

High-fidelity quantum state transfer in multimode resonators via tunable pulses

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(Received 26 March 2026; accepted 22 July 2026; published 17 September 2026)

Quantum state transfer between distant nodes is essential for distributed quantum information processing. Existing protocols are typically optimized for specific coupling regimes, such as adiabatic dark-state transfer in the single-mode limit and pitch-and-catch schemes in the multimode regime, leaving the crossover between them without a simple and unified control strategy. Here, we identify a minimal two-parameter control framework that enables high-fidelity quantum state transfer across this single-mode-to-multimode crossover in a multimode quantum channel. Using a pulse-shaped pitch-and-catch protocol controlled only by the pulse ramp rate and the emission-absorption delay, we achieve transfer fidelities exceeding 99.9%, extending pitch-and-catch protocols toward the single-mode limit without requiring dark-state protection or complex pulse design. We further demonstrate robustness against dissipation, disorder, detuning, and imperfect initialization under experimentally realistic conditions. These results provide a simple and broadly applicable framework for state transfer in multimode quantum channels, with relevance to circuit-QED and hybrid quantum-acoustic systems.

DOI: [10.1103/brt1-c8yd](https://doi.org/10.1103/brt1-c8yd)

I. INTRODUCTION

Practical quantum computing at scale will likely require millions of qubits distributed across many interconnected modules [1,2]. While current superconducting quantum processors integrate only hundreds of qubits on a single chip [3,4], modular architectures address this scalability challenge by coherently interconnecting smaller processing units using quantum state transfer (QST) and remote entanglement generation [5–12]. These capabilities are central to scalable superconducting quantum processors and the emerging quantum internet [13,14]. However, achieving robust, high-fidelity QST over centimeter- to meter-scale distances remains challenging due to dissipation, decoherence, non-Markovian channel dynamics, and the absence of control protocols that operate reliably across different coupling regimes [15,16].

A representative superconducting circuit-QED architecture is shown schematically in Fig. 1(a): Two qubits are coupled to a common resonator that serves as a quantum communication channel. The channel supports a set of discrete standing-wave modes separated by the free spectral range ν_{fsr} , and each qubit couples dynamically to these modes via a tunable coupler [17,18]. Depending on the ratio between the qubit-channel coupling strength g and ν_{fsr} , qualitatively different state-transfer mechanisms emerge.

In the single-mode strong-coupling (SMSC) limit, $\nu_{\text{fsr}} \gg g \gg$ dissipation, only a single resonant mode participates in the dynamics. In this regime, QST can be implemented using adiabatic dark-state protocols analogous to stimulated Raman adiabatic passage (STIRAP) [19,20]. The Hamiltonian supports a dark eigenstate with negligible channel population, allowing coherent transfer of the state via adiabatic variation of the relative qubit-mode coupling strengths [Fig. 1(b)].

When the coupling strength becomes comparable to the free spectral range ($g \sim \nu_{\text{fsr}}$), the qubits hybridize simultaneously with many resonator modes. This multimode strong-coupling (MMSC) regime can be realized using long coplanar resonators in circuit QED [21,22] or by exploiting the slow group velocity of acoustic waves in hybrid quantum-acoustic systems [23–25]. In this regime, state transfer is no longer well described by adiabatic eigenstate following but instead relies on the controlled emission and reabsorption of itinerant wave packets formed from coherent superpositions of multiple standing-wave modes. Time-symmetric emission and capture of shaped wave packets—often termed pitch and catch—enable high-fidelity state transfer [26–31].

While the SMSC and MMSC limits are individually well understood, control in the intermediate crossover regime remains challenging. In this regime, dark eigenstates underlying adiabatic protocols are degraded by strong multimode hybridization, whereas wave-packet-based approaches suffer from dispersion and uncontrolled non-Markovian memory effects [16,32]. Previous work extended dark-state protocols to multimode systems [20,32,33] and developed non-Markovian frameworks that bridge adiabatic and wave-packet regimes [16]. However, these approaches typically require engineered eigenstate protection, auxiliary driving, or complex pulse design, increasing calibration complexity and making the transfer mechanism less transparent. As a result, a minimal and experimentally accessible protocol that operates

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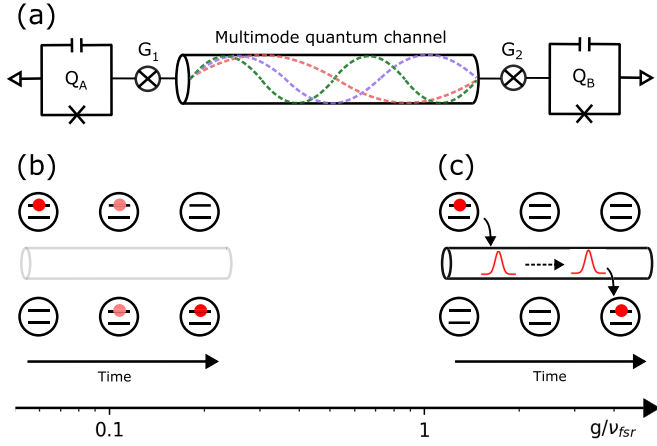


FIG. 1. State-transfer schematics. (a) Two qubits (labeled Q_A and Q_B) are coupled to a common multimode resonator acting as a quantum channel. Remote state transfer is implemented by dynamically tuning the qubit-channel coupling via tunable couplers (labeled G_1 and G_2). (b) In the single-mode limit, the system supports a dark eigenstate with negligible population in the resonator. A STIRAP-like adiabatic sequence transfers the state from Q_A to Q_B while avoiding excitation of the channel. (c) In the multimode limit, the dark-state condition breaks down. State transfer is achieved using the pitch-and-catch protocol: Q_A emits a shaped photon or phonon wave packet into the multimode resonator (pitch), and Q_B time reverses the process to reabsorb it (catch).

efficiently across the multimode-to-single-mode crossover remains lacking.

In this work, we numerically study a pulse-shaped pitch-and-catch protocol that enables high-fidelity quantum state transfer in the crossover between the single-mode and multimode coupling regimes using two control parameters: the pulse ramp rate and the emission-absorption delay. By optimizing these parameters, we achieve transfer fidelities exceeding 99.9%, continuously extending pitch-and-catch protocols from the multimode regime toward the single-mode limit. Importantly, these two parameters admit direct physical interpretations: The ramp rate controls the degree of adiabaticity, while the delay captures the propagation time of the itinerant wave packet. We further show that it remains robust under experimentally relevant conditions, including dissipation, disorder, detuning, imperfect initial states, and residual thermal excitations in the channel.

Rather than introducing additional control Hamiltonians or complex pulse engineering, our approach provides a simple control framework for designing state-transfer protocols in multimode channels. Because all relevant timescales scale naturally with the free spectral range ν_{fsr} , the results presented here offer a broadly applicable prescription for state transfer, with particular relevance to circuit-QED and hybrid quantum-acoustic architectures.

II. MODEL

The system consists of two qubits (Q_A and Q_B) coupled to a multimode quantum channel via tunable couplers (G_1 and G_2), as illustrated in Fig. 1(a). The couplers allow

time-dependent control of the interaction strengths $g_A(t)$ and $g_B(t)$. The quantum channel supports discrete standing-wave modes with frequencies ω_k separated by the free spectral range ν_{fsr} .

In the interaction picture and under the rotating-wave approximation (RWA), the effective Hamiltonian is [16]

$$H_I(t) = g_A(t) \hat{\sigma}_A^\dagger \sum_k \hat{c}_k e^{-i\Delta_k^A t} + g_B(t) \hat{\sigma}_B^\dagger \sum_k (-1)^k \hat{c}_k e^{-i\Delta_k^B t} + \text{H.c.} \quad (1)$$

Here, $\hat{\sigma}_A$ and $\hat{\sigma}_B$ denote the lowering operators of Q_A and Q_B , respectively, and $\hat{c}_k$ annihilates a photon (or phonon) in the k th mode of the channel. The phase factor $(-1)^k$ accounts for the qubits' approximate half-wavelength separation: Adjacent standing-wave modes have alternating field parity, causing opposite coupling signs [16,20]. The detunings are defined as $\Delta_k^A = \omega_k - \omega_A$ and $\Delta_k^B = \omega_k - \omega_B$. The RWA is valid when the coupling strengths $g_{A,B}$ and detunings are small compared to the qubit and mode frequencies, i.e., $\omega_{A,B}, \omega_k \gg g_{A,B}, |\Delta_k^{A,B}|$.

Before addressing state transfer between two qubits, we first examine the dynamics when only Q_A is coupled to the multimode channel ($g_B = 0$). We take Q_A to be resonant with the central channel mode and include 51 resonator modes symmetrically around this frequency. This finite-mode truncation balances numerical efficiency and accuracy: The resulting bandwidth ($\sim 25\nu_{\text{fsr}}$ on either side) greatly exceeds the largest coupling strength considered, ensuring that the emitted excitation remains spectrally confined and that edge-mode populations remain negligible throughout the dynamics [25,34]. The system is initialized with a single excitation in Q_A .

In the absence of pulse shaping, i.e., for constant coupling g , the resulting dynamics are determined by the competition between the coupling strength g and the free spectral range ν_{fsr} . In the single-mode limit, the excitation exchanges coherently between the qubit and a single cavity mode, giving rise to simple Rabi oscillations with period $1/2g$. In the multimode limit, the excitation spreads into several modes and returns to the qubit as pulsed revivals at time intervals $t \sim 1/\nu_{\text{fsr}}$ [35–37]. The ratio g/ν_{fsr} therefore controls the crossover between localized Rabi exchange and itinerant wave-packet dynamics. An example in the crossover regime ($2g = \nu_{\text{fsr}}$) is shown in Fig. 2(a), where the qubit population displays incomplete revivals with gradually decreasing amplitude. The corresponding frequency-resolved mode population in Fig. 2(b) reveals the origin of this behavior: The emitted wave packet spreads over several resonator modes while the accumulated modal phases are not efficiently reversed during reabsorption. As a result, each emission-capture cycle produces a more dispersive wave packet that is only partially reabsorbed by the qubit, leading to progressively weaker revivals.

Having established the characteristic dynamics under constant coupling, we then apply a pulse-shaped extension of the pitch-and-catch protocol to recover the qubit population. Specifically, we employ a hyperbolic-secant pulse with three

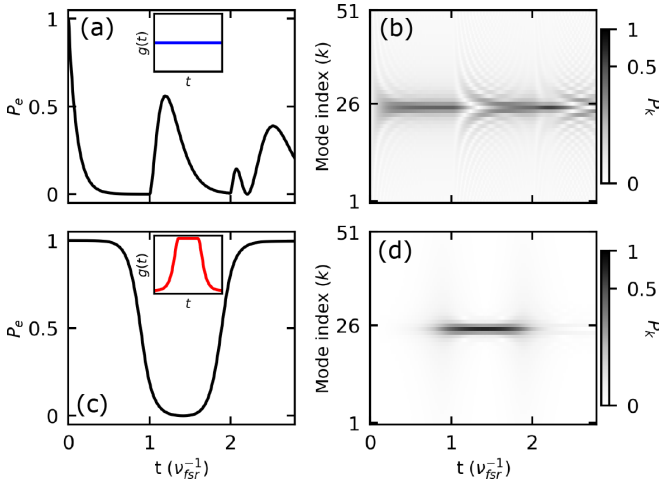


FIG. 2. Pulse shaping suppresses multimode dispersion and enables high capture efficiency. We consider an intermediate coupling ratio ($g/v_{\text{fsr}} = 0.5$) and examine single-qubit round-trip dynamics by setting $g_B = 0$, so that only Q_A interacts with the multimode channel. The top (bottom) panels show constant coupling (hyperbolic-secant-shaped pulses), including qubit population and mode-resolved dynamics. (a) With constant coupling, the excitation emitted by Q_A is only weakly reabsorbed, resulting in incomplete and progressively weaker revivals over successive round trips. (b) The corresponding modal population shows strong multimode dispersion and clear asymmetry between emission and capture, leading to wave-packet dispersion and poor reabsorption. (c) With shaped coupling $g_A(t)$, Q_A fully reabsorbs the returning wave packet, yielding near-unit return probability. (d) The shaped pulse suppresses multimode dispersion and enforces time-reversal symmetry between emission and capture, enabling complete reabsorption of the wave packet.

segments,

$$g(t) = \begin{cases} g_0 \operatorname{sech}[\kappa(t - \tau)], & 0 < t < \tau, \\ g_0, & \tau \leq t < \tau + \tau_d, \\ g_0 \operatorname{sech}[\kappa(t - (\tau + \tau_d))], & \tau + \tau_d \leq t < 2\tau + \tau_d, \end{cases} \quad (2)$$

where $\tau = 6/\kappa$ defines the ramp duration, κ is the ramp rate, and τ_d is the interpulse delay, i.e., the holding time at maximum coupling g_0 .

We emphasize that the specific choice of the hyperbolic-secant pulse is not essential to the protocol. Rather, its use is motivated by two generic features: (1) The smooth turn-on and turn-off suppress nonadiabatic spectral leakage during emission, and (2) the approximate time-reversal symmetry of the pulse facilitates efficient reabsorption of the returning wave packet [29,30]. Similar performance can be achieved with other smooth, band-limited pulse shapes, such as Gaussian and raised-cosine ramps. The present choice therefore serves as a concrete and experimentally realistic pulse family that allows the protocol to be characterized using only two control parameters.

When κ and τ_d are chosen appropriately, Figs. 2(c) and 2(d) show that the qubit excitation is fully recovered after one round trip. The frequency-resolved mode dynamics yield two observations. First, the shaped pulse significantly

suppresses spectral broadening during emission, in contrast to the constant-coupling case shown in Fig. 2(b). Second, the symmetric pulse enforces a reversed spectral evolution during capture, effectively unwinding the modal phases acquired during emission and restoring the wave packet to the qubit without distortion.

Having characterized the single-qubit dynamics, we now activate the second coupling $g_B(t)$ to perform quantum state transfer from Q_A to Q_B . Both qubits are tuned into mutual resonance and are resonant with the central resonator mode. The system is initialized with a single excitation in Q_A , and the objective is to transfer this excitation to Q_B by extending the pitch-and-catch protocol from the multimode limit into the crossover toward the single-mode limit.

For numerical simplicity, we assume equal maximum coupling strengths ($g_A^{\text{max}} = g_B^{\text{max}} = g$) and employ identical hyperbolic-secant ramps for $g_A(t)$ and $g_B(t)$ [38]. The protocol is therefore governed by only two independent control parameters: (1) the normalized ramp rate κ/v_{fsr} and (2) the normalized delay $\tau_d v_{\text{fsr}}$ between the emission and absorption ramps.

For each coupling ratio g/v_{fsr} , we sweep the two-dimensional parameter space (κ, τ_d) to maximize the transfer fidelity F , defined as the final population of qubit B, $P_B(t_{\text{cycle}})$. For clarity, we plot the infidelity $1 - F$ throughout. Representative color maps for $g/v_{\text{fsr}} = 0.2$ and 0.8 are shown in Figs. 3(a) and 3(b), where red markers indicate the optimal parameters. We note that Fig. 3(b) also shows a high-fidelity region at small κ . This branch corresponds to a longer protocol involving additional exchange and rephasing dynamics before final capture, rather than a single emission-absorption event (see Fig. 6 in Appendix A). Here, we focus on the fastest high-fidelity transfer process. The extracted optimal values are summarized in Figs. 3(c) and 3(d), together with empirical fits, revealing an approximately exponential dependence of the optimal ramp rate κ (and the total cycle time τ_{cycle}) and a logarithmic dependence of the optimal delay τ_d on g/v_{fsr} . Figure 3(e) shows the corresponding time-domain dynamics under optimal conditions for representative coupling ratios. The solid curves denote the transfer infidelity $1 - P_B(t)$, while the dashed curves show the depletion of qubit A $1 - P_A(t)$, both evaluated using the optimal parameters extracted from Figs. 3(c) and 3(d).

Remarkably, the pulse-shaped pitch-and-catch protocol achieves near-unity transfer fidelity ($F > 99.9\%$) across the crossover regime using a single pulse family with only two tunable parameters. The optimal parameter trends reveal two distinct limiting behaviors. In the vicinity of the single-mode limit [Fig. 3(a)], the transfer is primarily sensitive to the ramp rate κ and only weakly dependent on the delay τ_d . Optimal performance requires slow ramps (small κ), such that the system evolves quasiadiabatically, while τ_d becomes short or negligible. In this regime, the dynamics deviate from the conventional pitch-and-catch picture and instead resemble a STIRAP-like adiabatic process. In contrast, close to the multimode limit [Fig. 3(b)], the dynamics are dominated by itinerant wave-packet transport. Here, the transfer becomes more sensitive to the delay τ_d , which sets the propagation time of the wave packet, while the dependence on the ramp rate κ is comparatively weaker. Optimal performance is obtained

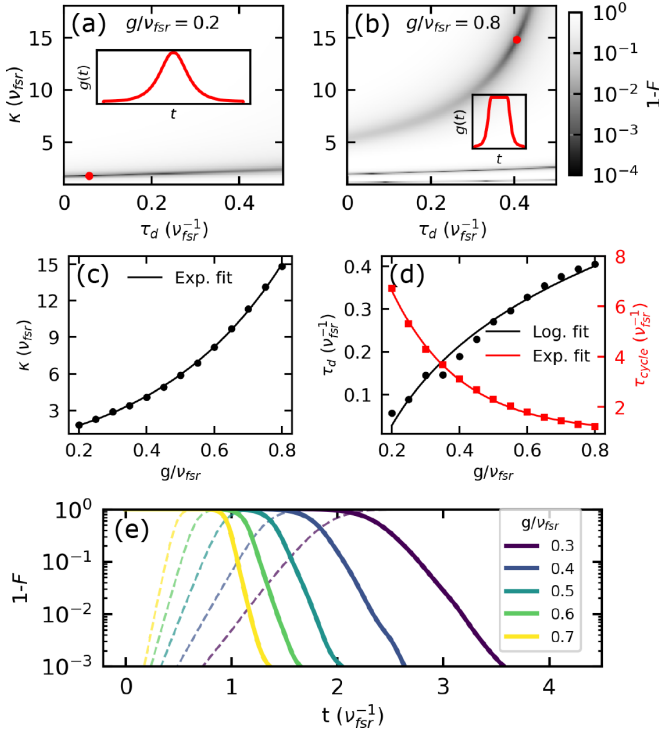


FIG. 3. State transfer at arbitrary interaction strength. We optimize the pitch-and-catch protocol to transfer a single excitation from Q_A to Q_B in the crossover regime ($g/v_{\text{fsr}} \in [0.2, 0.8]$) by tuning two control parameters: the ramp speed κ and the delay τ_d between the emission and absorption ramps. (a) and (b) Infidelity $1 - F$ as a function of (κ, τ_d) for $g/v_{\text{fsr}} = 0.2$ and $g/v_{\text{fsr}} = 0.8$, respectively. Red markers indicate the optimal points that maximize the transfer fidelity F , with the insets showing the corresponding ramp functions. (c) and (d) Optimal parameters extracted from two-dimensional scans across multiple coupling ratios. The optimal ramp speed κ , optimal delay τ_d , and total cycle duration τ_{cycle} are plotted as a function of g/v_{fsr} , together with exponential and logarithmic fits (solid lines). (e) Time-domain dynamics under optimal conditions for representative values of g/v_{fsr} . Solid curves show the transfer infidelity $1 - P_b(t)$, while dashed curves show $1 - P_a(t)$, the depletion of qubit A.

with fast ramps (large κ) and longer delays, with the total transfer duration approaching $1/(2v_{\text{fsr}})$. This scaling reflects the wave-packet propagation time: $1/v_{\text{fsr}}$ corresponds to a full round trip in the channel, while the two-qubit transfer protocol requires only a single traversal from one qubit to the other.

Although we do not derive analytical expressions for the optimal ramp rate κ and delay τ_d , their dependence on g/v_{fsr} , as shown in Figs. 3(c) and 3(d), captures the crossover from localized, adiabatic dynamics in the single-mode limit to wave-packet-mediated transport in the multimode limit. The empirical fits further provide a practical guideline for parameter selection: Once they are calibrated at a few representative coupling strengths, optimal values at nearby regimes can be obtained by interpolation, reducing the need for exhaustive parameter scans. However, this interpolation breaks down deep in the single-mode limit, where τ_d cannot be reduced below zero.

Several points regarding the scope of the protocol are worth noting. First, the robustness of the protocol originates from ap-

proximate time-reversal symmetry between the emission and absorption processes. As a result, both amplitude and phase information are preserved during transfer, and the protocol remains effective for arbitrary superpositions within the qubit $\{|g\rangle, |e\rangle\}$ manifold. Unequal maximum coupling strengths or nonidentical pulse shapes partially break this symmetry and generally reduce the transfer fidelity by causing incomplete reabsorption of the emitted wave packet. Second, the present work primarily focuses on the crossover regime between the single-mode and multimode limits. For deeper multimode coupling ($g > v_{\text{fsr}}$), the dynamics become increasingly wave-packet-like, making the pitch-and-catch picture directly applicable. Numerically, however, the stronger multimode hybridization leads to broader spectral participation, requiring a larger number of resonator modes to avoid finite-mode truncation effects. Third, the optimization presented here targets the fundamental $|g\rangle \leftrightarrow |e\rangle$ transition. For multilevel systems such as transmons, state transfer involving higher excited states constitutes a distinct scattering problem due to anharmonicity-induced detunings (e.g., between $|e\rangle \leftrightarrow |f\rangle$ and $|g\rangle \leftrightarrow |e\rangle$ transitions) and different coupling matrix elements and would therefore require reoptimization of the pulse parameters.

Overall, the pulse shaping considered here provides a minimal and experimentally realistic control strategy. While higher fidelities may be achievable using more elaborate pulse shapes or additional control parameters, the simplicity of the present approach—based on a single smooth pulse family and only two tunable parameters—makes it directly applicable to existing circuit-QED and hybrid quantum-acoustic platforms with tunable couplers [17,18] and enables extension of pitch-and-catch protocols beyond the purely multimode regime.

III. ROBUSTNESS UNDER SYSTEM IMPERFECTIONS

Having established the optimal coherent protocol, we now test its tolerance to realistic device imperfections. We assess the transfer fidelity in the presence of qubit relaxation, channel loss, multimode frequency disorder, and qubit-qubit detuning. In all cases, the control pulses are fixed to the optimal ramp parameters extracted in Figs. 3(c) and 3(d).

Dissipation is incorporated through qubit relaxation at rate γ and resonator decay at rate κ_c , using the Lindblad master equation

$$\frac{d\rho}{dt} = -i[H_I(t), \rho] + \gamma \sum_{j \in \{A,B\}} \mathcal{D}[\hat{\sigma}_j] \rho + \kappa_c \sum_k \mathcal{D}[\hat{c}_k] \rho, \quad (3)$$

where $\mathcal{D}[\hat{L}]\rho = \hat{L}\rho\hat{L}^\dagger - \frac{1}{2}\{\hat{L}^\dagger\hat{L}, \rho\}$. Figures 4(a) and 4(b) show the infidelity as a function of γ/v_{fsr} and κ_c/v_{fsr} , respectively. We sweep γ/v_{fsr} from 10^{-5} to 10^{-2} and κ_c/v_{fsr} from 10^{-5} to 10^{-1} , covering the parameter ranges relevant to current superconducting-circuit and quantum-acoustic systems. For example, transmon qubits typically exhibit T_1 times from a few microseconds up to several hundred microseconds, while microwave and phononic resonators can exhibit linewidths ranging from tens of kilohertz to a few megahertz, with v_{fsr} spanning from a few to hundreds of megahertz depending on geometry [24,29,39,40]. Across these realistic ranges the

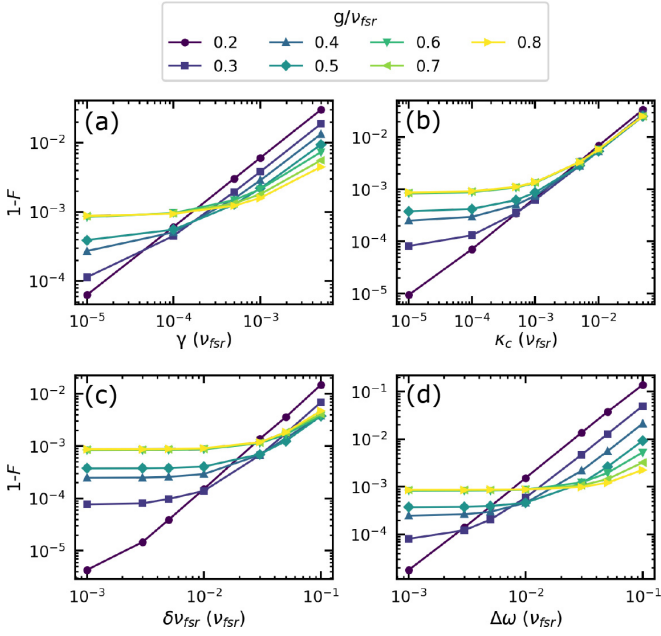


FIG. 4. Robustness of state transfer against dissipation, disorder, and frequency mismatch. Transfer infidelity $1 - F$ for different coupling ratios g/v_{fsr} in the presence of realistic imperfections. (a) Infidelity versus qubit decay rate γ . (b) Infidelity versus resonator decay rate κ_c . (c) Infidelity versus mode-frequency disorder, with Gaussian fluctuations of standard deviation $\sigma = \delta v_{\text{fsr}}/3$ (data averaged over 100 realizations). (d) Infidelity versus qubit frequency mismatch $\Delta\omega$. In the low-loss, low-disorder, and small-detuning limits, the curves saturate at the intrinsic unitary limit obtained from Fig. 3; the corresponding fidelity exceeds 99.9% and is slightly lower in the multimode regime, which may originate from the increased sensitivity of the multimode phase evolution to the restricted pulse family and finite parameter resolution used in the present optimization. Across all imperfections, the protocol remains most robust in the multimode limit due to the shorter transfer time and larger hybridization bandwidth.

protocol maintains high fidelity, with infidelity generally remaining below 10^{-2} . Larger values of g/v_{fsr} are naturally more tolerant due to shorter transfer durations.

We next consider fabrication-induced frequency disorder in the multimode channel, modeled as static Gaussian fluctuations of the resonator mode frequencies with standard deviation $\sigma = \delta v_{\text{fsr}}/3$, such that nearly all modes lie within $\pm \delta v_{\text{fsr}}$. Small deviations from uniform mode spacing can arise from geometric inhomogeneity, coupling-induced boundary conditions, and lithographic disorder and have been observed in multimode spectra of both superconducting and acoustic platforms [21,41]. Figure 4(c) shows the disorder-averaged infidelity (100 realizations) as a function of δ . The transfer fidelity remains high across the experimentally relevant range. The multimode limit is more tolerant of disorder because the transfer involves the collective hybridization of many modes and therefore partially averages over random frequency offsets, whereas in the single-mode limit the dynamics rely on a single resonant mode and are correspondingly more sensitive to frequency perturbations.

Finally, we examine qubit-qubit frequency mismatch by introducing a static detuning $\Delta\omega$ between the two qubits. Small

offsets of the order of 1–5 MHz, typical in tunable transmon devices due to flux noise and calibration drift [39], have a negligible influence on the fidelity, as shown in Fig. 4(d). The protocol remains robust for $|\Delta\omega| \lesssim 10^{-2} v_{\text{fsr}}$, where the infidelity stays below 10^{-3} . Larger detunings eventually degrade the transfer, but the experimentally relevant range lies well within the tolerant regime. As before, the multimode limit accommodates larger detunings due to its broader hybridization bandwidth, while the single-mode limit is more sensitive because it relies on a sharp qubit-mode resonance.

IV. ROBUSTNESS TO IMPERFECT INITIAL STATES

In the previous section we assumed an ideal initial state, where the qubit is perfectly prepared in $|e\rangle$, the channel is in the vacuum state, and the dynamics are restricted to the single-excitation manifold of two-level systems. In practice, however, superconducting artificial atoms are multilevel systems, and state preparation and the channel initialization are subject to finite errors. In this section we examine how such nonideal initial conditions affect the transfer fidelity. The control pulses are kept fixed at the values optimized for the ideal two-level, vacuum-channel case, and only the initial state is varied.

Throughout this analysis we remain within the rotating-wave approximation, so that the total excitation number is conserved. Imperfections are therefore modeled as classical mixtures in the initial density matrix rather than as coherent transitions between excitation manifolds.

To capture leakage to higher levels during state preparation, we model Q_A as a three-level system and initialize the system in the mixed state

$$\rho(0) = [(1 - \epsilon_f)|e\rangle\langle e| + \epsilon_f|f\rangle\langle f|]_A \otimes |g\rangle\langle g|_B \otimes |\text{vac}\rangle\langle \text{vac}|_{\text{ch}}. \quad (4)$$

Such leakage can arise from finite pulse selectivity, residual thermal population, or measurement-based reset errors. In state-of-the-art superconducting platforms, leakage outside the computational subspace is typically at or below the 10^{-3} level for calibrated single-qubit operations [42,43].

The subsequent evolution is computed using the pulse parameters that maximize the ideal two-level transfer fidelity. Because the dynamics are linear in the density matrix, the final excited-state population of qubit B is given by a weighted sum of contributions from the $|e\rangle$ and $|f\rangle$ manifolds. The resulting infidelity $1 - P_{B,e}$ as a function of the preparation error probability ϵ_f is shown in Fig. 5(a) for $\alpha/v_{\text{fsr}} = 1$ and 10, where α is the qubit anharmonicity spanning experimentally relevant regimes. For small ϵ_f the curves are dominated by the intrinsic two-level infidelity, while for larger ϵ_f the infidelity increases approximately linearly, reflecting the first-order sensitivity to population outside the computational subspace. For experimentally realistic leakage levels $\epsilon_f \lesssim 10^{-3}$, the transfer fidelity remains essentially unchanged.

We next consider the effect of a stray thermal or spurious photon in the multimode channel. For a thermal occupation $n_{\text{th}} \ll 1$, the probability of having more than one photon is $O(n_{\text{th}}^2)$, so the dominant correction comes from single-photon contamination [44]. We therefore initialize the system in the

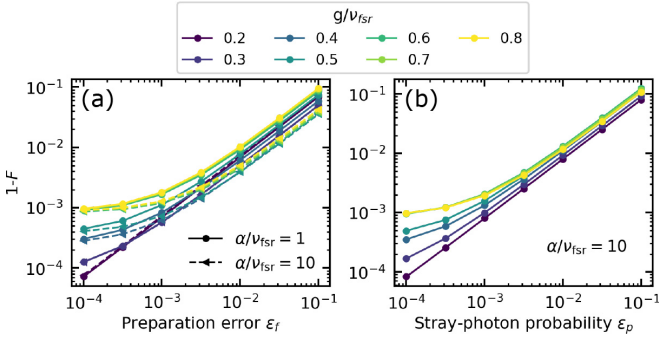


FIG. 5. Robustness to imperfect initial states. (a) Transfer infidelity as a function of the preparation error probability ϵ_f , where qubit A is initialized in the mixed state $(1 - \epsilon_f)|e\rangle\langle e| + \epsilon_f|f\rangle\langle f|$. Solid and dashed lines correspond to $\alpha/\nu_{\text{fsr}} = 1$ and 10, respectively. (b) Transfer infidelity in the presence of a residual single photon in the channel with probability ϵ_p , averaged uniformly over all channel modes. In both panels the control pulses are optimized for the ideal two-level, vacuum-channel case. The linear increase at large error probability reflects the first-order sensitivity to nonideal initial conditions, while the saturation at small error probability is set by the intrinsic two-level infidelity.

mixed state

$$\rho(0) = |e\rangle\langle e|_A \otimes |g\rangle\langle g|_B \otimes \rho_{\text{ch}}, \quad (5)$$

with

$$\rho_{\text{ch}} = (1 - \epsilon_p)|\text{vac}\rangle\langle \text{vac}| + \epsilon_p \sum_k w_k |1_k\rangle\langle 1_k|, \quad (6)$$

where $|1_k\rangle$ denotes a single photon in channel mode k , $\sum_k w_k = 1$, and for simplicity we take a uniform distribution $w_k = 1/N$ over the N modes. The final population $P_{B,e}$ is obtained by averaging over all such single-photon configurations.

The resulting infidelity is shown in Fig. 5(b). As in the case of preparation errors, the leading correction scales linearly with the stray-photon probability ϵ_p . For 5–7 GHz resonators at 10–20 mK, the equilibrium thermal occupation is at most 6×10^{-6} , while experimental upper bounds on residual photon occupation as low as $\bar{n} \lesssim 2 \times 10^{-4}$ have been reported [45]. In this regime the transfer fidelity remains limited by the intrinsic two-level performance.

These results show that pulse parameters optimized for the ideal two-level, vacuum-channel model remain effective under realistic state-preparation and thermal conditions and that no additional reoptimization is required for experimentally relevant error levels.

V. CONCLUSION

We numerically demonstrated that a two-parameter pitch-and-catch protocol enables high-fidelity quantum state transfer across the crossover between single-mode and multimode limits in a multimode quantum channel. By optimizing the ramp rate and the emission-absorption delay, the protocol continuously interpolates between STIRAP-like dynamics in the single-mode limit and wave-packet-mediated transfer in the multimode limit, achieving transfer fidelities exceeding 99.9%.

The protocol remains robust against dissipation, disorder, detuning, and imperfect initial states. Its simplicity—requiring no auxiliary driving or complex pulse engineering—makes it well suited for scalable modular quantum architectures based on tunable couplers, including superconducting circuit-QED and hybrid quantum-acoustic platforms.

Looking ahead, several directions remain open. First, further analytical understanding of the single-mode-to-multimode crossover would complement the present numerical study, including analytical estimates for optimal pulse parameters and their scaling for general pulse shapes. Second, our analysis is restricted to the excitation-conserving regime; extending quantum state transfer into the ultrastrong-coupling domain, where the rotating-wave approximation breaks down, remains an open challenge [46,47]. Experimentally, the pulse-shaping protocol presented here is directly accessible with existing hardware, and future work may explore refined pulse families based on optimal control techniques [48,49], data-driven optimization strategies [50–52], and integration into larger-scale modular quantum-network architectures [13,14,53].

ACKNOWLEDGMENTS

We would like to thank Johannes Borregaard and Marius Villiers for insightful discussions and comments on the manuscript. This work was supported by the European Research Council (ERC CoG Q-ECHOS, Grant No. 101001005). It is part of the research program of the Netherlands Organisation for Scientific Research (NWO), supported by the NWO Frontiers of Nanoscience program and the Quantum Limits project (Grant No. SUM MIT.1.016). This research was also supported by the Kavli Foundation.

DATA AVAILABILITY

Source data for the plots are available on Zenodo [54].

APPENDIX A: TIME-DOMAIN DYNAMICS ON THE SMALL- κ BRANCH

Figure 6 shows the time-domain dynamics for a representative point on the small- κ high-fidelity branch in Fig. 3(b) in the main text. Compared with the fastest transfer process discussed in the main text, where the transfer duration approaches $1/(2\nu_{\text{fsr}})$, this branch corresponds to a significantly longer protocol, extending over several $1/\nu_{\text{fsr}}$ timescales. The excitation undergoes an initial partial capture by Q_B before additional exchange and rephasing dynamics lead to the final capture.

APPENDIX B: PERFORMANCE IN THE DEEPER MULTIMODE REGIME

To examine the transfer performance beyond the crossover regime studied in the main text, we extended the optimization to coupling ratios up to $g/\nu_{\text{fsr}} = 1.5$. At each coupling ratio, the pulse parameters were independently optimized using the same pulse family and parameter-grid resolution as in the original analysis.

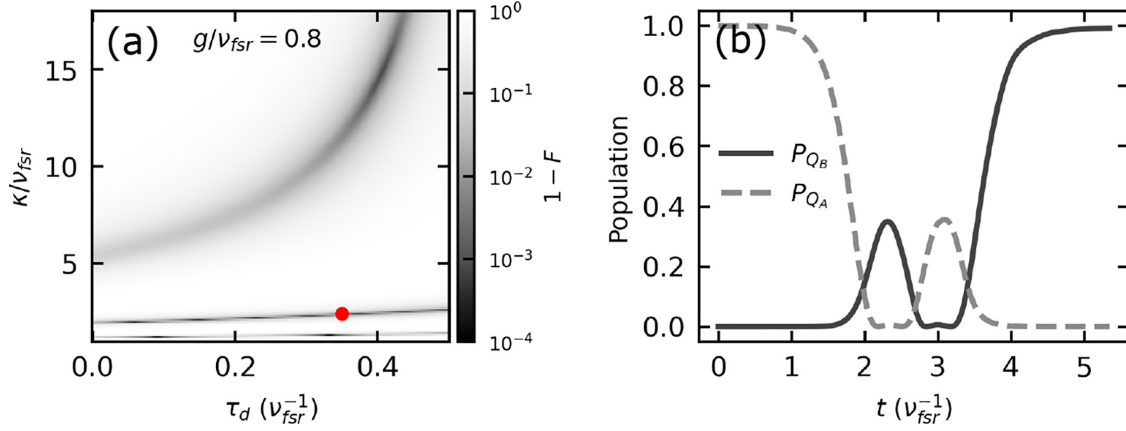


FIG. 6. Time-domain dynamics on the small- κ branch. (a) Representative point on the small- κ high-fidelity branch for $g/v_{\text{fsr}} = 0.8$. (b) Corresponding time-domain populations of Q_A and Q_B . The protocol duration is significantly longer than the fastest transfer process discussed in the main text and involves an intermediate partial capture before the final capture.

Figure 7(a) shows the optimized time-domain dynamics for representative coupling ratios $g/v_{\text{fsr}} = 0.8, 1.0, 1.2$, and 1.5 . High-fidelity transfer is maintained throughout this range, while the transfer duration decreases with increasing coupling strength.

Figure 7(b) shows the optimized final infidelity as a function of g/v_{fsr} in the presence of representative qubit decay, $\gamma/v_{\text{fsr}} = 10^{-3}$, and qubit-frequency mismatch, $\Delta\omega/v_{\text{fsr}} = 5 \times 10^{-2}$. The infidelity decreases with increasing coupling

in both cases. The improved tolerance to qubit decay results primarily from the shorter protocol duration, whereas the improved tolerance to frequency mismatch reflects the broader hybridization bandwidth in the multimode regime.

The present mode window remains numerically converged up to $g/v_{\text{fsr}} = 1.5$. Extending the calculation substantially further would require including additional resonator modes to capture the broader spectral participation and avoid finite-mode truncation effects.

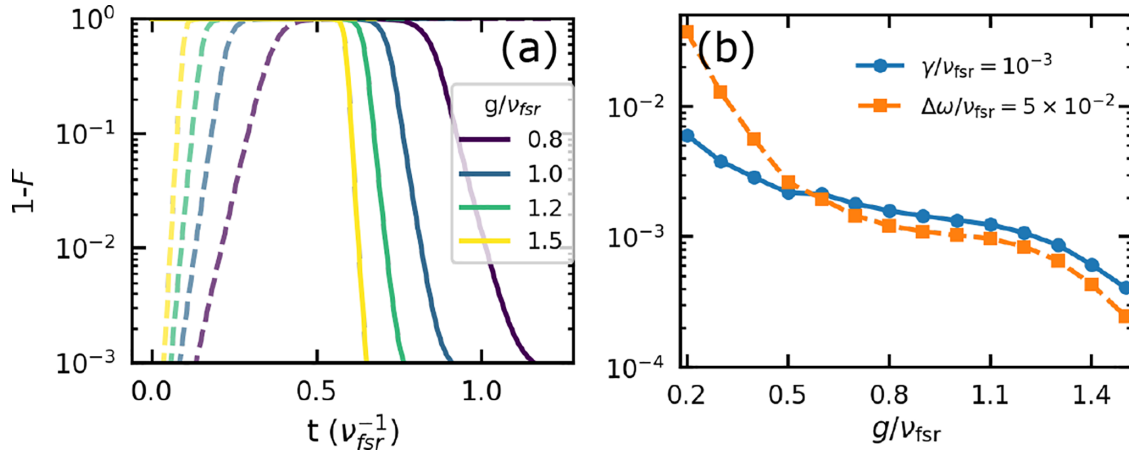


FIG. 7. State-transfer performance in the deeper multimode regime. (a) Optimized time-domain dynamics for $g/v_{\text{fsr}} = 0.8, 1.0, 1.2$, and 1.5 . Solid curves show the transfer infidelity $1 - P_B(t)$, while dashed curves show $1 - P_A(t)$. The protocol duration decreases with increasing coupling while high-fidelity transfer is maintained. (b) Optimized final infidelity as a function of g/v_{fsr} for representative qubit decay $\gamma/v_{\text{fsr}} = 10^{-3}$ and qubit-frequency mismatch $\Delta\omega/v_{\text{fsr}} = 5 \times 10^{-2}$. In both cases, the infidelity decreases with increasing coupling.

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