Universal Fidelity Reduction of Quantum Operations from Weak Dissipation

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Quantum information processing is in real systems often limited by dissipation, stemming from remaining uncontrolled interaction with microscopic degrees of freedom. Given recent experimental progress, we consider weak dissipation, resulting in a small error probability per operation. Here, we find a simple formula for the fidelity reduction of any desired quantum operation, where the ideal evolution is confined to the computational subspace. Interestingly, this reduction is independent of the specific operation; it depends only on the operation time and the dissipation. Using our formula, we investigate the situation where dissipation in different parts of the system has correlations, which is detrimental for the successful application of quantum error correction. Surprisingly, we find that a large class of correlations gives the same fidelity reduction as uncorrelated dissipation of similar strength.

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Introduction.—Numerous architectures are being explored for quantum computers [1], e.g., circuit quantum electrodynamics [2–5], trapped ions [6,7], quantum dots [8], and photonics [9]. The long-term goal is solving useful problems where classical computers fall short [10] and in the nearer term to outperform classical supercomputers for specific computing tasks [11]. However, uncontrolled interactions between the quantum system and its surroundings destroy quantum coherence and thus reduce the fidelity of the quantum operations (gates). How to create high-fidelity quantum gates in the presence of this environmentally induced decoherence is probably the most important problem to solve, both for near-term quantum computation and for the long-term goal of fault-tolerant quantum computing [1,12,13].

With gate fidelities approaching the fault-tolerant threshold, characterizing and reducing the remaining errors becomes increasingly challenging [14,15]. A well-used tool for characterization is Clifford-based randomized benchmarking [16,17], which enables mapping gate errors onto control parameters and feeding this back to optimize the gates. With optimized control, the fidelity is limited by decoherence processes such as energy decay and dephasing. Explicit analytical expressions for this fidelity reduction has been derived for single-qubit Clifford gates [18] as well as certain two-qubit gates [11,19], to first order in the ratio between the gate time τ and the decoherence time $1/\Gamma$. In Ref. [20], a gate-independent formula was derived for the unitarity [21] of a multiqubit system subject to weak relaxation and dephasing acting independently on the individual qubits. The unitarity provides an upper bound for the average gate fidelity.

Here, we derive general analytical results showing how the fidelity of single-, two-, as well as general multiqubit gates is affected by weak decoherence. We consider the standard model for interaction with a Markovian environment, using a Lindblad master equation, and find that to first order in $\Gamma\tau$, the reduction in fidelity is *independent of the specific gate*. This result holds for all single- and multiqubit gates, where the ideal evolution is confined to the computational subspace. It also holds for the case when different qubits see the same environment, i.e., correlated multiqubit noise processes. We discuss in particular the effect of energy relaxation and dephasing, and give explicit formulas for the reduction of the average gate fidelity, which only depends on the number of qubits involved in the gate and the rates of the decoherence processes affecting those qubits. We then explicitly explore the difference between uncorrelated dissipation and two scenarios of fully correlated multiqubit dissipation. Our results provide bounds that allow for robust estimation and optimization of single- as well as multiqubit gate fidelities, and may enable establishing constraints on the power of noisy quantum computers.

Method.—The average gate fidelity $\bar{F}$ of a trace-preserving quantum operation $\mathcal{E}$, acting on an N-qubit system, is defined as [22]

$$\bar{F} \equiv \int d\psi \langle\psi| U_g^\dagger \mathcal{E}(|\psi\rangle\langle\psi|) U_g |\psi\rangle, \tag{1}$$

where the integral is over all pure initial states $|\psi\rangle$ and U_g is the unitary operator corresponding to the ideal gate operation. Note that $\bar{F} = 1$ if and only if $\mathcal{E}$ implements

U_g perfectly, while lower values indicate that $\mathcal{E}$ is a noisy or otherwise imperfect implementation of U_g. The gate operation in Eq. (1) can be generated by a time-dependent Hamiltonian $H(t)$ applied for a time τ, such that $U_g = U(0,\tau)$, where we have introduced the time-evolution operator for the ideal gate operation $U(t_1,t_2) = \mathcal{T}\exp[-(i/\hbar)\int_{t_1}^{t_2} H(t)dt]$ and $\mathcal{T}$ is the time-ordering operator.

We describe the effect of decoherence using the standard Lindblad superoperator

$$\mathcal{D}[\hat{L}]\rho = \hat{L}\rho\hat{L}^\dagger - \frac{1}{2}\{\hat{L}^\dagger\hat{L},\rho\} \tag{2}$$

acting on the system density matrix ρ (others have considered Kraus operators [11,23]). The time evolution of the system with N_L different dissipative processes is then given by the master equation

$$\dot{\rho}(t) = -\frac{i}{\hbar}[\hat{H}(t),\rho(t)] + \sum_{k=1}^{N_L}\Gamma_k\mathcal{D}[\hat{L}_k]\rho(t), \tag{3}$$

where each process has its corresponding rate Γ_k and Lindblad jump operator $\hat{L}_k$. We will later discuss specifically energy relaxation and dephasing acting on individual qubits, but for now the jump operators can be any multi-qubit operator. Note that in contrast to the ideal gate evolution, the jump operators are allowed to take the system out of the computational subspace, and thus include, e.g., heating processes.

Inspired by the current experimental state of the art, where incoherent errors are on the percent level or less [24–33], we now expand the solution to the master equation in the small parameter $\Gamma_k\tau \ll 1$ for a pure initial state $|\psi\rangle$. The unperturbed solution is simply $\rho_\psi^{(0)}(t) = |\psi(t)\rangle\langle\psi(t)|$, where $|\psi(t)\rangle = U(0,t)|\psi\rangle$. The first-order correction due to the kth decoherence process is [34]

$$\rho_{\psi,k}^{(1)}(t) = \Gamma_k\int_0^t dt' U(t',t)[\mathcal{D}[\hat{L}_k]\rho_\psi^{(0)}(t')]U(t',t)^\dagger, \tag{4}$$

which corresponds to applying the dissipator $D[\hat{L}_k]$ to the ideal pure state $|\psi(t')\rangle$ once, at any time $t' < t$. In Ref. [34], the Hamiltonian is assumed to be time-independent, but we show in [35] that their expression can be straightforwardly generalized to time-dependent Hamiltonians, giving Eq. (4).

Main result.—Each dissipative process contributes independently to first order, and with this correction to the ideal density matrix at the end of the gate, we can evaluate the gate fidelity using Eq. (1):

$$\bar{F} = 1 + \sum_{k=1}^{N_L}\int d\psi\langle\psi|U(0,\tau)^\dagger\rho_{\psi,k}^{(1)}(\tau)U(0,\tau)|\psi\rangle. \tag{5}$$

Evaluating the second term by inserting Eq. (4) and first performing the integral over initial states $\int d\psi$, we find

$$\int d\psi[\langle\psi(t')|\hat{L}|\psi(t')\rangle\langle\psi(t')|\hat{L}^\dagger|\psi(t')\rangle - \langle\psi(t')|\hat{L}^\dagger\hat{L}|\psi(t')\rangle]$$
$$= \int d\psi[\langle\psi|\hat{L}|\psi\rangle\langle\psi|\hat{L}^\dagger|\psi\rangle - \langle\psi|\hat{L}^\dagger\hat{L}|\psi\rangle] \equiv \delta F(\hat{L}). \tag{6}$$

The first expression contains only expectation values of jump operators with respect to the intermediate pure state $|\psi(t')\rangle$. Since the unitary gate evolution $U(0,t')$ only performs a rotation in the computational Hilbert space, it leaves the set of *all* initial states $|\psi\rangle$ invariant. Integrating over all initial states $|\psi\rangle$ in Eq. (5) is thus identical to integrating over all states $|\psi(t')\rangle$ for *any* t'. This renders the remaining integrand *time-independent* such that from the remaining time integral we obtain [35]

$$\bar{F} = 1 + \tau\sum_{k=1}^{N_L}\Gamma_k\delta F(\hat{L}_k) + \mathcal{O}(\tau^2\Gamma_k^2). \tag{7}$$

This is *the main result* of this Letter. The reduction of gate fidelity is thus *independent* of which unitary gate U_g is performed and proportional to the time τ it takes to perform the gate.

By denoting the (unnormalized) state after the action of the jump operator as $|\psi_L\rangle = \hat{L}^\dagger|\psi\rangle$, the integrand in Eq. (6) can be written as $\langle\psi_L|\psi\rangle\langle\psi|\psi_L\rangle - \langle\psi_L|\psi_L\rangle$. This is clearly negative, since the second term corresponds to the full length of $\langle\psi_L|$, while the first term is the length of $\langle\psi_L|$ projected onto the unperturbed state $\langle\psi|$. In other words, the second term is proportional to the probability for a quantum jump to occur, while the first term is proportional to the probability that this jump leaves the system in the unperturbed ideal state.

Each dissipative channel contributes independently, proportional to its rate Γ_k and the factor $\delta F(\hat{L}_k)$, which we now proceed to evaluate for a few relevant processes. We note that weak coherent errors also contribute independently to first order [35]. We also note that we would obtain the same expression by applying the first-order error map either before or after the ideal gate and then averaging over all initial states [36].

General formula for fidelity reduction of N-qubit gates.—To evaluate the integral over all pure states in Eq. (6), we first rewrite it using a density-matrix representation,

$$\delta F(\hat{L}) = \int d\psi(\mathrm{Tr}[\hat{L}^\dagger\rho_\psi\hat{L}\rho_\psi] - \mathrm{Tr}[\hat{L}^\dagger\hat{L}\rho_\psi]). \tag{8}$$

In the case of a single qubit, we can expand the density matrix in four terms: $\rho_\psi = \frac{1}{2}(\sigma_0 + n_x\sigma_x + n_y\sigma_y + n_z\sigma_z)$, where σ_0 is the 2×2 identity matrix and σ_i for $i \in \{x, y, z\}$ are the corresponding Pauli matrices. Inserting this expression in Eq. (8), the first term expands into 16 terms, while the second gives four terms. The average over $d\psi$ now corresponds to a an integral over the three real-valued coefficients n_x, n_y, and n_z under the normalization constraint $n_x^2 + n_y^2 + n_z^2 = 1$, i.e., the Bloch sphere. This can be calculated explicitly [37], but here we follow Ref. [38] and note that the symmetries of the Hilbert space imply that $\langle n_i \rangle = 0$ and $\langle n_i n_j \rangle = \delta_{ij}/3$ for $i, j \in \{x, y, z\}$, where angular brackets denote integration over the Bloch sphere, δ_{ij} is the Kronecker delta, and the factor $1/3$ follows from the normalization. Thus, for a single qubit Eq. (8) reduces to

$$\delta F_1(\hat{L}) = -\frac{1}{4}\mathrm{Tr}[\hat{L}^\dagger \hat{L}] + \frac{1}{12}\sum_{j\in\{x,y,z\}}\mathrm{Tr}[\hat{L}^\dagger \sigma_j \hat{L} \sigma_j]. \quad (9)$$

For a system with N qubits, we can expand any density matrix in a basis consisting of all 4^N possible tensor-product combinations of Pauli matrices and identity. The element consisting of only identity matrices is the identity matrix in $d = 2^N$ dimensions and thus has trace d, fixing the overall normalization to $1/d$. Denoting the other $d^2 - 1$ traceless basis matrices as $\hat{f}_i$, we write $\rho_\psi = (1/d)(\hat{1}_d + \sum_{i=1}^{d^2-1} n_i \hat{f}_i)$. Following Ref. [38] again, we find similar rules for averages over the real-valued coefficients n_i as in the single-qubit case [35]: $\langle n_i \rangle = 0$ and $\langle n_i n_j \rangle = \delta_{ij}/(d+1)$. Thus, for operations on N qubits, Eq. (8) reduces to

$$\delta F_N(\hat{L}) = \frac{1-d}{d^2}\mathrm{Tr}[\hat{L}^\dagger \hat{L}] + \frac{\sum_{i=1}^{d^2-1}\mathrm{Tr}[\hat{L}^\dagger \hat{f}_i \hat{L} \hat{f}_i]}{d^2(d+1)}, \quad (10)$$

giving a general formula for the reduction of fidelity of general N-qubit gates to first order in Markovian dissipation. The expression is indeed gate-independent, but depends on the nature of the dissipative processes, expressed through the corresponding Lindblad jump operator $\hat{L}$. We now proceed to discuss different forms of this operator, in particular the difference between processes that act independently or in a correlated fashion on different qubits.

Effect of uncorrelated relaxation and dephasing.—We first consider individual qubit energy relaxation acting on one qubit with jump operator $\hat{L} = \sigma_-$ and rate Γ_1, and additional pure dephasing with jump operator σ_z and rate Γ_ϕ [note that the rate multiplying the dissipator in Eq. (3) is $\Gamma_\phi/2$, making the coherences decay with the rate Γ_ϕ]. For uncorrelated dissipation, the N-qubit jump operators are tensor products with identity matrices acting on all other qubits. Since the trace operations in Eq. (10) then factorize into products of single-qubit traces, we straightforwardly find

$$\delta F_N(\sigma_z^1 \otimes \sigma_0^2 \ldots \sigma_0^N) = 2\delta F_N(\sigma_-^1 \otimes \sigma_0^2 \ldots \sigma_0^N) = -\frac{d}{d+1}, \quad (11)$$

extending the expressions for single- and two-qubit Clifford gates given in Ref. [11] to arbitrary gates on an arbitrary number of qubits.

Remembering that different dissipators add independently to the gate fidelity according to Eq. (7), we can then find the first-order reduction in gate fidelity due to uncorrelated energy relaxation and pure dephasing on all N qubits [35]:

$$\bar{F}_N^{\mathrm{uc}} = 1 - \frac{d}{2(d+1)}\tau\sum_{k=1}^{N}(\Gamma_1^k + \Gamma_\phi^k), \quad (12)$$

where $\Gamma_1^k = 1/T_1^k$ ($\Gamma_\phi^k = 1/T_\phi^k$) is the relaxation (dephasing) rate of qubit k and T_1^k (T_ϕ^k) is the relaxation (dephasing) time. We note that the effect of heating with jump operator $\hat{L} = \sigma_+$ and rate Γ_+ enters in the same way as the relaxation in Eq. (12). By comparing the single and two-qubit gate fidelities in an experimental system, this formula allows one to assess to what extent the gates are decoherence-limited. However, as we will see below, a multiqubit gate error that agrees with this expression does not guarantee that the noise processes are indeed uncorrelated between qubits.

We stress that the gate independence of the gate fidelity is only valid to first order in the dissipative correction. For single-qubit rotations around the x and z axes, this is illustrated by the analytical solutions to the master equation with energy relaxation and dephasing, which, for π rotations, to second order in the dissipation yield the gate fidelities

$$\bar{F}_{\sigma_x} = 1 - \frac{\Gamma_1 + \Gamma_\phi}{3}\tau + \frac{1}{8}\left(\frac{11}{12}\Gamma_1^2 + \frac{5}{3}\Gamma_1\Gamma_\phi + \Gamma_\phi^2\right)\tau^2, \quad (13)$$

$$\bar{F}_{\sigma_z} = 1 - \frac{\Gamma_1 + \Gamma_\phi}{3}\tau + \frac{1}{8}\left(\Gamma_1^2 + \frac{4}{3}[\Gamma_1\Gamma_\phi + \Gamma_\phi^2]\right)\tau^2. \quad (14)$$

The limitation of gate independence to first order is also clear from the fact that in the second-order expansion, the dissipator will act two times, so the expressions include averages that are not over the full Hilbert space and thus depend on the relation between the gate operation and the dissipation. In [35], we provide exact expressions for the fidelity reduction for a few important single- and two-qubit gates.

Results for correlated noise.—Dissipation can be correlated in many different ways. Here, we discuss two cases that affect the gate fidelity differently. First, we treat correlated decoherence arising from many qubits connected to the same environmental mode, e.g., an extended microwave mode in the packaging of a superconducting qubit chip [39,40]. For simplicity, we consider equal coupling of all N qubits, leading to the jump operator $\hat{L}_{\phi c}^{N} = \sum_{k=1}^{N} \sigma_z^k$ describing correlated dephasing with rate $\Gamma_{\phi c}$ [again corresponding to a rate $\Gamma_{\phi c}/2$ in Eq. (3)], as well as the jump operator $\hat{L}_{1c}^{N} = \sum_{k=1}^{N} \sigma_-^k$ describing correlated relaxation with rate Γ_{1c}. The correlated dephasing corresponds to a decay of the coherence between two multiqubit states, with a rate $\delta n^2 \Gamma_{\phi c}$, where δn is the difference in excitation number between the two states [41]. In a three-qubit system, the coherence between $|000\rangle$ and $|111\rangle$ thus decays with the rate $9\Gamma_{\phi c}$, while the subspace spanned by states with the same number of excitations, e.g., $|100\rangle$, $|010\rangle$, and $|001\rangle$, is not affected by dephasing. In a similar fashion, the correlated relaxation gives rise to nondecaying multiqubit dark states as well as bright states decaying quickly due to superradiance.

We can straightforwardly evaluate the reduction of N-qubit gate fidelity due to correlated dephasing and relaxation using Eq. (10), finding [35]

$$\bar{F}_N^c = 1 - \frac{Nd}{2(d+1)} \tau (\Gamma_{1c} + \Gamma_{\phi c}), \tag{15}$$

which somewhat surprisingly is identical to the reduction in fidelity when all N qubits are subject to uncorrelated dephasing with rate $\Gamma_{\phi c}$ and uncorrelated relaxation with rate Γ_{1c}. This illustrates that the average gate fidelity is *not* a sensitive probe for detecting whether the dissipation arises from this type of additive linear coupling to a common bath. Averaging over all initial states tends to hide the fact that this type of correlated dissipation acts very differently on different parts of the computational Hilbert space and thus creates correlated errors between qubits, which is potentially detrimental for quantum error correction [42].

Finally, consider instead a two-photon relaxation process, where two qubits can relax to a bath accepting only the sum of the two qubits' energies, corresponding to the jump operator $\hat{L}_{2p} = \sigma_- \otimes \sigma_-$ and a rate Γ_{2p}. If one measures the relaxation time of the qubits individually, with the other qubits in their ground states, this process will not contribute. However, for the two-qubit gate fidelity one finds an extra reduction [35],

$$\bar{F} = \bar{F}_2^{\mathrm{uc}} - \frac{\Gamma_{2p}\tau}{5}, \tag{16}$$

which would add to the reduction predicted by the measured single-qubit relaxation and dephasing rates. The average two-qubit gate fidelity can thus detect this type of two-photon relaxation process.

Conclusion and outlook.—In this Letter, we investigated the effect of weak dissipative processes on the fidelity of quantum operations. For operations remaining in the computational subspace, the reduction is independent of the operation to first order in the product of the dissipation rate and the gate time. We presented a simple formula for the reduction of a general multiqubit operation in terms of the dissipative rates and the corresponding Lindblad jump operators. We also discussed the difference between uncorrelated and correlated dissipation and found that the fidelity reduction for a large class of correlated dissipation is similar to uncorrelated dissipation of similar strength.

The results presented here are widely applicable in the field of quantum computing since they enable simple and fast calculation and optimization of fidelities for single- and multiqubit gates, and can help estimate the computational power of noisy quantum hardware. Such analysis was, e.g., performed in Refs. [11,18,19,25] and our general formula reduces to and agrees with the expressions used there. Our formula was also used explicitly in the analysis of a recent experiment [43]. A natural extension of this work is to investigate operations going outside of the computational subspace, something that is currently used in many quantum-computing architectures. Also, as we highlight in two simple examples, the second-order correction to the average gate fidelity is indeed gate-dependent. Based on our approach, it is straightforward to analyze the effect of weak dissipation to second order, which could guide the choice of gates as the dissipation is further reduced.

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Note added.—After this manuscript was submitted for publication, we became aware of the unpublished manuscript [44] from Alexander N. Korotkov, who calculates the first-order contribution to the process fidelity due to Lindblad-form decoherence, and observes that in this approximation the fidelity does not depend on the desired unitary evolution.

After this manuscript was submitted for publication, we also became aware of the code documentation of IBM's QISKIT IGNIS [36], which provides the exact fidelity reduction for two cases, single-qubit Z rotations and the two-qubit CZ gate, in agreement with our results in Eq. (14) and [35].

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[1] T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, and J. L. O'Brien, Quantum computers, Nature (London) **464**, 45 (2010).
[2] G. Wendin, Quantum information processing with superconducting circuits: A review, Rep. Prog. Phys. **80**, 106001 (2017).
[3] X. Gu, A. F. Kockum, A. Miranowicz, Y.-X. Liu, and F. Nori, Microwave photonics with superconducting quantum circuits, Phys. Rep. **718–719**, 1 (2017).
[4] P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, A quantum engineer's guide to superconducting qubits, Appl. Phys. Rev. **6**, 021318 (2019).
[5] A. Blais, A. L. Grimsmo, S. M. Girvin, and A. Wallraff, Circuit quantum electrodynamics, Rev. Mod. Phys. **93**, 025005 (2021).
[6] H. Häffner, C. F. Roos, and R. Blatt, Quantum computing with trapped ions, Phys. Rep. **469**, 155 (2008).
[7] C. D. Bruzewicz, J. Chiaverini, R. McConnell, and J. M. Sage, Trapped-ion quantum computing: Progress and challenges, Appl. Phys. Rev. **6**, 021314 (2019).
[8] A. Chatterjee, P. Stevenson, S. De Franceschi, A. Morello, N. P. de Leon, and F. Kuemmeth, Semiconductor qubits in practice, Nat. Rev. Phys. **3**, 157 (2021).
[9] F. Flamini, N. Spagnolo, and F. Sciarrino, Photonic quantum information processing: A review, Rep. Prog. Phys. **82**, 016001 (2019).
[10] A. Montanaro, Quantum algorithms: An overview, npj Quantum Inf. **2**, 15023 (2016).
[11] F. Arute *et al.*, Quantum supremacy using a programmable superconducting processor, Nature (London) **574**, 505 (2019).
[12] J. Preskill, Reliable quantum computers, Proc. R. Soc. A **454**, 385 (1998).
[13] E. Knill, Quantum computing, Nature (London) **463**, 441 (2010).
[14] J. Benhelm, G. Kirchmair, C. F. Roos, and R. Blatt, Towards fault-tolerant quantum computing with trapped ions, Nat. Phys. **4**, 463 (2008).
[15] R. Barends *et al.*, Superconducting quantum circuits at the surface code threshold for fault tolerance, Nature (London) **508**, 500 (2014).
[16] E. Knill, D. Leibfried, R. Reichle, J. Britton, R. B. Blakestad, J. D. Jost, C. Langer, R. Ozeri, S. Seidelin, and D. J. Wineland, Randomized benchmarking of quantum gates, Phys. Rev. A **77**, 012307 (2008).
[17] E. Magesan, J. M. Gambetta, and J. Emerson, Scalable and Robust Randomized Benchmarking of Quantum Processes, Phys. Rev. Lett. **106**, 180504 (2011).
[18] P. J. J. O'Malley *et al.*, Qubit Metrology of Ultralow Phase Noise Using Randomized Benchmarking, Phys. Rev. Appl. **3**, 044009 (2015).
[19] E. A. Sete, N. Didier, A. Q. Chen, S. Kulshreshtha, R. Manenti, and S. Poletto, Parametric-Resonance Entangling Gates with a Tunable Coupler, Phys. Rev. Appl. **16**, 024050 (2021).
[20] N. Sundaresan, I. Lauer, E. Pritchett, E. Magesan, P. Jurcevic, and J. M. Gambetta, Reducing unitary and spectator errors in cross resonance with optimized rotary echoes, PRX Quantum **1**, 020318 (2020).
[21] J. Wallman, C. Granade, R. Harper, and S. T. Flammia, Estimating the coherence of noise, New J. Phys. **17**, 113020 (2015).
[22] M. A. Nielsen, A simple formula for the average gate fidelity of a quantum dynamical operation, Phys. Lett. A **303**, 249 (2002).
[23] L. H. Pedersen, N. M. Møller, and K. Mølmer, Fidelity of quantum operations, Phys. Lett. A **367**, 47 (2007).
[24] A. Bengtsson, P. Vikstål, C. Warren, M. Svensson, X. Gu, A. F. Kockum, P. Krantz, C. Križan, D. Shiri, I.-M. Svensson, G. Tancredi, G. Johansson, P. Delsing, G. Ferrini, and J. Bylander, Improved Success Probability with Greater Circuit Depth for the Quantum Approximate Optimization Algorithm, Phys. Rev. Appl. **14**, 034010 (2020).
[25] M. Ganzhorn, G. Salis, D. J. Egger, A. Fuhrer, M. Mergenthaler, C. Müller, P. Müller, S. Paredes, M. Pechal, M. Werninghaus, and S. Filipp, Benchmarking the noise sensitivity of different parametric two-qubit gates in a single superconducting quantum computing platform, Phys. Rev. Res. **2**, 033447 (2020).
[26] S. Krinner, S. Lazar, A. Remm, C. K. Andersen, N. Lacroix, G. J. Norris, C. Hellings, M. Gabureac, C. Eichler, and A. Wallraff, Benchmarking Coherent Errors in Controlled-Phase Gates due to Spectator Qubits, Phys. Rev. Appl. **14**, 024042 (2020).
[27] Y. Sung, L. Ding, J. Braumüller, A. Vepsäläinen, B. Kannan, M. Kjaergaard, A. Greene, G. O. Samach, C. McNally, D. Kim, A. Melville, B. M. Niedzielski, M. E. Schwartz, J. L. Yoder, T. P. Orlando, S. Gustavsson, and W. D. Oliver, Realization of High-Fidelity CZ and ZZ-Free iSWAP Gates with a Tunable Coupler, Phys. Rev. X **11**, 021058 (2021).
[28] V. Negîrneac, H. Ali, N. Muthusubramanian, F. Battistel, R. Sagastizabal, M. S. Moreira, J. F. Marques, W. J. Vlothuizen, M. Beekman, C. Zachariadis, N. Haider, A. Bruno, and L. DiCarlo, High-Fidelity Controlled-Z Gate with Maximal Intermediate Leakage Operating at the Speed Limit in a Superconducting Quantum Processor, Phys. Rev. Lett. **126**, 220502 (2021).
[29] J. Stehlik, D. M. Zajac, D. L. Underwood, T. Phung, J. Blair, S. Carnevale, D. Klaus, G. A. Keefe, A. Carniol, M. Kumph, M. Steffen, and O. E. Dial, Tunable Coupling Architecture for Fixed-Frequency Transmon Superconducting Qubits, Phys. Rev. Lett. **127**, 080505 (2021).
[30] R. Srinivas, S. C. Burd, H. M. Knaack, R. T. Sutherland, A. Kwiatkowski, S. Glancy, E. Knill, D. J. Wineland, D. Leibfried, A. C. Wilson, D. T. Allcock, and D. H. Slichter, High-fidelity laser-free universal control of trapped ion qubits, Nature (London) **597**, 209 (2021).
[31] C. R. Clark, H. N. Tinkey, B. C. Sawyer, A. M. Meier, K. A. Burkhardt, C. M. Seck, C. M. Shappert, N. D. Guise, C. E. Volin, S. D. Fallek, H. T. Hayden, W. G. Rellergert, and K. R. Brown, High-Fidelity Bell-State Preparation with $^{40}Ca^{+}$ Optical Qubits, Phys. Rev. Lett. **127**, 130505 (2021).
[32] X. Gu, J. Fernández-Pendás, P. Vikstål, T. Abad, C. Warren, A. Bengtsson, G. Tancredi, V. Shumeiko, J. Bylander, G. Johansson, and A. F. Kockum, Fast multiqubit gates through simultaneous two-qubit gates, PRX Quantum **2**, 040348 (2021).

[33] Y. Kim, A. Morvan, L. B. Nguyen, R. K. Naik, C. Jünger, L. Chen, J. M. Kreikebaum, D. I. Santiago, and I. Siddiqi, High-fidelity iToffoli gate for fixed-frequency superconducting qubits, Nat. Phys. **18**, 783 (2022).

[34] B. M. Villegas-Martínez, F. Soto-Eguibar, and H. M. Moya-Cessa, Application of perturbation theory to a master equation, Adv. Theor. Math. Phys. **2016**, 9265039 (2016).

[35] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.129.150504 for detailed derivations of the results presented in the main text.

[36] G. Aleksandrowicz *et al.*, QISKIT: An open-source framework for quantum computing (2019), 10.5281/zenodo.2562111.

[37] M. D. Bowdrey, D. K. Oi, A. J. Short, K. Banaszek, and J. A. Jones, Fidelity of single qubit maps, Phys. Lett. A **294**, 258 (2002).

[38] R. Cabrera and W. E. Baylis, Average fidelity in n-qubit systems, Phys. Lett. A **368**, 25 (2007).

[39] U. von Lüpke, F. Beaudoin, L. M. Norris, Y. Sung, R. Winik, J. Y. Qiu, M. Kjaergaard, D. Kim, J. Yoder, S. Gustavsson, L. Viola, and W. D. Oliver, Two-qubit spectroscopy of spatiotemporally correlated quantum noise in superconducting qubits, PRX Quantum **1**, 010305 (2020).

[40] S. Huang, B. Lienhard, G. Calusine, A. Vepsäläinen, J. Braumüller, D. K. Kim, A. J. Melville, B. M. Niedzielski, J. L. Yoder, B. Kannan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, Microwave package design for superconducting quantum processors, PRX Quantum **2**, 020306 (2021).

[41] J. Jeske and J. H. Cole, Derivation of Markovian master equations for spatially correlated decoherence, Phys. Rev. A **87**, 052138 (2013).

[42] C. D. Wilen, S. Abdullah, N. A. Kurinsky, C. Stanford, L. Cardani, G. D’Imperio, C. Tomei, L. Faoro, L. B. Ioffe, C. H. Liu, A. Opremcak, B. G. Christensen, J. L. DuBois, and R. McDermott, Correlated charge noise and relaxation errors in superconducting qubits, Nature (London) **594**, 369 (2021).

[43] S. Kosen *et al.*, Building blocks of a flip-chip integrated superconducting quantum processor, Quantum Sci. Technol. **7**, 035018 (2022).

[44] A. N. Korotkov, Error matrices in quantum process tomography, arXiv:1309.6405.