

Quantum Teleportation over Thermal Microwave Network

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(Received 15 October 2025; revised 23 January 2026; accepted 9 March 2026; published 4 May 2026)

Quantum communication in the microwave regime is set to play an important role in distributed quantum computing and hybrid quantum networks. However, typical superconducting quantum circuits require millikelvin temperatures for operation, which poses a significant challenge for large-scale microwave quantum networks. Here, we present a solution to this challenge by demonstrating the successful quantum teleportation of microwave coherent states between two spatially separated dilution refrigerators over a thermal microwave channel in the temperature range up to 4 K. We distribute two-mode squeezed states over this noisy channel and employ the resulting quantum entanglement for quantum teleportation of coherent states with fidelities of $72.3 \pm 0.5\%$ at 1 K and $59.9 \pm 2.5\%$ at 4 K, exceeding the no-cloning and classical communication thresholds, respectively. We successfully model the teleportation protocol using a Gaussian operator formalism that includes losses and noise. Our analysis shows that the teleportation infidelity mainly stems from a parasitic heating of the cold quantum nodes due to the hot network connection. These results demonstrate the experimental feasibility of distributed superconducting architectures and motivate further investigations of noisy quantum networks in various frequency regimes.

DOI: 10.1103/n8j9-63mz

Introduction—Microwave quantum communication is an important aspect of future quantum networks due to its compatibility with superconducting quantum circuits and modern telecommunication standards. Superconducting quantum circuits are currently one of the leading platforms in quantum information processing [1], achieving a computational power beyond that of classical systems [2,3]. They operate at microwave frequencies around 5 GHz and in dilution refrigerators at temperatures around 10 mK. While modern superconducting processors demonstrate coherent operations with more than 100 superconducting qubits in individual dilution cryostats [4,5], it is well understood that millions of physical qubits will be required to tackle practical problems [6,7]. However, the task of scaling up the number of superconducting qubits faces multiple challenges due to limitations in monolithic fabrication [8], spatial constraints [9], or available cooling power [10]. A potential solution is to rely on distributed architectures [11] by connecting multiple cryogenic

quantum nodes, with moderate numbers of qubits, into one large quantum network [12,13].

A particular approach to build such a quantum network is to couple remote quantum nodes directly at microwave carrier frequencies [14–16]. Recent successful realizations of deterministic microwave entanglement distribution between spatially separated dilution refrigerators via cryolinks [17,18] demonstrate the experimental feasibility and efficiency of this approach. Moreover, it has been demonstrated that microwave channels can be used for the distribution of quantum correlations at temperatures $T \gg 10$ mK as long as the channel intrinsic losses are sufficiently low [18,19]. These findings promise to relax technical requirements for future microwave quantum links and enable large-scale superconducting quantum networks. At the same time, noisy quantum networks are becoming a focus of intense research, also at optical frequencies [20–22] and for other material systems [23–25].

In this Letter, we report on the experimental realization of a superconducting microwave quantum network with channel temperatures up to 4 K, mimicking a “hot” quantum channel compared to the millikelvin operation temperature of superconducting quantum circuits. We demonstrate its potential by distributing continuous-variable entanglement between two spatially separated dilution refrigerators and exploiting it for coherent state teleportation [26–28] with fidelities exceeding the classical threshold. Specifically, we use steady-state, two-mode squeezed

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(TMS) states as the entanglement resource to teleport coherent states over a 6.6 m long cryolink [18], achieving teleported state fidelities up to $72.6 \pm 0.1\%$ at the channel base temperature of 170 mK. We demonstrate that the quantum entanglement is preserved even when the TMS microwave states pass through a 4 K thermal channel and permits the deterministic quantum teleportation with fidelity of $59.9 \pm 2.5\%$. This key achievement of our Letter is enabled by the low microwave losses of the superconducting niobium-titanium (NbTi) cables [18,29], with critical temperature $T_c \simeq 10$ K, used as the quantum channel. As a consequence, the fluctuation-dissipation theorem [30] dictates that propagating photonic modes are effectively decoupled from their ambient hot environment, thus preserving the quantum correlations therein. In comparison with other related experiments [17–19], this Letter presents the first implementation of microwave quantum teleportation between spatially separated dilution refrigerators by utilizing a shared entanglement resource. While cryogenic engineering and microwave losses remain substantial technical challenges toward scalability, the achievement of nonclassical teleported state fidelities over the 4 K microwave link is an important proof-of-principle milestone. It paves the way towards large-scale, cryogen-free interconnects between superconducting quantum systems.

Experimental setup—The cryolink used in our experiment consists of two dilution refrigerators (Alice and Bob) separated center to center by 6.6 m and connected via a cold network node (Eve) [18]. As illustrated in Fig. 1(a), the quantum channel between the mixing chamber (MC) stages of Alice and Bob consists of 6-m-long superconducting NbTi coaxial cables with characteristic losses of 1 dB km^{-1} . The channel temperature at its center, T_{cen} , can be varied in the range between the cryolink base temperature 170 mK and 4 K by using an embedded heater.

We generate and control microwave quantum states in Alice by using four flux-driven Josephson parametric amplifiers (JPAs) [31] in combination with linear microwave elements, such as hybrid rings, circulators, and directional

couplers. The microwave signals propagate through two parallel superconducting coaxial cables toward Bob. These signals distribute quantum entanglement and provide the measurement feedforward, thereby implementing the quantum teleportation protocol [27]. In our experiment, we tune all four JPAs to the frequency $\omega_0/2\pi = 5.35$ GHz and perform squeezing operations by introducing a strong coherent pump tone at the frequency $\omega_p = 2\omega_0$ [32,33]. During state tomography, the output signals are amplified, down-converted, and detected with a field-programmable gate array receiver. The receiver calculates signal statistical moments up to the fourth order in order to reconstruct the corresponding quantum states in the Gaussian approximation [34] and verify their Gaussianity. We calibrate the gain and noise of our amplification chain using the Planck spectroscopy [35]. More details about the devices and experimental setup are provided in Supplemental Material [36].

Interfidge microwave teleportation—Quantum teleportation is an entanglement-assisted communication protocol that allows disembodied transfer of unknown quantum states [26]. While quantum teleportation of optical photonic states has been demonstrated in various experimental settings, including ground-to-satellite realizations [50], quantum teleportation of microwave states has so far been constrained to experiments within individual cryogenic nodes [27,28,51,52]. Here, we successfully implement an analog (or measurement-device-free [27,53]) quantum teleportation of coherent microwave states between spatially separated dilution refrigerators.

We employ two “entanglement JPAs” [see Fig. 1(c)] to generate a balanced TMS state, characterized by a squeezing level, S_{TMS} , between Alice and Bob [33]. Then, we perform a Bell-type measurement operation on Alice’s state, where the latter is obtained by superimposing an input coherent state and Alice’s part of the TMS state via a hybrid ring (balanced microwave beam splitter). The measurement operation utilizes two “measurement JPAs” [see Fig. 1(d)] in a Josephson interferometer configuration [54] in the regime of high degenerate gain $G \gg 1$ [55].

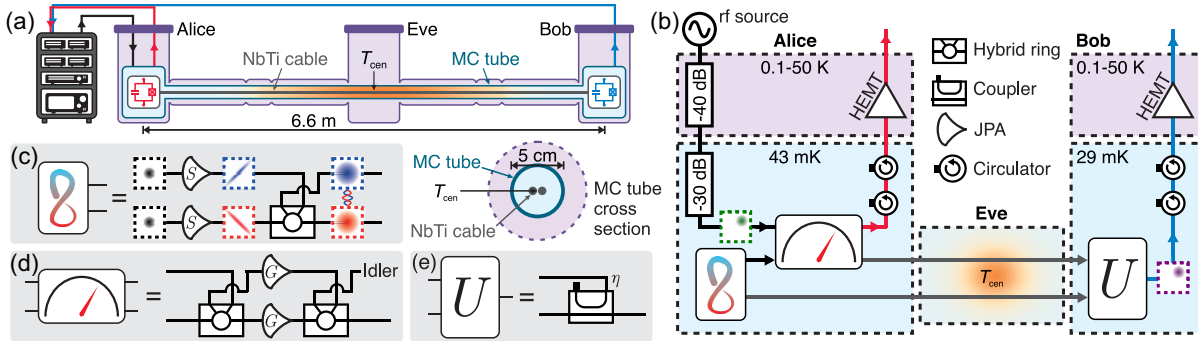


FIG. 1. Cryolink and experimental setup. (a) Schematic of the cryolink connecting Alice and Bob, including a cross-sectional view of the MC tube at the cryolink center. (b) Schematic representation of the coherent quantum teleportation protocol with an analog feedforward. Schematics of (c) the TMS state generation, (d) the feedforward generation with a Josephson interferometer, and (e) Bob’s local displacement operation.

The produced analog measurement result can be treated as a classical feedforward signal and is sent to Bob through a separate coaxial cable in the cryolink. Combined with Bob's part of the TMS state via a directional coupler with coupling η [see Fig. 1(e)], the feedforward signal determines the displacement amplitude and quadrature variance of a teleported state [27,56]. To produce a correct complex displacement amplitude, we require $G = 4\eta$ in the ideal case of zero losses in all experimental elements. Our particular directional coupler has $\eta = 15$ dB, hence, we operate the measurement JPAs around $G = 21$ dB. Bob's teleported state at the directional coupler output, ideally, has the complex displacement perfectly matching that of Alice's input state and quadrature variances at the vacuum level.

Figure 2(a) shows calibration measurements of our TMS resource states. Here, we sweep the squeezing level of the entanglement JPAs from 1 to 7 dB and observe that the negativity N (purity μ) increases (decreases) with increasing S_{TMS} . Negativity is an entanglement monotone derived from the Peres–Horodecki criterion, where $N > 0$ implies entanglement [57,58], and purity describes how much classical noise is admixed into a quantum state, with $\mu = 1$ corresponding to a pure state. For high-fidelity quantum teleportation, we want both high N and μ . However, in our experiment, large microwave parametric pump powers (around -40 dBm at the JPA pump input) are needed to achieve squeezing levels around 5 dB below vacuum. Those strong pump signals introduce additional noise due to higher-order nonlinearities and photon number uncertainty in the JPAs [55,59]. As a practical compromise, we use TMS states with $S_{\text{TMS}} = 5$ dB, corresponding to $N = 0.922 \pm 0.009$ and $\mu = 0.846 \pm 0.007$. The rate of entanglement generation can be characterized using the relationship $R = B \times E_F$, where B is the device bandwidth and E_F is the entanglement of formation, which can be directly estimated for general two-mode squeezed states [60,61]. For the TMS squeezing level $S_{\text{TMS}} = 5$ dB, our entanglement JPAs have $B \approx 17$ MHz and $E_F = 1.01 \pm 0.05$ ebit, resulting in the entanglement bit rate $R \approx 17$ Mebit s $^{-1}$.

The quantum teleportation protocol is typically characterized by its fidelity, F , which is defined as the overlap between Alice's input and Bob's output states [34]. Figure 2(b) shows the measured fidelities for teleported coherent states at the carrier frequency of 5.35 GHz with average photon numbers, n_{in} , in the range from 10^{-2} to 10^2 and averaged across all displacement angles $\theta_{\text{in}} \in [0, 2\pi)$. First, we consider the classical teleportation case by turning off the entanglement JPAs, $S_{\text{TMS}} = 0$ dB, to provide a fidelity reference for teleported states. We measure fidelities up to 56% for coherent states with low photon numbers $n_{\text{in}} \ll 1$. For larger values of $n_{\text{in}} > 1$, the fidelities drop below the asymptotic classical threshold $F_{\text{cl}} = 1/2$ [62]. Near-vacuum input states can be teleported with fidelities above F_{cl} due to losses in the experimental setup, which admix vacuum into the teleported states.

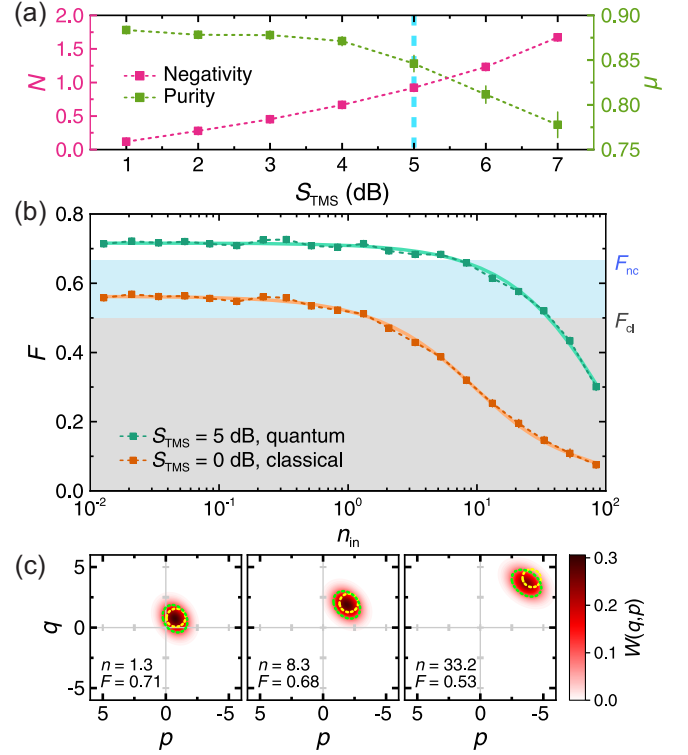


FIG. 2. Quantum teleportation between distant dilution refrigerators. (a) Negativity N and purity μ of TMS states distributed over the cryolink for various squeezing levels S_{TMS} . The vertical dashed line indicates the chosen operating point of $S_{\text{TMS}} = 5$ dB. (b) Teleported state fidelities F of quantum and classical teleportation protocols as a function of the input state photon number n_{in} and averaged across displacement angles. Solid lines represent fits using our theoretical model. Gray- and blue-shaded regions indicate fidelities below the classical F_{cl} and no-cloning F_{nc} thresholds, respectively. (c) Exemplary Wigner functions of relevant coherent states. Yellow and green dashed lines denote the $1/e$ Gaussian contours of the input and teleported states, respectively. Error bars denote the standard error of the experimental data and are smaller than the symbol size when not shown.

For the teleportation protocol with finite quantum entanglement, $S_{\text{TMS}} = 5$ dB, we observe fidelities exceeding those of the classical case, thus, demonstrating a quantum advantage across the entire parameter range. We are able to teleport low photon number coherent states with fidelities of around 72%, reaching a maximum of $F = 72.6 \pm 0.1\%$. This value substantially exceeds the asymptotic no-cloning fidelity of $F_{\text{nc}} = 2/3$ [63], which implies the possibility to guarantee unconditional security when using quantum teleportation as a communication protocol for a codebook of coherent states with $n_{\text{in}} \in [0, \infty)$. The communication bit rate C has an upper bound according to Holevo's theorem of $C = \Delta f \times \chi$, where $\Delta f = 200$ kHz is the measurement bandwidth and χ is the Holevo quantity [64,65]. Considering a uniformly distributed codebook of coherent states that satisfy $F > F_{\text{nc}}$ (hence constraining $n_{\text{in}} \leq 8.3$) and the experimentally

measured Gaussian noise variance of $\sigma^2 = 0.443$, we obtain $\chi = 3.38$ bit per channel use and estimate the communication bit rate encoded in teleported states to be $C = 0.68$ Mbit s⁻¹. As seen in Fig. 2(b), experimental imperfections, such as losses and JPA compression effects, cause F to decrease with n_{in} , such that fidelities exceed F_{nc} (F_{cl}) only up to $n_{\text{in}} = 8.3$ ($n_{\text{in}} = 33.2$). To understand this drop in F , we consider the reconstructed Wigner functions in Fig. 2(c). We observe elliptical Wigner functions due to small asymmetries in our experimental implementation of quantum teleportation, such as nonidentical noise properties of the JPAs and small imbalances in the microwave hybrid rings used for the beam splitter operations. From $n_{\text{in}} = 1.3$ to $n_{\text{in}} = 33.2$, the displacement mismatch between the teleported and input state distributions grows up to 0.554 photons, which corresponds to an estimated 15.9% decrease in fidelity. Thus, the drop in F is mainly caused by a mismatch in teleported state displacement, which results from losses in the experimental setup. This behavior is well-described by our theoretical model [solid lines in Fig. 2(b)], which incorporates losses and noise to simulate the teleportation protocol [27,66]. An analytic expression can be obtained for the teleported state fidelity,

$$F(\alpha, \kappa, \zeta) = \frac{2}{\zeta + \kappa + 1} \exp \left[-2 \frac{(\sqrt{\kappa} - 1)^2}{\zeta + \kappa + 1} |\alpha|^2 \right], \quad (1)$$

$$\zeta = (1 + \kappa) \cosh 2r - 2\sqrt{\kappa} \sinh 2r + n_{\text{dev}} + n_{\text{th}}, \quad (2)$$

where α is the input coherent state amplitude, κ the effective gain, ζ the effective added noise, r the resource squeezing parameter, n_{dev} the added device noise, and n_{th} the coupled thermal noise. Fitting the teleportation data for $S_{\text{TMS}} = 5$ dB with this expression, we obtain $\kappa = 0.778$, which implies an overall attenuation of about 1.09 dB in our implementation of quantum teleportation, and $\zeta = 1.015$, which can be attributed to finite squeezing, noisy devices, and losses in the setup. In the current experiment, the largest source of infidelity for the teleported states, especially at large n_{in} , is the microwave insertion losses in passive microwave devices, such as the hybrid rings, circulators, and directional couplers. Substituting those with low-loss superconducting devices [67,68] could substantially increase the teleportation fidelities by $\sim 15\%$. More details about our model of the quantum teleportation protocol are provided in Supplemental Material [36].

Teleportation through a thermal channel—In the next step, we use the cryolink to mimic a noisy thermal communication channel by heating its center temperature up to $T_{\text{cen}} = 4$ K. This is accomplished by using a proportional–integral–derivative-controlled heater clamped to the NbTi cables at the center of the cryolink. However, the local heating also affects the MC temperatures of the Alice and Bob cryostats, as shown in Fig. 3(a), due to a direct (parasitic) thermal coupling to the heater. This thermal

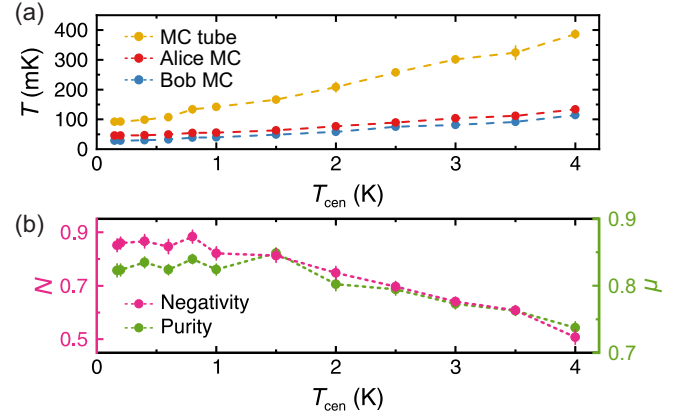


FIG. 3. Entanglement distribution through the 4 K thermal channel. (a) Average temperatures T of various MC sections as a function of the cryolink center temperature T_{cen} . (b) Negativity N and purity μ of the TMS states as a function of T_{cen} . Error bars denote the standard error of the experimental data and are smaller than the symbol size when not shown.

coupling eventually limits the teleportation fidelities at high channel temperatures. More details about the heating procedure and calibration are available in Supplemental Material [36].

Figure 3(b) shows the measured negativity and purity values of the TMS states distributed between Alice and Bob at various T_{cen} . We see that as T_{cen} rises from 0.17 to 4 K, N decreases from 0.851 ± 0.024 to 0.508 ± 0.027 and μ decreases from 0.823 ± 0.010 to 0.737 ± 0.009 . This decrease in entanglement can be attributed to the additional thermal noise. Importantly, N remains above zero, demonstrating that quantum entanglement survives even when passing through a hot quantum link.

Next, we perform microwave quantum teleportation over the described thermal channel. Figure 4(a) shows the teleported coherent state fidelities F for $n_{\text{in}} = 1.3$ as a function of T_{cen} . We observe that the teleported state fidelities stay above the no-cloning limit $F > F_{\text{nc}}$ up to $T_{\text{cen}} \sim 2$ K and then decrease to $F = 59.9 \pm 2.5\%$ at $T_{\text{cen}} = 4$ K. In the whole temperature range, the quantum teleportation fidelities consistently remain above the classical teleportation fidelities, demonstrating an overall quantum advantage of the implemented communication protocol. We fit the collected data using Eq. (1), taking into account the increased Alice MC temperatures and the resulting thermal noise n_{th} . The outcome is shown by solid lines in Fig. 4(a). Observing the reconstructed Wigner functions in Fig. 4(b), we see that when sweeping $T_{\text{cen}} = 0.2$ K to $T_{\text{cen}} = 4$ K, the teleported state variance increases up to 0.412 photons, which implies an estimated 13.6% decrease in F . Within this variance change, the lossy components in the Alice (quantum link) setup contribute 0.38 (0.02) of added noise photons, and hence, a 12.7% (0.8%) decrease in F . Thus, we find that microwave quantum communication over the cryolink is robust against

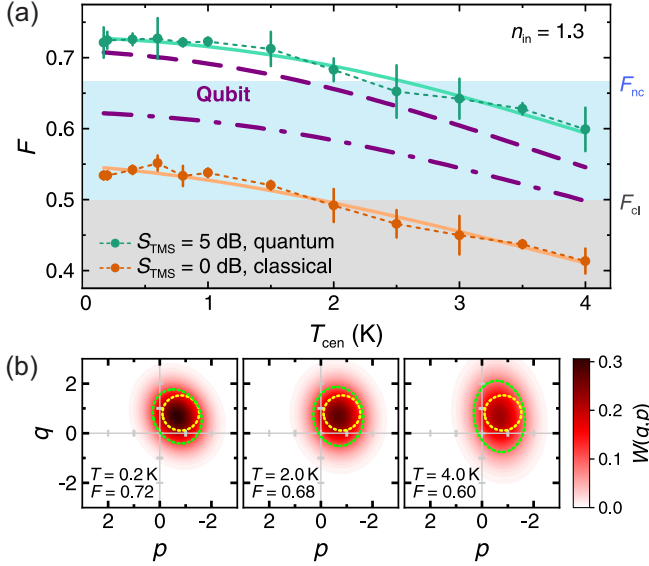


FIG. 4. Quantum teleportation through the 4 K thermal channel. (a) Teleported state fidelities F of quantum and classical teleportation for various T_{cen} . Solid lines represent fits using our theoretical model. Gray- and blue-shaded regions indicate fidelities below the classical F_{cl} and no-cloning F_{nc} thresholds, respectively. Purple dash-dotted and dashed lines represent predicted qubit state teleportation fidelities for $S_{\text{TMS}} = 5$ dB and $S_{\text{TMS}} = 10$ dB, respectively. (b) Wigner functions of exemplary teleported coherent states. Yellow and green dashed lines denote the $1/e$ contours of the input and teleported states, respectively. Error bars denote the standard error of the experimental data and are smaller than the symbol size when not shown.

its center temperature. This observation can be explained by the fluctuation-dissipation theorem [30] and interpreted using the beam splitter model from quantum optics [34]. Here, the thermal noise coupled to a quantum channel is described by its mean photon number, $n_{\text{th}} = \varepsilon n_{\text{env}}$, where ε is the channel losses and n_{env} is the mean noise photon number of the ambient thermal environment. For vanishing losses $\varepsilon \rightarrow 0$, the coupled noise n_{th} is strongly suppressed, despite a hot environment with $n_{\text{env}} \gg 1$. The current limitation of the demonstrated protocol rather stems from the parasitic temperature increase of the Alice MC itself. For better teleportation fidelities at high T_{cen} , one has to improve thermal isolation between the cold nodes (Alice and Bob) and the hot cryolink center by exploiting various cryogenic techniques, such as heat switches [69], on-demand thermal couplers [19], multilayer insulation against black-body radiation, and thermal breaks.

Qubit state teleportation—Finally, we theoretically examine implications of our continuous-variable protocol for a hybrid quantum teleportation of an input qubit state $|\psi\rangle = \cos(\theta/2)|0\rangle + e^{i\varphi} \sin(\theta/2)|1\rangle$. Since the TMS state contains contributions from all photon number states, it is theoretically possible to employ it for teleportation of qubits. We analyze the performance of this hybrid teleportation protocol using fidelity $F(\theta, \kappa, \zeta)$ in terms of the

aforementioned parameters κ and ζ . This analysis is enabled by the Weyl-Wigner transformation, mapping our coherent state teleportation results from the Wigner function formalism to the density matrix formalism, suitable for Fock and qubit states. We follow the formalism provided in Refs. [70,71] to find expressions for the ground state $|0\rangle$ teleportation fidelity,

$$F(0, \kappa, \zeta) = \frac{2}{\zeta + \kappa + 1}, \quad (3)$$

which recovers the scenario of teleporting a coherent state with $\alpha = 0$, and the excited state $|1\rangle$ teleportation fidelity,

$$F(\pi, \kappa, \zeta) = \frac{2\zeta^2 - 2\kappa^2 + 12\kappa - 2}{(\zeta + \kappa + 1)^3}. \quad (4)$$

In order to quantify the hybrid teleportation of an arbitrary pure qubit state, we integrate over θ and φ to find the average qubit state teleportation fidelity

$$\begin{aligned} \bar{F}(\kappa, \zeta) &= \frac{1}{4\pi} \int_0^{2\pi} \int_0^\pi F(\theta, \kappa, \zeta) \sin \theta d\theta d\varphi \\ &= \frac{6\zeta + 4\sqrt{\kappa}}{3(\zeta + \kappa + 1)^2} + \frac{16\kappa}{3(\zeta + \kappa + 1)^3}. \end{aligned} \quad (5)$$

Now, we can use the parameters obtained from fitting the experimental data of coherent state teleportation to predict $\bar{F}(\kappa, \zeta)$ using our setup, as shown by the purple dash-dotted and dashed lines in Fig. 4(a). We estimate the average qubit teleportation fidelities of $\bar{F} = 62.2\%$ for $S_{\text{TMS}} = 5$ dB, and $\bar{F} = 70.7\%$ when $S_{\text{TMS}} = 10$ dB, which are experimentally feasible squeezing levels with our JPAs [31]. While teleportation fidelities can be degraded by residual thermal excitations at the qubit end nodes [12,72], our estimates assume that the photonic temperature at the qubit node coincides with the ambient MC temperature. This can be accomplished by placing large attenuators at the input nodes, which act as heat sinks for back-propagating microwave modes and match the channel temperature to that of these attenuators [18]. Another viable, albeit technically more complex, approach is to utilize on-demand tunable couplers to limit coupling to hot thermal baths [12,19]. Although these fidelities are not yet as high as they have to be for direct applications in distributed quantum computing, they nevertheless represent the potential and universality of hybrid quantum communication protocols that combine continuous-variable and discrete-variable states. More details about our model for the hybrid quantum teleportation and its potential improvements are available in Supplemental Material [36].

Discussion—Our realization of quantum teleportation over a noisy quantum channel demonstrates the potential of microwave communication in practical quantum networks. We successfully teleport microwave states across spatially separated dilution refrigerators, achieving

fidelities of $F > F_{\text{nc}}$ for $n_{\text{in}} \leq 8.3$ in the low temperature regime, $T \lesssim 1$ K. At the same time, in the high temperature regime, teleportation fidelities degrade due to a parasitic coupling to the channel heater but still remain above the classical threshold, $F > F_{\text{cl}}$, even at $T_{\text{cen}} = 4$ K. The capabilities to extend beyond a single dilution refrigerator and operate at high temperatures are crucial for incorporating superconducting circuits into heterogeneous quantum networks [73]. Furthermore, one can enhance the demonstrated experimental techniques by combining the Gaussian entanglement resources with non-Gaussian operations provided by qubits, such as teleporting Fock states [74], entanglement distillation of TMS states [75], or autonomous qubit entanglement [76]. In a more general context, our results demonstrate that thermal equilibrium fluctuations do not necessarily limit the distribution of quantum entanglement through noisy quantum channels, as long as the channel losses are low. It also motivates further investigation of quantum networks in nonequilibrium scenarios related to the question of how quantum states thermalize in distributed quantum systems.

Acknowledgments—We acknowledge support by the German Research Foundation via Germany's Excellence Strategy (No. EXC-2111-390814868), the EU Quantum Flagship project QMiCS (Grant No. 820505), the German Federal Ministry of Education and Research via the project QUARATE (Grant No. 13N15380). This research is part of the Munich Quantum Valley, which is supported by the Bavarian state government with funds from the Hightech Agenda Bayern Plus.

Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

- [1] M. Kjaergaard, M. E. Schwartz, J. Braumüller, P. Krantz, J. I.-J. Wang, S. Gustavsson, and W. D. Oliver, Superconducting qubits: Current state of play, *Annu. Rev. Condens. Matter Phys.* **11**, 369 (2020).
- [2] F. Arute *et al.*, Quantum supremacy using a programmable superconducting processor, *Nature (London)* **574**, 505 (2019).
- [3] D. Gao *et al.*, Establishing a new benchmark in quantum computational advantage with 105-qubit Zuchongzhi 3.0 processor, *Phys. Rev. Lett.* **134**, 090601 (2025).
- [4] Y. Kim, A. Eddins, S. Anand, K. X. Wei, E. van den Berg, S. Rosenblatt, H. Nayfeh, Y. Wu, M. Zaletel, K. Temme, and A. Kandala, Evidence for the utility of quantum computing before fault tolerance, *Nature (London)* **618**, 500 (2023).
- [5] Google Quantum AI and Collaborators, Quantum error correction below the surface code threshold, *Nature (London)* **638**, 920 (2025).

- [6] A. J. Daley, I. Bloch, C. Kokail, S. Flannigan, N. Pearson, M. Troyer, and P. Zoller, Practical quantum advantage in quantum simulation, *Nature (London)* **607**, 667 (2022).
- [7] M. Mohseni *et al.*, How to build a quantum supercomputer: Scaling from hundreds to millions of qubits, *arXiv:2411.10406*.
- [8] T. Brecht, W. Pfaff, C. Wang, Y. Chu, L. Frunzio, M. H. Devoret, and R. J. Schoelkopf, Multilayer microwave integrated quantum circuits for scalable quantum computing, *npj Quantum Inf.* **2**, 16002 (2016).
- [9] M. I. Hollister, R. C. Dhuley, C. James, and G. L. Tatkowski, An update on the Colossus mK platform at Fermilab, *IOP Conf. Ser.: Mater. Sci. Eng.* **1302**, 012030 (2024).
- [10] S. Krinner, S. Storz, P. Kurpiers, P. Magnard, J. Heinsoo, R. Keller, J. Lütolf, C. Eichler, and A. Wallraff, Engineering cryogenic setups for 100-qubit scale superconducting circuit systems, *Eur. Phys. J. Quantum Technol.* **6**, 2 (2019).
- [11] S. Bravyi, O. Dial, J. M. Gambetta, D. Gil, and Z. Nazario, The future of quantum computing with superconducting qubits, *J. Appl. Phys.* **132**, 160902 (2022).
- [12] Z.-L. Xiang, M. Zhang, L. Jiang, and P. Rabl, Intracavity quantum communication via thermal microwave networks, *Phys. Rev. X* **7**, 011035 (2017).
- [13] G. F. Peñas, R. Puebla, T. Ramos, P. Rabl, and J. J. García-Ripoll, Universal deterministic quantum operations in microwave quantum links, *Phys. Rev. Appl.* **17**, 054038 (2022).
- [14] Y. Zhong, H.-S. Chang, A. Bienfait, É. Dumur, M.-H. Chou, C. R. Conner, J. Grebel, R. G. Povey, H. Yan, D. I. Schuster, and A. N. Cleland, Deterministic multi-qubit entanglement in a quantum network, *Nature (London)* **590**, 571 (2021).
- [15] B. Abdo, W. Shanks, O. Jinka, J. R. Rozen, and J. Orcutt, Teleportation and entanglement swapping of continuous quantum variables of microwave radiation, *Phys. Rev. X* **15**, 031075 (2025).
- [16] A. Almanakly, B. Yankelevich, M. Hays, B. Kannan, R. Assouly, A. Greene, M. Gingras, B. M. Niedzielski, H. Stickler, M. E. Schwartz, K. Serniak, J. Í.-j. Wang, T. P. Orlando, S. Gustavsson, J. A. Grover, and W. D. Oliver, Deterministic remote entanglement using a chiral quantum interconnect, *Nat. Phys.* **21**, 825 (2025).
- [17] P. Magnard, S. Storz, P. Kurpiers, J. Schär, F. Marxer, J. Lütolf, T. Walter, J.-C. Besse, M. Gabureac, K. Reuer, A. Akin, B. Royer, A. Blais, and A. Wallraff, Microwave quantum link between superconducting circuits housed in spatially separated cryogenic systems, *Phys. Rev. Lett.* **125**, 260502 (2020).
- [18] W. K. Yam, M. Renger, S. Gandorfer, F. Fesquet, M. Handschuh, K. E. Honasoge, F. Kronowetter, Y. Nojiri, M. Partanen, M. Pfeiffer, H. van der Vliet, A. J. Matthews, J. Govenius, R. N. Jabbaraghi, M. Prunnila, A. Marx, F. Deppe, R. Gross, and K. G. Fedorov, Cryogenic microwave link for quantum local area networks, *npj Quantum Inf.* **11**, 87 (2025).
- [19] J. Qiu, Z. Zhang, Z. Wang, L. Zhang, Y. Zhou, X. Sun, J. Zhang, X. Linpeng, S. Liu, J. Niu, Y. Zhong, and D. Yu, A thermal-noise-resilient microwave quantum network traversing 4 K, *arXiv:2503.01133*.
- [20] D.-G. Im, C.-H. Lee, Y. Kim, H. Nha, M. S. Kim, S.-W. Lee, and Y.-H. Kim, Optimal teleportation via noisy quantum

- channels without additional qubit resources, *npj Quantum Inf.* **7**, 86 (2021).
- [21] B. C. Coutinho, W. J. Munro, K. Nemoto, and Y. Omar, Robustness of noisy quantum networks, *Commun. Phys.* **5**, 105 (2022).
- [22] F. Grasselli, G. Murta, J. de Jong, F. Hahn, D. Bruß, H. Kampermann, and A. Pappa, Secure anonymous conferencing in quantum networks, *PRX Quantum* **3**, 040306 (2022).
- [23] N. H. Nickerson, J. F. Fitzsimons, and S. C. Benjamin, Freely scalable quantum technologies using cells of 5-to-50 qubits with very lossy and noisy photonic links, *Phys. Rev. X* **4**, 041041 (2014).
- [24] A. Beckert, M. Grimm, N. Wili, R. Tschaggelar, G. Jeschke, G. Matmon, S. Gerber, M. Müller, and G. Aeppli, Emergence of highly coherent two-level systems in a noisy and dense quantum network, *Nat. Phys.* **20**, 472 (2024).
- [25] Y.-C. Wei, P.-J. Stas, A. Suleymanzade, G. Baranes, F. Machado, Y. Q. Huan, C. M. Knaut, S. W. Ding, M. Merz, E. N. Knall, U. Yazlar, M. Sirotnin, I. W. Wang, B. Machielse, S. F. Yelin, J. Borregaard, H. Park, M. Lončar, and M. D. Lukin, Universal distributed blind quantum computing with solid-state qubits, *Science* **388**, 509 (2025).
- [26] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels, *Phys. Rev. Lett.* **70**, 1895 (1993).
- [27] K. G. Fedorov, M. Renger, S. Pogorzalek, R. D. Candia, Q. Chen, Y. Nojiri, K. Inomata, Y. Nakamura, M. Partanen, A. Marx, R. Gross, and F. Deppe, Experimental quantum teleportation of propagating microwaves, *Sci. Adv.* **7**, eabk0891 (2021).
- [28] J. Qiu, Y. Liu, L. Hu, Y. Wu, J. Niu, L. Zhang, W. Huang, Y. Chen, J. Li, S. Liu, Y. Zhong, L. Duan, and D. Yu, Deterministic quantum state and gate teleportation between distant superconducting chips, *Sci. Bull.* **70**, 351 (2025).
- [29] P. Kurpiers, T. Walter, P. Magnard, Y. Salathe, and A. Wallraff, Characterizing the attenuation of coaxial and rectangular microwave-frequency waveguides at cryogenic temperatures, *Eur. Phys. J. Quantum Technol.* **4**, 8 (2017).
- [30] H. B. Callen and T. A. Welton, Irreversibility and generalized noise, *Phys. Rev.* **83**, 34 (1951).
- [31] K. E. Honasoge, M. Handschuh, W. K. Yam, S. Gandorfer, D. Bazulin, N. Bruckmoser, L. Koch, A. Marx, R. Gross, and K. G. Fedorov, Fabrication of low-loss Josephson parametric devices, *Phys. Rev. B* **111**, 214508 (2025).
- [32] L. Zhong, E. P. Menzel, R. D. Candia, P. Eder, M. Ihmig, A. Baust, M. Haeberlein, E. Hoffmann, K. Inomata, T. Yamamoto, Y. Nakamura, E. Solano, F. Deppe, A. Marx, and R. Gross, Squeezing with a flux-driven Josephson parametric amplifier, *New J. Phys.* **15**, 125013 (2013).
- [33] K. G. Fedorov, S. Pogorzalek, U. Las Heras, M. Sanz, P. Yard, P. Eder, M. Fischer, J. Goetz, E. Xie, K. Inomata, Y. Nakamura, R. Di Candia, E. Solano, A. Marx, F. Deppe, and R. Gross, Finite-time quantum entanglement in propagating squeezed microwaves, *Sci. Rep.* **8**, 6416 (2018).
- [34] C. Weedbrook, S. Pirandola, R. García-Patrón, N. J. Cerf, T. C. Ralph, J. H. Shapiro, and S. Lloyd, Gaussian quantum information, *Rev. Mod. Phys.* **84**, 621 (2012).
- [35] S. Gandorfer, M. Renger, W. K. Yam, F. Fesquet, A. Marx, R. Gross, and K. G. Fedorov, Two-dimensional Planck spectroscopy for microwave photon calibration, *Phys. Rev. Appl.* **23**, 024064 (2025).
- [36] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/n8j9-63mz> for details about (i) devices and experimental implementation and (ii) the model for quantum teleportation of coherent and qubit states, which includes Refs. [37–49].
- [37] M. Marianoni, E. P. Menzel, F. Deppe, M. A. Araque Caballero, A. Baust, T. Niemczyk, E. Hoffmann, E. Solano, A. Marx, and R. Gross, Planck spectroscopy and quantum noise of microwave beam splitters, *Phys. Rev. Lett.* **105**, 133601 (2010).
- [38] T. Yamamoto, K. Inomata, M. Watanabe, K. Matsuba, T. Miyazaki, W. D. Oliver, Y. Nakamura, and J. S. Tsai, Flux-driven Josephson parametric amplifier, *Appl. Phys. Lett.* **93**, 042510 (2008).
- [39] A. Marx, J. Hoess, and K. Uhlig, Dry dilution refrigerator for experiments on quantum effects in the microwave regime, *arXiv:1412.3619*.
- [40] E. P. Menzel, R. Di Candia, F. Deppe, P. Eder, L. Zhong, M. Ihmig, M. Haeberlein, A. Baust, E. Hoffmann, D. Ballester, K. Inomata, T. Yamamoto, Y. Nakamura, E. Solano, A. Marx, and R. Gross, Path entanglement of continuous-variable quantum microwaves, *Phys. Rev. Lett.* **109**, 250502 (2012).
- [41] R. Di Candia, K. G. Fedorov, L. Zhong, S. Felicetti, E. P. Menzel, M. Sanz, F. Deppe, A. Marx, R. Gross, and E. Solano, Quantum teleportation of propagating quantum microwaves, *Eur. Phys. J. Quantum Technol.* **2**, 25 (2015).
- [42] H. Scutaru, Fidelity for displaced squeezed thermal states and the oscillator semigroup, *J. Phys. A* **31**, 3659 (1998).
- [43] V. V. Schmidt, P. Müller, and A. V. Ustinov, Microscopic theory of superconductivity, in *The Physics of Superconductors* (Springer, Berlin, Heidelberg, 1997), pp. 139–166.
- [44] M. Pfeiffer, Superconducting cables for quantum microwave communication, Bachelor's thesis, Technical University of Munich, 2020.
- [45] R. Kubo, Statistical-mechanical theory of irreversible processes. I. General theory and simple applications to magnetic and conduction problems, *J. Phys. Soc. Jpn.* **12**, 570 (1957).
- [46] J. P. Turneaure and I. Weissman, Microwave surface resistance of superconducting niobium, *J. Appl. Phys.* **39**, 4417 (1968).
- [47] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Theory of superconductivity, *Phys. Rev.* **108**, 1175 (1957).
- [48] W. K. Yam, M. Renger, S. Gandorfer, R. Gross, and K. G. Fedorov, Practical quantum teleportation with finite-energy codebooks, *arXiv:2512.23388*.
- [49] S. H. Lie and H. Jeong, Limitations of teleporting a qubit via a two-mode squeezed state, *Photonics Res.* **7**, A7 (2019).
- [50] J.-G. Ren *et al.*, Ground-to-satellite quantum teleportation, *Nature (London)* **549**, 70 (2017).
- [51] L. Steffen, Y. Salathe, M. Oppliger, P. Kurpiers, M. Baur, C. Lang, C. Eichler, G. Puebla-Hellmann, A. Fedorov, and A. Wallraff, Deterministic quantum teleportation with feed-forward in a solid state system, *Nature (London)* **500**, 319 (2013).
- [52] K. S. Chou, J. Z. Blumoff, C. S. Wang, P. C. Reinhold, C. J. Axline, Y. Y. Gao, L. Frunzio, M. H. Devoret, L. Jiang, and

- R. J. Schoelkopf, Deterministic teleportation of a quantum gate between two logical qubits, *Nature (London)* **561**, 368 (2018).
- [53] T. Yamashima, T. Kashiwazaki, T. Suzuki, R. Nehra, T. Nakamura, A. Inoue, T. Umeki, K. Takase, W. Asavanant, M. Endo, and A. Furusawa, All-optical measurement-device-free feedforward enabling ultra-fast quantum information processing, *Opt. Express* **33**, 5769 (2025).
- [54] F. Kronowetter, F. Fesquet, M. Renger, K. Honasoge, Y. Nojiri, K. Inomata, Y. Nakamura, A. Marx, R. Gross, and K. G. Fedorov, Quantum microwave parametric interferometer, *Phys. Rev. Appl.* **20**, 024049 (2023).
- [55] M. Renger, S. Pogorzalek, Q. Chen, Y. Nojiri, K. Inomata, Y. Nakamura, M. Partanen, A. Marx, R. Gross, F. Deppe, and K. G. Fedorov, Beyond the standard quantum limit for parametric amplification of broadband signals, *npj Quantum Inf.* **7**, 160 (2021).
- [56] K. G. Fedorov, L. Zhong, S. Pogorzalek, P. Eder, M. Fischer, J. Goetz, E. Xie, F. Wulschner, K. Inomata, T. Yamamoto, Y. Nakamura, R. Di Candia, U. Las Heras, M. Sanz, E. Solano, E. P. Menzel, F. Deppe, A. Marx, and R. Gross, Displacement of propagating squeezed microwave states, *Phys. Rev. Lett.* **117**, 020502 (2016).
- [57] A. Peres, Separability criterion for density matrices, *Phys. Rev. Lett.* **77**, 1413 (1996).
- [58] G. Adesso and F. Illuminati, Gaussian measures of entanglement versus negativities: Ordering of two-mode Gaussian states, *Phys. Rev. A* **72**, 032334 (2005).
- [59] S. Boutin, D. M. Toyli, A. V. Venkatramani, A. W. Eddins, I. Siddiqi, and A. Blais, Effect of higher-order nonlinearities on amplification and squeezing in Josephson parametric amplifiers, *Phys. Rev. Appl.* **8**, 054030 (2017).
- [60] S. L. Braunstein and P. van Loock, Quantum information with continuous variables, *Rev. Mod. Phys.* **77**, 513 (2005).
- [61] C. H. Bennett, D. P. DiVincenzo, J. A. Smolin, and W. K. Wootters, Mixed-state entanglement and quantum error correction, *Phys. Rev. A* **54**, 3824 (1996).
- [62] S. L. Braunstein, C. A. Fuchs, H. J. Kimble, and P. van Loock, Quantum versus classical domains for teleportation with continuous variables, *Phys. Rev. A* **64**, 022321 (2001).
- [63] F. Grosshans and P. Grangier, Quantum cloning and teleportation criteria for continuous quantum variables, *Phys. Rev. A* **64**, 010301(R) (2001).
- [64] L. Gyongyosi, S. Imre, and H. V. Nguyen, A survey on quantum channel capacities, *IEEE Commun. Surv. Tutor.* **20**, 1149 (2018).
- [65] A. S. Holevo, Bounds for the quantity of information transmitted by a quantum communication channel, *Probl. Inf. Transm.* **9**, 177 (1973).
- [66] A. S. Holevo, One-mode quantum Gaussian channels: Structure and quantum capacity, *Probl. Inf. Transm.* **43**, 1 (2007).
- [67] B. Kannan, A. Almanakly, Y. Sung, A. Di Paolo, D. A. Rower, J. Braumüller, A. Melville, B. M. Niedzielski, A. Karamlou, K. Serniak, A. Vepsäläinen, M. E. Schwartz, J. L. Yoder, R. Winik, J. I.-J. Wang, T. P. Orlando, S. Gustavsson, J. A. Grover, and W. D. Oliver, On-demand directional microwave photon emission using waveguide quantum electrodynamics, *Nat. Phys.* **19**, 394 (2023).
- [68] R. Navarathna, D. T. Le, A. R. Hamann, H. D. Nguyen, T. M. Stace, and A. Fedorov, Passive superconducting circulator on a chip, *Phys. Rev. Lett.* **130**, 037001 (2023).
- [69] Q.-S. Shu, J. Demko, and J. Fesmire, Cryogenic heat switches for thermal management, in *Cryogenic Heat Management* (CRC Press, Boca Raton, 2022), pp. 243–272.
- [70] S. Takeda, T. Mizuta, M. Fuwa, H. Yonezawa, P. van Loock, and A. Furusawa, Gain tuning for continuous-variable quantum teleportation of discretevariable states, *Phys. Rev. A* **88**, 042327 (2013).
- [71] M. Renger, Inter-lab quantum microwave teleportation, Ph.D. thesis, Technical University of Munich, 2023.
- [72] B. Vermersch, P.-O. Guimond, H. Pichler, and P. Zoller, Quantum state transfer via noisy photonic and phononic waveguides, *Phys. Rev. Lett.* **118**, 133601 (2017).
- [73] A. A. Clerk, K. W. Lehnert, P. Bertet, J. R. Petta, and Y. Nakamura, Hybrid quantum systems with circuit quantum electrodynamics, *Nat. Phys.* **16**, 257 (2020).
- [74] S. Takeda, T. Mizuta, M. Fuwa, P. van Loock, and A. Furusawa, Deterministic quantum teleportation of photonic quantum bits by a hybrid technique, *Nature (London)* **500**, 315 (2013).
- [75] Y. Kurochkin, A. S. Prasad, and A. I. Lvovsky, Distillation of the two-mode squeezed state, *Phys. Rev. Lett.* **112**, 070402 (2014).
- [76] J. Agustí, X. H. H. Zhang, Y. Minoguchi, and P. Rabl, Autonomous distribution of programmable multiqubit entanglement in a dual-rail quantum network, *Phys. Rev. Lett.* **131**, 250801 (2023).