Multiplexed superconducting qubit control at millikelvin temperatures with a low-power cryo-CMOS multiplexer

R. Acharya1,2, S. Brebels1, A. Grill1, J. Verjauw1,3, Ts. Ivanov1, D. Perez Lozano1, D. Wan1, J. Van Damme1,2, A. M. Vadiraj1, M. Mongillo1, B. Govoreanu1, J. Craninckx1, I. P. Radu1,4, K. De Greve1,2, G. Gielen1,2, F. Catthoor1,2 & A. Potočnik1

Large-scale superconducting quantum computers require the high-fidelity control and readout of large numbers of qubits at millikelvin temperatures, resulting in a massive input–output bottleneck. Cryo-electronics based on complementary metal–oxide–semiconductor technology could provide a scalable and versatile solution. However, detrimental effects due to cross-coupling between the qubits and the electronic and thermal noise generated during cryo-electronics operation need to be avoided. Here we report a low-power radio-frequency multiplexing cryo-electronics system that operates below 15 mK with a minimal cross-coupling. We benchmark its performance by interfacing the system with a superconducting qubit and observe that the qubit's relaxation times are unaffected, whereas the coherence times are marginally affected in both static and dynamic operations. Using the multiplexer, single-qubit gate fidelities above 99.9%—that is, above the threshold for surface-code-based quantum error correction—can be achieved with appropriate thermal filtering. We also demonstrate time-division multiplexing capabilities by dynamically windowing calibrated qubit control pulses.

Quantum information processing on error-corrected quantum computers promises a computational advantage over classical computers in solving particular problems that are otherwise intractable1–4. Many physical systems are under active investigation5–7, but superconducting quantum circuits have emerged as arguably the most developed platform8–11 with recent proof-of-principle demonstrations of verifiable quantum advantage12–14. State-of-the-art superconducting quantum processors15,16 use external circuits with at least one control line per qubit running from the room-temperature stage to the base-temperature stage of a dilution refrigerator (Fig. 1a). This approach can be extended to a few hundred qubits16, but is not scalable to build a large-scale quantum computer that requires dynamic circuit operations, such as quantum error correction and active reset on a large number of high-fidelity qubits15–19, due to the limited number of input–output ports on the dilution refrigerator20. Such an approach will also limit the throughput for the large-scale statistical characterization of quantum devices at millikelvin temperatures, which will be crucial to enable qubit fabrication at scale.

An architecture involving multiplexing elements employed at the base-temperature stage of a dilution refrigerator can alleviate such an input–output bottleneck for qubit characterization and control19–23 (Fig. 1b). This approach is complementary to high-density
levels are acceptable in practice are yet to be experimentally explored. At the same time, multiplexers must also support wideband operation in the 4–8 GHz bandwidth 15,16, a high dynamic range between –60 to –120 dBm (ref. 16) and fast nanosecond-scale switching for multiplexed control at microwave frequencies. Active time-division multiplexing (TDM) requires maximum dynamic switching rates of 0.25–1.00 MHz for readout multiplexing with pulse widths of 0.5–2.0 µs and 10.00–50.00 MHz for control multiplexing with pulse widths of 10–50 ns (refs. 11,15,16). Furthermore, the port-to-port isolation of the multiplexer must be greater than 30 dB to ensure signal crosstalk infidelity of <0.1% for high-fidelity qubit operations.

Several technologies have been explored for functional signal multiplexing, including mechanical switches33, superconducting nanowires34 and Josephson-junction-based switches 35,36. Promising results have been demonstrated with two-dimensional electron-gas-based radio-frequency (RF) switching using the capacitive depletion of electron gas or a high-electron-mobility transistor 37. However, the low on–off ratio of ∼20 dB in the 4–8 GHz bandwidth of interest renders them unsuitable for superconducting qubits. Encouraging developments have also been made in approaches using optical links38 or rapid wiring solutions being developed, resulting in a continual increase in the system’s input–output capability. Such functional multiplexing has already been demonstrated for solid-state spin-qubit systems, where quantum devices can also be co-integrated with multiplexers39–42 and control electronics30–32, but at elevated temperatures (1–4 K) to account for the finite heat dissipation of the electronics. However, the stringent requirements of superconducting quantum processors in terms of low electromagnetic and thermal noise35,36 makes such direct co-integration with dissipative cryo-electronics, such as multiplexers, extremely challenging33–36.

Consequently, a practical multiplexing solution for superconducting quantum devices must provide cryogenic compatibility at operating temperatures below 50 mK. It must also ensure low-noise performance, with the noise power spectral density (PSD) in the order of yoctowatts per hertz, corresponding to occupation probabilities of less than one photon at the gigahertz-level operating frequencies of quantum devices. Due to the large sensitivity of superconducting qubits to thermal electromagnetic radiation, the power consumption should be well below the cooling budget of the dilution refrigerator (∼20 µW). How much power can be exactly tolerated and what noise levels are acceptable in practice are yet to be experimentally explored. At the same time, multiplexers must also support wideband operation in the 4–8 GHz bandwidth43,44, a high dynamic range between −60 to −120 dBm (ref. 16) and fast nanosecond-scale switching for multiplexed control at microwave frequencies. Active time-division multiplexing (TDM) requires maximum dynamic switching rates of 0.25–1.00 MHz for readout multiplexing with pulse widths of 0.5–2.0 µs and 10.00–50.00 MHz for control multiplexing with pulse widths of 10–50 ns (refs. 11,15,16). Furthermore, the port-to-port isolation of the multiplexer must be greater than 30 dB to ensure signal crosstalk infidelity of <0.1% for high-fidelity qubit operations.

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single flux quantum electronics\(^9\). Nevertheless, it remains unclear if these superconducting quantum computing systems

The cryo-complementary metal–oxide–semiconductor (CMOS) platform offers a versatile, scalable and mature solution that is readily available to be leveraged in quantum computing\(^{20,21,40}\). Although RF signal multiplexing at millikelvin temperatures has also been demonstrated using cryo-CMOS-based devices\(^{41,42}\), the devices have not been shown to satisfy the demanding power, RF and noise specifications needed for superconducting qubits. In this Article, we report a cryo-CMOS-based multiplexing system operating at the base temperature of a dilution refrigerator. Our approach combines the requisite bandwidth, speed, dynamic range and noise performance for functional interfacing with superconducting qubits, as well as minimally loading and heating the fridge. In particular, we use a d.c.-to-10 GHz single-pole four-throw RF multiplexer based on 28 nm bulk CMOS technology and verify its operation for qubit control and interfacing.

The multiplexer is operated at the base-temperature stage of a dilution refrigerator, and its full-chip low static (0.6 µW) and dynamic (\(-0.48 \text{ pW Hz}^{-1}\) of switching) power dissipation result in minimal heating of the system of only a few millikelvins, despite the minute power-handling capabilities of the fridge at these extremely low temperatures. In terms of RF behaviour, we observe a high isolation (35 dB at 6 GHz) and a low insertion loss (3 dB at 6 GHz), confirming its viability as a multiplexer for superconducting qubits. We verify the interfacing capability with superconducting qubits by measuring a qubit with coherence times exceeding 20 µs and single-qubit gate fidelities surpassing 99.9%. In addition, we demonstrate that the active TDM of qubits is possible using our multiplexer, and verify its performance by selectively windowing a calibrated qubit pulse with over 30 dB port-to-port crosstalk suppression.

### Design and characterization of cryo-CMOS multiplexer

The multiplexer chip is custom designed and fabricated in a commercial foundry using a 28 nm bulk CMOS process (Methods; Supplementary Section 1 provides the RF design considerations). The multiplexer has four RF input ports (RF1–RF4) and a common RF output port (RFc) that can be programmed using either serial or parallel control; Fig. 1c shows the schematic. The roles of the ports can also be reversed to operate the device as a demultiplexer. The micrograph of the multiplexer chip along with the different building blocks of the multiplexer and the physical location of the ports are shown in Fig. 1d,e.

In contrast to the previous design\(^9\), a high degree of isolation between the RF ports is provided by employing two levels of series-shunt switches, as illustrated by the simplified circuit schematic in Fig. 2a. The isolation is further enhanced by minimizing the mutual coupling between the printed circuit board (PCB) tracks and bond wires. This is achieved using resonant LC structures made of the parasitic pad capacitance and on-chip inductance, with a resonance frequency of 6 GHz. The number of electrostatic discharge (ESD) protection cells is reduced to four to provide requisite protection against ESD events and substantially reducing the power consumption\(^{41}\). For faster switching times, the static bias resistance (\(\sim 1 \text{k} \Omega\)) at the gate of the RF switch transistors is shunted by means of a pair of diode-connected transistors (Supplementary Section 2 and Supplementary Fig. 1).

The multiplexer PCB is anchored and thermallyized to the 10 mK base-temperature stage of a dilution refrigerator (Methods and Extended Data Fig. 1 show the details of the measurement setup). The static power consumption of the multiplexer is measured as a function of the applied bias voltage \(V_{dd}\) and plotted in Fig. 2b. The multiplexer turns on at a threshold voltage of \(-0.6 \text{ V}\) and has a low power consumption of 0.60 µW at \(V_{dd} = 0.7 \text{ V}\) (Fig. 2b, red circles). This dissipation results in a slight increase in the fridge temperature of less than 2 mK. Approximately 60% of the temperature increase can be attributed to the dissipation in the ESD protection circuit (Fig. 2b, grey diamonds; Supplementary Section 3 and Supplementary Fig. 2), which is not directly related to the size of the multiplexer and would therefore allow for scaling to larger systems.

Dynamic switching between the RF ports results in additional power dissipation due to the charging and discharging of the circuit’s internal capacitive nodes. Figure 2c shows the dynamic power consumption (with the static offset removed) measured as a function of the switching rate for \(V_{dd}\) of 0.7 and 0.9 V. An extremely low dynamic power consumption of \(-1 \text{ pW Hz}^{-1} \text{ V}^{-2}\) (\(-0.48 \text{ pW Hz}^{-1}\) at \(V_{dd} = 0.7 \text{ V}\) ) is obtained, which is dominated by the gate capacitance of the bulky RF switch transistors (Supplementary Section 4 and Supplementary Fig. 3). Although cryo-electronic multiplexing solutions have been demonstrated with a minimal impact on the base temperature in static or low-frequency systems like spin qubits\(^{22,23}\), extending these results to the dynamic high-frequency regime of superconducting qubits requires different circuit designs, accounting for the novelty of our approach.

The port-to-port isolation measured as a function of the signal frequency is plotted in Fig. 2d (Methods). The isolation shows a weak frequency dependence with a minimum value of 30 dB and maximum value exceeding 40 dB at 0.7 V, most probably due to reflections and impedance mismatches in the cryogenic measurement setup. The inset in this plot shows that the normal operation begins at around the threshold voltage of 0.6 V and the isolation is approximately constant above 0.7 V. As shown in Fig. 2e, an average insertion loss of 2.3 dB is obtained in the 4–8 GHz bandwidth (Methods). Unsurprisingly, it exhibits a similar bias voltage dependence as the port-to-port isolation (Fig. 2e, inset). The port-to-port isolation is still limited by the inductive coupling between the bond wires and PCB tracks, although to a lower value due to the included LC resonance. The insertion loss can be accounted for by the two series switches and the parasitic losses of the bond wires, PCB traces and connectors.

These results show that both dynamic and static power dissipation have a strong dependence on the operating voltage, whereas the RF performance of the multiplexer is practically constant above the threshold voltage. Hence, the power consumption can be substantially reduced by designing devices for lower threshold voltages without compromising the RF performance. For example, by extrapolating the measurement data to \(V_{dd} = 0.3 \text{ V}\), the estimated static and dynamic power dissipation would be 30 nW and 90 fJ Hz\(^{-1}\), respectively. A process technology with a lower or tunable threshold voltage, such as fully depleted silicon-on-insulator technology, offers an attractive platform for the realization of future devices and is being actively investigated for use in millikelvin electronics\(^{24,25}\). Our results also show that design optimizations, particularly the ESD protection cells and RF switching transistors, can further reduce the power dissipation. Additionally, employing advanced process nodes with shorter channel lengths and lower channel resistance could potentially enhance performance.

### Multiplexer noise benchmarking using high-coherence qubits

The carrier temperature of cryo-CMOS devices operating at millikelvin temperatures is, in general, higher than the temperature of the surrounding bath\(^{20,24}\). Therefore, introducing these devices for delivering control signals disrupts the low-noise environment designed for superconducting qubits in state-of-the-art dilution refrigerator systems\(^2\). To quantify these effects, the noise performance of the multiplexer is benchmarked using a fixed-frequency high-coherence superconducting transmon qubit, fabricated using a fab-compatible superconducting qubit fabrication process\(^{25}\). The standard circuit quantum electrodynamics architecture is adopted\(^2\), where the qubit is dispersively coupled to a readout resonator, which, in turn, is coupled to a feed line for control and readout (Supplementary Fig. 4). Extended Data Table 1 lists the relevant device parameters. All the required RF signals for qubit manipulation and readout are sent...
The solid black lines are cubic fits to the data. These fits are used to calculate the threshold voltage of the device, which is around 0.6 V. The solid black lines correspond to the transition region from the off to on state.

The multiplexer noise on the feed line can be reduced by using a directional coupler and a total of 13 dB of attenuation to the feed line. Alternatively, if the multiplexer is intentionally chosen to exploit the higher sensitivity of the qubit to multiplexer noise, the noise sensitivity of the qubit would be affected even above this voltage, maintaining a mean value of ∼0.6 V.

The effect of electronic heating on the qubit can be minimized by additional attenuation. The measured dephasing channels show no dependence on temperature. The measured dephasing time T^2 and spin-echo decoherence time T^* are functions of bias voltage V\text{dd} of the multiplexer chip measured at the base temperature and of the ESD protection cells measured at 4 K.

Characterization of this noise, a direct RF path that bypasses the multiplexer, is used to examine the effect of the multiplexer-induced photon shot noise on the qubit. The inset shows the isolation measured as a function of bias voltage at 6 GHz. The plotted insertion loss and the associated error bar corresponds to the mean and standard deviation of a moving 20-point window, respectively.

The dependence of the qubit’s energy relaxation time T_\text{1} and Ramsey decoherence time T^*_\text{R} and spin-echo decoherence time T^*_\text{SE} is measured as a function of bias voltage V\text{dd} of the multiplexer. These characteristic lifetimes show no dependence on V\text{dd} until the multiplexer turns on at the threshold voltage of ∼0.6 V. The T_\text{1} value remains unaffected above this voltage, maintaining a mean value of ∼30 μs, whereas the T^*_\text{R} and T^*_\text{SE} values show a notable voltage dependence and decrease from ∼40 to ∼25 μs at the nominal operating voltage of V\text{dd} = 0.7 V. This decrease is due to the additional dephasing caused by the multiplexer-induced photon shot noise (T^\text{photo}) in the readout resonator. From the dephasing rate Γ/(1/T^*_\text{R}) (Fig. 3c), the effective noise temperature (T^\text{eff}) of the multiplexer of ∼150 mK and a thermal photon flux of ∼0.15 photons s^{-1} Hz^{-1} at the frequency of the readout resonator is extracted (Methods). The effect of electronic heating on the qubit performance can be further minimized by additional attenuation. For example, 20 dB of total attenuation between the multiplexer and qubit would push T^\text{photo} over 400 μs—much longer than the intrinsic decoherence channels. The measured T^* values for the qubit would then recover to values obtained in the absence of the multiplexer, where it is
Fig. 3 | Benchmarking the cryo-CMOS multiplexer performance using a high-coherence qubit. a, Simplified RF signal path (Extended Data Fig. 1 and Methods). The qubit can either be measured using the direct RF input line or using the RF line routed through multiplexer port RF1. The multiplexer also adds a voltage- and switching-rate-dependent noise. The multiplexer bias voltage, $V_\text{bias}$, is unaffected but $T_1^*$ and $T_2^*$ decrease from $\sim 35$ to $\sim 25$ μs at $V_\text{bias} = 0.7$ V. b, $T_1^*$ and $T_2^*$ measured using the direct line as a function of the multiplexer bias voltage. $T_1^*$ is unaffected but $T_2^*$ and $T_2^*$ decrease from $\sim 35$ to $\sim 25$ μs at $V_\text{bias} = 0.7$ V. c, Decoherence rate $\Gamma = 1/T_2^*$ versus the bias voltage and extracted thermal photon numbers at the readout resonator. d, $T_1^*$, $T_2^*$, and $T_2^*$ times measured using RF signals routed through the multiplexer at $V_\text{bias} = 0.7$ V. The obtained values are similar to the values measured using the direct RF line, confirming that the noise added by the multiplexer is independent of the chosen RF line for qubit measurements. e, $T_1^*$, $T_2^*$, and $T_2^*$ values measured versus the switching rate of the multiplexer at $V_\text{bias} = 0.7$ V. The $T_1^*$ value is unaffected, whereas the $T_2^*$ values decrease further from $\sim 25$ to $\sim 10$ μs at 1 MHz switching. f, Extracted decoherence rate and thermal photon number versus switching rate, showing an additional 88.66 kHz of dephasing per megahertz of multiplexer switching. The markers and error bars in b and e represent the best-fit values and their estimated standard errors (1σ confidence intervals), respectively, obtained from individual measurements.

limited by the intrinsic decoherence channels ($\sim 40$ μs for the presented qubit). Additionally, it is verified that pair-breaking quasiparticle generation mechanisms are not present (Supplementary Fig. S5), which is also indicated by the independence of $T_1$ as a function of $V_\text{dd}$. The $T_1^*$, $T_2^*$, and $T_2^*$ measurements obtained with signals routed through the multiplexer are shown in Fig. 3d for $V_\text{bias} = 0.7$ V. The obtained qubit lifetimes are similar to the values measured using the direct line (Fig. 3d). This result confirms that the multiplexer noise can be independently treated, validating the adopted approach of characterizing the noise by measuring the qubit using the direct RF line and exclusively using the multiplexer as a noise source. Moreover, the measurement also confirms that the multiplexer supports the dynamic range required for both qubit control and resonator readout signals.

The described characterization approach is especially useful to assess the effect of multiplexer noise generated during dynamic switching. The multiplexer is programmed to operate in the parallel operation mode (Supplementary Section 4) and control line D0 is continuously switched so that the multiplexer switches between ports RF1 and RF2. The obtained $T_1^*$, $T_2^*$, and $T_2^*$ values of the qubit and decoherence rate $\Gamma = 1/T_2^*$ as a function of the multiplexer switching rate are shown in Fig. 3e,f, respectively. The $T_1^*$ times show no dependence up to the measured switching rate of 1 MHz. However, the $T_2^*$ and $T_2^*$ values decrease from the static-mode value of $\sim 25$ to $\sim 10$ μs at 1 MHz of switching, corresponding to an effective multiplexer temperature of $\sim 300$ mK and a thermal photon flux of $\sim 1.10$ photons s$^{-1}$ Hz$^{-1}$ at the frequency of the readout resonator. It is important to note that the measured decoherence times correspond to the lower limit when the multiplexer is continuously switched during a pulse sequence. Nevertheless, using a total attenuation of 20 dB after the multiplexer, the decoherence limit set by the multiplexer ($T_2^*$) could be pushed to over 50 μs.

In future experiments involving multi-qubit devices, the multiplexer is advocated for either multiplexed readout or multiplexed control of superconducting qubits. In the former case, the multiplexer will only be switched during readout pulses at a maximum rate dictated by the readout pulse duration, which is typically around 1 MHz (refs. 11,50) for a fast high-fidelity readout. For the latter case, the multiplexer will have to switch much faster at 10–50 MHz, defined by the typical qubit gate lengths of 10–50 ns (ref. 11). However, it is crucial to note that in this configuration, the multiplexer will drive the qubit through a dedicated charge line and not via the feed line. The multiplexer noise on the charge line transversely couples to the qubit quantization axis, thereby affecting its $T_1$ and not $T_2$. For an average switching rate of 20 MHz and standard charge-line coupling parameters (Methods), a limit of $\sim 50$ μs on $T_1$ can be estimated without attenuation. This limit could be further increased to $\sim 5$ ms with an attenuation of 20 dB, far beyond the state-of-the-art energy relaxation times.
Fig. 4 | Randomized benchmarking and TDM using a cryo-CMOS multiplexer. **a.** Simplified signal path and pulse sequence for randomized benchmarking (Extended Data Fig. 1 and Methods). Randomized benchmarking fidelity versus $1/T_2^*$ for the multiplexer off (green), multiplexer on at 0.7 V (red) and multiplexer on and switching (blue). The dynamic switching rates from left to right are 55 kHz, 135 kHz, 200 kHz, 265 kHz, 465 kHz, 785 kHz, 1 MHz, 2 MHz and 5 MHz, chosen to get a distribution in decoherence times $T_2^*$. The dashed grey line represents a guide to the eye for the limit in fidelity arising due to finite pulse calibration errors (~99.93%) and the dashed black line represents a linear fit to the data as a function of $1/T_2^*$ (Methods). The inset shows the individual randomized benchmarking fidelity measurements obtained with a sequence length of 1,000 Clifford gates. The markers and error bars represent the best-fit values and the propagated standard errors with 1σ confidence intervals, respectively (Methods). **b.** Simplified signal path and pulse sequence for the demonstration of TDM. The RF signal is normally routed to port RF2 ($D_0 = 1$), except for the time windows where $D_0$ is set low, in which case it is routed to the qubit via port RF1. The measured excited-state population of the qubit, $p_e$, versus the multiplexer window length (pink), showing that below the 2 ns time window, the population is below the detection limit of the qubit ground state. The solid black lines are the simulation data obtained using a 0 ns rise and fall time for signal $D_0$. The discrepancy between simulations and experiments in smaller time windows can be explained by the finite rise and fall times, which results in an effective qubit excitation slightly smaller than expected. The plot of $1 - p_e$ (touque) shows that for time windows larger than 30 ns, there is no discernable change in the excited-state population, implying that the multiplexer time window can be exactly as long as the qubit π pulse.

dimensions\textsuperscript{31}. The integration scheme of such compact attenuators with the multiplexer chip would strongly depend on the origin of the observed noise temperature. Although thermal transport and noise modelling are not well studied for cryo-CMOS devices at millikelvin temperatures, previous reports\textsuperscript{32, 41} suggest that the measured noise temperature is probably the effective carrier temperature, and not the lattice temperature. Consequently, the attenuators could be implemented on the same chip as the multiplexer. Alternatively, the attenuators could be implemented on a separate chip or as surface-mounted devices on the PCB to ensure proper thermalization. Further research is required to explore the limits of thermalization, attenuation and associated scaling at millikelvin temperatures.

**Cryo-CMOS multiplexer for time-multiplexed quantum gates**

The CMOS multiplexer is intended for applications that demand high-fidelity static and dynamic qubit operations (Supplementary Information section 7 and Supplementary Table 1 provide the envisioned use cases and their corresponding requirements). To assess the impact of the multiplexer on single-qubit gate fidelities, randomized benchmarking\textsuperscript{32, 35} is performed under various operating conditions of the multiplexer, which encompass both static biasing and dynamic switching. For each condition, the randomized benchmarking fidelity measured using gate pulses of duration $t_g = 40$ ns is plotted as a function of the qubit's $T_2^*$ (Fig. 4a). Here the inset shows the individual curves obtained with the multiplexer turned off (green) and multiplexer switching at 5 MHz at $V_{\text{bias}} = 0.7$ V (violet). The data show two distinct regimes: for low $T_2^*$ (~10 µs), the gate fidelities are limited by the coherence time of the qubit (black dashed line), whereas for long $T_2^*$, the fidelity saturates at ~99.93% (grey dashed line) due to imperfect pulse calibration\textsuperscript{44, 45}. Nevertheless, for nominal operating conditions of the multiplexer with dynamic switching of 1 MHz, $T_2^*$ exceeds 10 µs and the measured gate fidelity is above 99.9%. The limit set by the coherence time can be increased with a better thermal filtering of the multiplexer noise and longer qubit lifetimes, whereas the threshold set by the pulse calibration errors can be improved by using shorter control pulses, adjusting the pulse shapes or using different Clifford gate sets\textsuperscript{46, 47}. Furthermore, the reduction in fidelity at higher switching rates is directly related to the reduction in $T_2^*$. This is a consequence of the chosen configuration—driving the multiplexer on the feed line. If the multiplexer were to drive the charge lines, the impact of the multiplexer noise could potentially be much lower.
In large-scale quantum systems, each qubit invariably requires a dedicated control line for state manipulation. The resulting hardware cost and wiring complexity can be substantially reduced by multiplexing the qubit control lines. However, operations involving more than one qubit will then require the TDM of control signals to the appropriate qubits. The corresponding output port needs to be active for an optimal time window around the control pulse to perform the intended qubit operation. Windows larger than the pulse width would result in wasted dead time between the pulses and windows shorter than the pulse width would distort it, reducing the gate fidelity in both cases. Furthermore, the multiplexer could introduce additional crosstalk as the drive signals intended for one qubit could leak through the multiplexing network to another qubit. This needs to be avoided for high-fidelity qubit operations.

To demonstrate the TDM capability and quantify the potential limitations mentioned above, an experiment is performed with a novel pulse sequence (Fig. 4b, top). The RF signals are exclusively routed through the multiplexer, which is initially programmed to port RF2 (D0 = 1). A fixed precalibrated 40 ns cosine-enveloped π pulse drives the qubit from the ground state to the excited state, when routed entirely to the qubit through port RF1 (D0 = 0). The amount of pulse excitation seen by the qubit is modified by reducing the signal time window centred around the π pulse by dynamically switching port D0 using the parallel operation mode.

The excited-state population \( p_e \) of the qubit is measured and plotted against the multiplexer time window (pink, left y axis; Fig. 4b, bottom). These data show excellent agreement with numerical simulations performed in QuTiP, where the instantaneous switching of the multiplexer with a rise/fall time of 0 ns is assumed (solid black line). In the absence of switching (that is, window time of 0 ns), the excited-state population is below the detection threshold of the setup, indicating that the qubit remains in the ground state. Even when ascribing the entire qubit population to crosstalk, a lower bound of 30 dB on port-to-port isolation is obtained, consistent with the reported values (Fig. 2d). The deviation in the excited-state population from simulations in short time windows can be attributed to the finite rise and fall times of the multiplexer of ~2.6 ns, resulting in a smaller excited-state population (Supplementary Fig. 1b,c shows the rise-time measurements). It is worthwhile to note that in practical devices, qubits are generally not degenerate but are detuned with different transition frequencies. This translates to easing the crosstalk constraint as the qubit is insensitive to (crosstalk) signals distant from its own transition frequency. For example, a qubit detuned by 20 MHz (Δ) from the target frequency of a 40 ns (\( t_e \)) single-sideband-modulated square pulse would experience ~10 dB lower crosstalk (\( \sim \text{sinc}(2\Delta t) \)), in addition to port-to-port isolation.

To quantify the minimum time window required for proper operation, the data are further examined by analysing \( 1 - p_e \) as a function of the multiplexer time window (Fig. 4b, turquoise, right y axis). A noticeable decrease in the measured excited-state population of the qubit is observed for multiplexer windows below 30 ns, although with a small offset to numerical simulations owing to the finite rise and fall times of the multiplexer. For time windows over 30 ns, there is no discernible difference in the excited-state population of the qubit due to the shallow pulse tails of the cosine envelope. Therefore, the length of the multiplexer switching window does not have to exceed the qubit control pulse width. This result is substantial as it enables pulse sequencing without any inactive time between the qubit control pulses to account for multiplexer switching delays. This illustrates the feasibility of performing time-multiplexed qubit control using the multiplexer.

It should be noted that TDM inherently introduces an additional overhead in pulse sequencing. The effective increase in gate time could consequently reduce the gate fidelities. However, this is not completely detrimental as physical circuits implementing quantum algorithms do not require constant access to all the qubits or read-out resonators. For example, the multiplexer could be used to switch between X and Z stabilizer measurements in a quantum error correction cycle with no additional pulsing overhead. Furthermore, a recent circuit compilation study has reported that it is possible to minimize this pulsing overhead, if not completely eliminate it.

With the compatibility of the cryo-CMOS multiplexer with superconducting qubits established, it is important to consider its scalability to larger systems. Commercially available dilution refrigerators have cooling powers in the order of 20 µW at the base-temperature stage. The presented cryo-CMOS multiplexer dissipates around 0.24 µW of static power (40% of 0.60 µW), barring the contribution of ESD cells (60% of 0.60 µW), and 0.50 µW of dynamic power with 1 MHz effective switching at 0.7 V, resulting in a total power consumption of 0.74 µW or ~0.18 µW per qubit channel. Therefore, it would be possible to interface with approximately 100 qubits within the cooling budget of the refrigerator. The effective switching rate sets the bound on the maximum number of switching events that are allowed within a pulse sequence. By lowering the threshold voltage and consequently reducing the operating voltage to 0.3 V, the static power consumption (excluding the contribution from ESD cells) would decrease to ~12 nW (extrapolating the fits in Fig. 2a) and total dynamic power consumption would reduce to ~30 nW. The resulting power consumption of ~25 nW per qubit channel would increase the interfacing capability to almost 1,000 qubits. In particular, the power dissipation would be comparable with the 20 nW passive heat load of superconducting cables that are used in current experimental setups. Scaling this number to a million qubits with current cooling powers is still extremely demanding, with power dissipation limited to ~20 pW per qubit channel. Therefore, further investigation into design and operation optimization, along with research into advanced process technologies with tunable threshold voltage, is required to understand the physical limitations on scalability.

**Conclusions**

We have reported a low-power cryo-CMOS multiplexer that is fabricated using commercially available 28 nm bulk CMOS technology and operates at the base-temperature stage of a dilution refrigerator. The RF and noise properties of the multiplexer characterized over a wide frequency range enables interfacing with high-coherence superconducting qubits to perform qubit control with single-qubit gate fidelities exceeding 99.9%. The nanosecond-scale fast switching of the multiplexer enables TDM with the signal crosstalk suppressed by greater than 30 dB. Our approach provides a route to address the wiring bottleneck in future large-scale quantum computing systems.

**Methods**

**Chip design**

The cryo-CMOS multiplexer is designed by performing device simulations at room temperature and ~40 °C—the lowest temperature at which the transistor models are reliable. Chip-level circuit simulations are done using Cadence Virtuoso IC6.1.8. Electromagnetic simulations are performed using integrated EMX for on-chip passives.

**Measurement setup**

The cryo-CMOS multiplexer and the qubit are measured with a Bluefors LD400 dilution refrigerator setup (Extended Data Fig. 1). Two separate input lines are used for qubit measurements and each of them is thermalized using 20 dB attenuators at two different temperature stages. High-frequency noise above the measured frequency range is filtered before reaching the qubit with a low-pass filter (VLF-8400+) with a cut-off frequency of 8.4 GHz. One input line is directly connected to the qubit via the ~20 dB port of a directional coupler (KRYTAR 120420). The other input line is routed to the qubit via the multiplexer, a 10 dB attenuator, the directional coupler and an additional 3 dB attenuator.
The attenuators are thermalized to the base plate of the fridge using copper braids. Multiplexer ports D0 and D1 are programmed in the parallel operation mode with low-pass-filtered (VLFX-780+) cut-off frequency, 780 MHz arbitrary waveform generator (Keysight M3202A) signals. Output signal lines are thermalized with two isolators (LNF-SC4_8A) and a circulator (LNF-LNC4_8C) with a total reverse isolation of ~60 dB and a 4–8 GHz band-pass filter (KBF-4/8-2S). The signal is amplified with a high-electron-mobility transistor amplifier (LNF-LNC4_8C) at the 4 K stage and an ultra-low noise amplifier (LNA-30-04000800-07-10P) at room temperature. Pulsed measurement signals are generated and acquired using the Keysight Quantum Engineering Toolbox: M3202A arbitrary waveform generators, M3102A digitizer and M9347A Dual DDS local oscillators. The qubit excitation and readout pulses are combined at room temperature and applied to the qubit’s feed line. No dedicated charge line or flux line is used to excite or bias the qubits.

The superconducting qubit chip is wire-bonded to a non-magnetic gold-plated copper PCB enclosed in an oxygen-free copper sample holder. The sample holder is thermalized to the mixing chamber plate in a dilution refrigerator and surrounded by a copper radiation shield as well as two cryopumps to minimize the magnetic fields at the sample. The cryo-CMOS multiplexer chip is placed on a four-layer PCB with a low-loss Rogers RO4350B microwave laminate.

Cryo-CMOS multiplexer: measurement and analysis

The power dissipation of the multiplexer is determined by measuring the voltage drop across a 1 kΩ series resistor on the power supply line of the multiplexer using a Keithley 2182A nanovoltmeter. The series current inferred using Ohm’s law is used to calculate the power dissipation.

The RF characterization of the multiplexer is limited to 4–8 GHz due to the band-pass filter and the high-electron-mobility transistor amplifier present in the output line. The port-to-port isolation is obtained by measuring the transmission $S_{21}$ between the RFC and RF3 ports and sequentially programming the multiplexer from port RF1 through port RF4. Port-to-port isolation is reported as the difference between the measured transmission $S_{21}$ when the multiplexer is programmed to the reference port RF3 and to one of the other ports. The insertion loss of the device is measured as a difference between $S_{21}$ obtained with and without the multiplexer PCB in independent measurements. For the latter, the multiplexer PCB was replaced by a sub miniature push-on (SMP) female–female bullet. We note that the insertion loss thus extracted includes the loss in the SMP connector in addition to the loss in the multiplexer and PCB lines. Owing to the variation in the residual mismatches in the input and output lines of the dilution refrigerator from one cool down to another, a window average of 20 data points is used to obtain the insertion loss. Therefore, we report the average value of insertion loss in the bandwidth of interest (4–8 GHz).

Thermal photon number and effective carrier temperature estimation

The thermal photon number $n$ in the readout resonator is estimated using the resonator linewidth $\kappa_r$, dispersive shift $\gamma$ and dephasing rate $\Gamma$ as:

$$n = \Gamma \frac{\kappa_r^2 + 4\chi^2}{4\chi^2}.$$  

(1)

Extended Data Table 1 lists the various parameters and their values. The thermal photon number is translated into the effective carrier temperature of the multiplexer using the Bose–Einstein distribution and signal attenuation. Similarly, following the inverse procedure, the effective temperature can be translated into the dephasing rate.

$T$, limit due to multiplexer thermal noise

Using the drive-line coupling $A_d$ to the qubit and the voltage noise PSD $S_{vv}(\omega)$ (ref. 61) at the qubit frequency, $T$, is estimated as:

$$T = \frac{1}{\Gamma} = \frac{\hbar^2}{\kappa^2 S_{vv}(\omega_q)}.$$  

(2)

where

$$S_{vv}(\omega) = \frac{4R_{\text{in}}\omega}{\kappa^2 e^{i\gamma\omega} - 1}.$$  

(3)

and

$$A_d = \sqrt{\frac{R C \omega_q}{2} \frac{C_d}{C_d + C_q}}.$$  

(4)

Using typical qubit-charge-line coupling capacitance $C_d$ of 0.1 fF, qubit capacitance $C_q$ of 110 fF, multiplexer resistance $R_m$ of 5 Ω and effective multiplexer carrier temperature of 7 K at 20 MHz switching with $V_{dd}=0.7$ V, a limit on the relaxation time of 50 μs is obtained.

RB: measurement and analysis

The average physical gate error $r_g$ and gate fidelity $F_{\text{IQ}}$ are measured by applying a random sequence of Clifford gates of varying lengths $n$ to the qubit initialized in the ground state. At the end of the sequence, an inverting gate is added to create an overall identity operation, and the final qubit state is measured to determine the fidelity. The measurement is repeated 80 times for each sequence length. Cosine pulses with derivative removal by adiabatic gate (DRAG) pulse calibration and a duration of 40 ns are used in the experiment. The averaged sequence fidelity is fitted to $F = A p + B$, where parameters $A$ and $B$ depend on the state preparation and measurement errors. From $p$, $r_g$ is determined as the error per Clifford $r_{\text{Cliff}}$ normalized by the average number of physical Clifford gates per gate (1.875):

$$r_g = \frac{r_{\text{Cliff}}}{1.875} = \frac{(1-p)(d-1)}{1.875d}.$$  

(5)

where $d = 2^n$ is the dimensionality of the Hilbert space, which is equal to 2 for a single qubit. The average physical gate fidelity is obtained from

$$F_{\text{IQ}} = 1 - r_g.$$  

(6)

Fidelity as a function of gate duration $t_g$, relaxation time $T_1$ and Ramsey decoherence time $T_2^*$ is modelled using:

$$F_{\text{IQ–fit}} = 1 - c_0 - \frac{k_1}{T_1^{\text{max}}},$$  

(7)

$$F_{\text{IQ–fit}} = 1 - c_0 - \frac{1}{T_2^{\text{max}}}.$$  

(8)

Here $c_0$ accounts for the gate error due to relaxation ($t_g/3T_1$) and other dephasing channels, $T_2^{\text{max}}$ is the dephasing time due to the multiplexer, $T_2^*$ is the measured decoherence time and $k_1$ is a scaling parameter that depends on the noise PSD seen by the qubit. The obtained value for fitting parameter $k_1$ is approximately 0.433$t_g/3$. For a white-noise PSD, the noise correlation time is small compared with the experimental timescales and the factor $k_1$ reduces to $t_g/3$. However, photon shot noise has a Lorentzian PSD with a two-photon correlation time in the order of a microsecond (inverse of resonator linewidth, $1/\kappa_r$), which being comparable with experimental timescales results in a deviation from the white-noise case.

Article

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Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability
The codes that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions
R.A. and A.P. planned the experiment. S.B. designed the multiplexer. A.P. designed the qubit samples. T.I. and D.P.L. fabricated the qubit samples, with contributions from D.W. R.A. and A.P. performed the measurement and analysis of qubit data at the base temperature. S.B. and A.G. performed the measurements and analysis of the ESD protection cells from room temperature to 4 K. R.A., A.P., J.V., J.V.D. and A.M.V. prepared the experimental setup and methods. R.A. and A.P. prepared the manuscript, with input from all authors. A.P., I.P.R., J.C., K.D.G., B.G., M.M., G.G. and F.C. supervised and coordinated the project.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to R. Acharya.

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Extended Data Fig. 1 | Experimental measurement setup. Room-temperature electronics and dilution refrigerator wiring for the measurement of the cryo-CMOS RF multiplexer performance with superconducting qubits.
Extended Data Table 1 | Device parameters

| Parameter                  | Notation | Value     |
|----------------------------|----------|-----------|
| Resonator frequency        | $\omega_r/2\pi$ | 6.471 GHz |
| Resonator linewidth        | $\kappa_r/2\pi$ | 0.697 MHz |
| Qubit frequency            | $\omega_{\Omega}/2\pi$ | 3.957 GHz |
| Qubit anharmonicity        | $\alpha/2\pi$ | -180 MHz  |
| Qubit-resonator coupling   | $g/2\pi$  | $\sim$ 90 MHz |
| Dispersive shift           | $\chi/2\pi$ | -0.259 MHz |

Relevant device parameters of the qubit sample.