synthesize shorter pulses at higher amplitudes with gate error remaining consistently below 4% (Fig. 4a), whereas the upconverted gate error rapidly exceeds 10% as pulse length decreases. The ability of the RF DAC to synthesize short gates is especially beneficial for high-depth quantum algorithms that depend on executing numerous entangling operations within the qubits’ coherence times.

For many types of two-qubit gates, if the relative phases between instrument channels drift, those channels will require recalibration in order to rotate the target state around the proper axis [11]. To characterize the extent to which naturally-occurring phase drift impacts gate performance, we calibrate CR gates of multiple lengths on both control systems and track their error rates over time by repeatedly measuring identical random sequences without pulse recalibration. To decouple the effect of inherent time-varying fluctuations, we use mechanical microwave switches to interleave experiments with each control system. The upconversion mixers are calibrated once at the start of the experiment, and error is measured over time both using the initial calibration parameters and after recalibrating them before each instance of randomized benchmarking. A 150 ns gate was chosen for the upconversion system as it showed minimal error and close performance to the RF DAC at a similar pulse length (Fig. 4a). A 150.4 ns and a 96 ns gate are tracked for the RF DAC in order to examine the performance of both the most similar gate to the one chosen for the upconversion system as well as the one that exhibited the lowest error.

Gates synthesized by the RF DAC exhibit a consistent reduction in two-qubit gate error that is maintained over the course of 125 hours (Fig. 4b). Significant fluctuations are consistent between the two control systems, indicating that such events are not due to particular deleterious effects of either system. Importantly, the results of this experiment indicate that separate RF DACs can maintain phase coherence with each other over long timescales without degrading two-qubit gate error com-
pared to sharing a single local oscillator among upconversion channels.

To investigate the divergence in error between the RF DAC and the upconversion system at short pulse lengths, we characterize the error rates of CR gates at various power levels and compare it to the linearity of the two control systems at similar power levels. We quantify the linearity $L$ of a control system as

$$L(A_n) = \frac{dV_o}{dA} |_{A=A_n},$$

where $V_o$ is the output voltage and $A$ is the programmed amplitude of the synthesizer, which we measure for various amplitudes $A_n$; in a perfectly linear system, $L$ would be a constant. We measure linearity for the RF DAC and for the output of the upconversion mixer, as well as for a single quadrature in the upconversion setup in order to decouple any nonlinearity arising from baseband amplification.

As linearity decreases, two-qubit gate error starts to rapidly increase (Fig. 5a), providing evidence for the strong sensitivity of gate performance to control system linearity. Comparing the results between the mixer output and a single input quadrature shows that the performance degradation is due to the mixer rather than any prior amplification; hence, even with extremely high-performance pulse synthesizers and local oscillators, the presence of a single nonlinear circuit element can degrade performance considerably.

To demonstrate the deleterious effects of nonlinearity in a control system, we measure the output voltage spectra at high amplitude. Harmonics have a strong presence in the output of the upconversion system, and because they have the same spectral profile as the primary pulse, they are not confined to a negligible bandwidth (Fig. 5c). The resulting low-amplitude tails of harmonics in the CR pulse overlap with the frequency space of the control qubit, and the harmonics of the $X_{\pi/2}$ pulse overlap with the frequency space of the target qubit. Though they are suppressed at low amplitude, the harmonics never fully vanish due to the inherent nonlinearity of the circuit [16]. This is especially detrimental for devices that are sensitive to single-photon perturbations, such as readout resonators [4], and attempting to achieve an optimal detuning for a CR gate [40] while avoiding a series of harmonics as well as LO leakage becomes a difficult task, especially for devices with higher connectivity.

Conversely, the RF DAC, being a linear control element, shows no spectral components except at desired locations (Fig. 5d). This further emphasizes the usefulness of the RF DAC for experiments that require spectral purity and simplifies the considerations needed when scaling to larger quantum devices.

V. CONCLUSION

We have demonstrated that an RF DAC operating in higher Nyquist zones can control qubits with fidelities exceeding those of conventional upconversion-based control systems as well as perform measurement without requir-
ing an additional instrument channel. Furthermore, the RF DAC can drive shorter gates than the upconversion setup while maintaining low error due to the increased linearity of the system. The gate error of RF DAC is stable over long timescales, indicating good phase stability, and the lack of harmonic content in its output greatly simplifies frequency planning. These observations emphasize the utility of an RF DAC in creating a flexible, scalable control system for superconducting qubits beyond the intermediate scale.

Whereas in this work we have demonstrated the capability of off-the-shelf hardware, certain engineering challenges remain in order to take full advantage of the flexibility offered by the RF DAC. In particular, the output of the DAC must be filtered to prevent interference from tones in Nyquist zones other than the one(s) desired and from spurious emissions at digital clock frequencies present in the system; in this work we mitigate these effects using commonly available microwave filters chosen to match the frequency bands of interest. Future work will address reconfigurable filtering electronics for compact integration as well as dynamic adjustment of digital clocks, allowing for optimal placement of Nyquist zones (many system architectures utilize digital phase-locked-loops for generating clock signals, enabling software-based adjustment).

VI. APPENDIX A: FREQUENCY SPECTRUM OF SAMPLED SIGNALS AND RECONSTRUCTION WAVEFORMS

We derive the synthesis of tones in higher Nyquist zones by first considering the voltage at the output of a DAC when playing samples of an analytical function $x(t)$ presented in Eq. 1:

$$v(t) = \left[ x(t) \sum_{k=-\infty}^{\infty} \delta(t - kT) \right] * r(t),$$

where $T$ is the sampling period, $r(t)$ is the reconstruction waveform, and ($*$) denotes convolution in time. We start computing the Fourier transform (FT) of this expression by applying multiplication and convolution identities:

$$V(\omega) = \mathcal{F}\{v(t)\} = \left[ X(\omega) * \mathcal{F}\{ \sum_{k=-\infty}^{\infty} \delta(t - kT) \} \right] R(\omega) \quad (3)$$

In this expression, $X(\omega) = \mathcal{F}\{x(t)\}$ is the spectrum of the original signal and $R(\omega) = \mathcal{F}\{r(t)\}$ is the spectrum of the chosen reconstruction waveform (derived below). To compute the FT of the impulse train (represented by the summation), we recognize its periodicity in time with period $T$ and express it as a Fourier series:

$$\sum_{k=-\infty}^{\infty} \delta(t - kT) \equiv \sum_{n=-\infty}^{\infty} c_n e^{2\pi int/T}$$

where $c_n$ are the Fourier series coefficients. We solve for $c_n$ by integrating over one period of the impulse train centered at $t = 0$; this reduces the summation to only a single term with $k = 0$:

$$c_n = \frac{1}{T} \int_{-T/2}^{T/2} \delta(t) e^{2\pi int} dt = \frac{1}{T}$$

Therefore:

$$\sum_{k=-\infty}^{\infty} \delta(t - kT) \equiv \sum_{n=-\infty}^{\infty} \frac{1}{T} e^{2\pi int/T}$$

We then solve for the FT of this expression:

$$\mathcal{F}\{ \sum_{n=-\infty}^{\infty} \frac{1}{T} e^{2\pi int/T} \} = \frac{1}{T} \mathcal{F}\{ e^{2\pi int/T} \}$$

$$= \frac{1}{T} \sum_{n=-\infty}^{\infty} \delta(\omega - 2\pi n/T) \quad (4)$$

$$= \sum_{n=-\infty}^{\infty} \delta(\omega T - 2\pi n)$$

Finally, we substitute this back into Eq. 3 to recover Eq. 2:

$$V(\omega) = R(\omega) \left[ X(\omega) * \sum_{n=-\infty}^{\infty} \delta(\omega T - 2\pi n) \right]$$

We can derive $R(\omega)$ for the three aforementioned reconstruction waveforms by directly computing their FT. We start with the non-return-to-zero (NRZ) reconstruction waveform:

$$r_{NRZ}(t) = u(t) - u(t - T) \quad (5)$$

where $u(t)$ is the step function. Using the known FT of the step function and the time shifting property of the FT, we can directly compute the FT of $r_{NRZ}$:

$$R_{NRZ}(\omega) = \mathcal{F}\{r_{NRZ}(t)\} = \mathcal{F}\{u(t)\} - \mathcal{F}\{u(t - T)\}$$

$$= (1 - e^{-i\omega T}) \frac{1}{i\omega} + \pi \delta(\omega)$$

$$= e^{-i\omega T/2} \frac{1}{i\omega} + \pi T e^{-i\omega T/2} \frac{1}{i\omega} \quad (6)$$

$$= 2i e^{-i\omega T/2} \sin(\omega T/2) \frac{T}{i\omega T/2}$$

$$= T e^{-i\omega T/2} \frac{\sin(\omega T/2)}{\omega T/2}$$
where \( \text{sinc}(x) = \frac{\sin(x)}{x} \).

The return-to-zero (RZ) reconstruction waveform is given by:

\[
R_{RZ}(t) = u(t) - u(t - T/2)
\]

this expression is identical to \( r_{NRZ} \) with \( T \rightarrow \frac{T}{2} \); hence, \( R_{RZ} \) is given simply by applying the same transformation to \( R_{NRZ} \):

\[
R_{RZ}(\omega) = \frac{T}{2} e^{-i\omega T/4} \text{sinc} \left( \frac{\omega T}{4} \right)
\]

The mix mode reconstruction waveform is given by:

\[
r_{\text{mix}}(t) = u(t) - u(t - T/2) - [u(t - T/2) - u(t - T)]
\]

We start by considering a time shift of \( T/2 \) on the term in brackets:

\[
R_{\text{mix}}(\omega) = \mathcal{F}\{ r_{\text{mix}}(t) \}
= \mathcal{F}\{ u(t) - u(t - T/2) \}
= e^{-i\omega T/2} \mathcal{F}\{ u(t) - u(t - T/2) \}
\]

We recognize the term in the Fourier transform as the expression for \( r_{RZ}(t) \) and substitute the transform for \( R_{RZ}(\omega) \):

\[
R_{\text{mix}}(\omega) = (1 - e^{-i\omega T/2})R_{RZ}(\omega)
= \frac{T}{2} (1 - e^{-i\omega T/2}) e^{-i\omega T/4} \text{sinc} \left( \frac{\omega T}{4} \right)
= \frac{T}{2} e^{-i\omega T/4} (e^{i\omega T/4} - e^{-i\omega T/4}) \text{sinc} \left( \frac{\omega T}{4} \right)
= T i e^{-i\omega T/2} \sin \left( \frac{\omega T}{4} \right) \text{sinc} \left( \frac{\omega T}{4} \right)
= \frac{\omega T^2}{4} e^{-i(\omega T - \pi)/2} \text{sinc}^2 \left( \frac{\omega T}{4} \right)
\]

The results of Eqs. 6-8 are plotted in Fig. 1c.

VII. APPENDIX B: DEVICE DETAILS AND TWO-QUBIT EXPERIMENTAL CONFIGURATION

We use a device with five fixed-frequency transmons (denoted \( q_1 \)–\( q_5 \)) located at the base of a Bluefors dilution refrigerator (the device is the same used in [7]; two-qubit gate experiments were conducted in a separate cooldown). On the device, one central qubit (\( q_3 \)) is coupled to two bus resonators; one resonator couples \( q_3 \) to \( q_1 \) and \( q_2 \), and the other couples \( q_3 \) to \( q_4 \) and \( q_5 \). Each qubit is dispersively coupled to a readout resonator through which single-qubit gates and two-qubit cross-resonance gates are driven. In addition, \( q_1 \) and \( q_4 \) have off-chip Purcell filters.

The two-qubit gates under examination use \( q_1 \) as the target and \( q_2 \) as the control, whose \(|0\rangle \rightarrow |1\rangle \) transition
Figure 7. Complete experimental setup for two-qubit gate measurements. Microwave switches allow interleaving experiments with each control system to decouple the effect of natural time-varying fluctuations in qubit performance. For components displayed with a part number but no vendor name, the vendor is Mini-Circuits.
frequencies are 5.3505 GHz and 5.4735 GHz respectively. They are coupled to readout resonators with frequencies 6.5138 GHz and 6.4616 GHz, respectively. In addition to two-qubit gate error, coherence and single-qubit gate error (as measured by randomized benchmarking) are tracked over the course of the experiment (Fig. 6). As with two-qubit error, single-qubit error and coherence are consistent between the RF DAC and the upconversion system, indicating that changes in these parameters are not due to deleterious effects of either control system.

Fig. 7 displays the complete experimental setup for all measurements involving two-qubit gates. To decouple the effects of natural time-varying fluctuations in coherence and gate error, experiments using the RF DAC and the upconversion system are interleaved. Two single-pole double-throw microwave switches are used to control the signal source for the two qubits, and a third switch is used to toggle the measurement trigger. We choose mechanical latching microwave switches controlled by DC power supplies, as other types of switches with integrated control electronics were found to degrade qubit coherence. The return line for each qubit is split and distributed to the downconversion circuitry for each control system, and the baseband measurement line for each system is combined and amplified before entering a DC-coupled digitizer. All instruments are locked to a 10 MHz reference generated by a rubidium frequency standard.

The upconversion system is comprised of an array of BBN second-generation Arbitrary Pulse Synthesizers (APS2) [33] and a Holzworth HS9003A ultra-low phase noise microwave source. Each APS2 synthesizes an IQ quadrature pair at 1.2 GSa/s, which is then upconverted with a shared LO signal derived from a single channel of the microwave source. A custom switchboard routes the output of the control upconversion mixers to either the qubit drive path or an input on a shared hybrid junction. The Σ port of the hybrid junction is connected to a BBN spectrum analyzer; this allows calibration of the mixers to ensure proper suppression of LO leakage and the undesired sideband. For each qubit, one APS2 unit is used for synthesizing control pulses and another is used for synthesizing measurement tones. A BBN Trigger Distribution Module (TDM) ensures synchronized triggering between all APS2 units.

VIII. APPENDIX C: SINGLE-CHANNEL CONTROL AND READOUT CONFIGURATION

A complete diagram of the setup implementing single-channel control and readout is shown in Fig. 8. In this configuration, we conduct experiments using a single qubit on the device. We choose $q_4$, which has a $|0\rangle \rightarrow |1\rangle$ transition frequency of 5.3622 GHz and is coupled to a readout resonator at 6.5705 GHz. A Josephson parametric converter (JPC) [41] located in a separate shielding can in the mixing chamber is used for enhancing the readout fidelity of the qubit.

Figure 8. Complete experimental setup for single-channel control and readout.

As described in the main text, the control signal is split and selectively filtered so that the measurement tone may be recovered for downconversion. The resultant DC signal is then amplified and filtered before entering a digitizer. After splitting the output channel, additional attenuation and amplification are used to maximize output.
power without entering nonlinear regimes of the amplifiers. The JPC is biased with a DC power supply and pumped with an additional microwave source.

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