One-way transfer of quantum states via decoherence

Yuichiro Matsuzaki,¹,² Victor M. Bastidas,¹,² Yuki Takeuchi,³ William J. Munro,¹,²,⁴ and Shiro Saito¹

¹NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan
²NTT Theoretical Quantum Physics Center, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan
³NTT Communication Science Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan
⁴National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan

In many quantum information processing applications, it is important to be able to transfer a quantum state from one location to another - even within a local device. Typical approaches to implement the quantum state transfer rely on unitary evolutions or measurement feedforward operations. However, these existing schemes require accurate pulse operations and/or precise timing controls. Here, we propose a one-way transfer of the quantum state with near unit efficiency using dissipation from a tailored environment. After preparing an initial state, the transfer can be implemented without external time dependent operations. Moreover, our scheme is irreversible due to the non-unitary evolution, and so the transferred state remains in the same site once the system reaches the steady state. This is in stark contrast to the unitary state transfer where the quantum states continue to oscillate between different sites. Our novel quantum state transfer via the dissipation paves the way towards robust and practical quantum control.

I. INTRODUCTION

Quantum state transfer is an essential technique to realize quantum computation and quantum communication. One of typical approaches is to use flying qubits such as optical photons. In this case, a quantum state of a stationary qubit can be transferred to the flying photons using a solid state system such that they can interact with another stationary qubit at a distant node. However, in such an approach, the quantum state transfer can be typically performed in a probabilistic way. Another approach is to use a stationary qubit array for sending quantum states. Although the maximum distance of the transfer is limited by the length of the array, it is in principle possible to realize deterministic state transfer. Such an approach would be useful to realize scalable quantum computation in a distributed architecture where quantum computers with a small size are connected by the qubit array, and there are many researches along this direction. In this paper, we focus on such a quantum state transfer by using the qubit array.

In the standard schemes, unitary evolution or measurement feed-forwards are adopted to perform quantum state transfer in a qubit array. A sequential implementation of SWAP gates between nearest neighbor qubits can transfer the quantum state from a node to any other nodes. Or combinations of the control-phase gates and measurement feed-forwards can teleport the quantum state from one site to another. However, these schemes require accurate operations and/or precise timing for the implementation of the state transfer. The operational inaccuracy and the time jivering might accumulates as an error, which could make it difficult to achieve threshold of the topological quantum error correction.

It is known that dephasing can improve an energy transfer in a qubit-array under the effect of inhomogeneous broadening of the qubit frequencies. When there is an energy detuning between the qubits, and in the absence of time-dependent pulsed operations, the flip-flop interaction between the qubits cannot induce an efficient energy transfer. Interestingly, the existence of dephasing on the qubits effectively compensates the energy detuning, and the energy transport can be enhanced. However, when this approach is applied to a one-dimensional system, the energy transfer is bidirectional and the excitations can be transferred to the right or left of the qubit array in a stochastic way. So the transfer is not as efficient as in the case of a sequential implementation of the SWAP gates or quantum teleportation. In these schemes, the experimentalist can choose the direction of the energy transfer by changing the timing, phase, and strength of the pulse sequence.

Here, by exploiting decoherence induced by an external environment, we propose a one-way transfer of quantum states, where no active control is needed. The distinct feature of our scheme is that, after we prepare an initial state, the transfer from the initial site to the target site can be implemented automatically by the environment. Moreover, due to the non-unitary properties of the decoherence, our transfer is one way so that the quantum state can be transferred along one direction, and the state remains in the target site after the state transfer.

It is worth mentioning that, by using a unitary evolution for the transfer, the quantum state typically oscillates between different sites, and time-dependent control such as turn on/off the interaction is required to make the state stay in the target site after the transfer. For example, since a flip-flop interaction between two qubits makes an oscillation of the quantum state between the two sites, we need to turn off the interaction to implement a SWAP gate between them where time-dependent control is required. For practical purposes, automatic one-way transfer might be suitable for quantum information processing.

*Electronic address: matsuzaki.yuichiro@lab.ntt.co.jp
because it can avoid potential timing errors that typical unitary approaches would suffer from.

Also, the one-way transfer of a quantum state has a fundamental interest. Significant effort has been made to realize high-performance circulators and isolators for superconducting quantum circuits [34–38]. The non-reciprocal properties of these devices are useful for protecting quantum states from noise and detecting signals from qubits. Understanding the mechanism of the non-reciprocal properties of quantum systems is important to develop future applications for such directional devices [39–44], and our results could contribute such a field.

Our paper is organized as follows. In Sec. II, we consider a two-qubit system collectively coupled to a dissipative cavity to implement the one-way transfer of an energy excitation from a qubit to the other qubit. In this case, the coherence of the initial state is not preserved. In Sec. III, we describe a four-qubit system collectively coupled to a dissipative cavity. Here, we use two qubits for the preparation of the initial state, and consider the other two qubits as the target sites for the transfer. We show that, by using a decoherence-free subspace [45–48], any single qubit information encoded in a logical qubit (composed of two qubits) can be directionally transferred to the target, while the coherence is preserved. In Sec. IV, we conclude our discussion.

II. ONE-WAY ENERGY TRANSFER

We describe the model of our system to implement the one-way energy transfer where the quantum coherence is not preserved. Here, we consider two qubits that interact via flip-flop interaction. There is also a cavity that is collectively coupled to the qubits. The Hamiltonian is given as follows:

$$
\hat{H} = \hat{H}_{\text{qubit}} + \hat{H}_{\text{cavity}} + \hat{H}_1
$$

$$
\hat{H}_{\text{qubit}} = \sum_{j=1}^{2} \frac{\hbar \omega_q^{(j)}}{2} \sigma_z^{(j)} + \hbar g (\sigma_+^{(1)} \sigma_-^{(2)} + \sigma_-^{(1)} \sigma_+^{(2)})
$$

$$
\hat{H}_{\text{cavity}} = \hbar \omega_c \hat{a}^\dagger \hat{a}
$$

$$
\hat{H}_1 = \hbar (\hat{a} + \hat{a}^\dagger) \left( \sum_{j=1}^{2} J_j \sigma_z^{(j)} \right)
$$

where $\omega_q^{(j)}$ denotes the $j$-th qubit frequencies. Also, $\omega_c$ denotes the frequency of the cavity, $g$ is the coupling between the qubits, and $J_j$ denotes the coupling between the qubits and cavity. Here, $\sigma_x^{(j)} = |\uparrow\rangle_j \langle \downarrow|_j$ and $\sigma_z^{(j)} = |\uparrow\rangle_j \langle \uparrow|_j$ ($j = 1, 2$) denote the ladder operators. We set the condition of $\hbar \omega_q^{(1)} > \hbar \omega_q^{(2)} > \omega_c \gg k_B T$ throughout of this paper where $k_B T$ denotes the thermal energy of the environment. Also, to rescale the qubit frequency, we move into a rotating frame defined by $U = e^{i \frac{\hbar \delta \omega_c}{2} \sum_{j=1}^{2} \sigma_z^{(j)}}$, and we obtain the same form of the Hamiltonian except that the qubit bare frequency $\omega_q^{(j)}$ is replaced by a detuning $\delta \omega_q^{(j)} = \omega_q^{(j)} - \omega$. It is worth mentioning that, our Hamiltonian is different from the standard Jaynes Cummings model where the interaction between the qubits and cavity is described by $(\hat{a} + \hat{a}^\dagger) (\sum_{j=1}^{2} J_j \sigma_z^{(j)})$ before the rotating wave approximation [49]. In our case, since the form of the qubit-cavity interaction is $(\hat{a} + \hat{a}^\dagger) (\sum_{j=1}^{2} J_j \sigma_z^{(j)})$, our Hamiltonian preserves the total number of the excitation of the qubit such as $|\hat{H}, \sum_{j=1}^{2} \sigma_z^{(j)}\rangle = 0$. This is a crucial property to implement our scheme, because otherwise the excitation of the qubits could be transferred into the cavity and could be lost from the qubits. Moreover, in our scheme, the cavity is supposed to be coupled with an environment that induces a
We will describe the reasons why our scheme can achieve almost the unit efficiency of one-way energy transfer as shown in the Fig. 2. For this purpose, we diagonalize \( \hat{H}_{\text{qubit}} = \sum_{j=1}^{4} E_{j}\hat{E}_{j}^{\dagger}\hat{E}_{j} \). The Hamiltonian preserves the total number of the excitation of the qubit such as \( [\hat{H}_{\text{qubit}}, \sum_{j=1}^{2} \hat{a}_{j}\hat{a}_{j}^{\dagger}] = 0 \), and so we can analytically obtain the eigenvectors as follows:

\[
|E_{1}\rangle = |\uparrow\uparrow\rangle_{12} \quad (4)
\]

\[
|E_{2}\rangle = \frac{\cos \theta}{2} |\uparrow\downarrow\rangle_{12} + \sqrt{\frac{\sin \theta}{2}} |\downarrow\uparrow\rangle_{12} \quad (5)
\]

\[
|E_{3}\rangle = \frac{\sin \theta}{2} |\uparrow\downarrow\rangle_{12} - \sqrt{\frac{\cos \theta}{2}} |\downarrow\uparrow\rangle_{12} \quad (6)
\]

\[
|E_{4}\rangle = |\downarrow\downarrow\rangle_{12} \quad (7)
\]

where we have

\[
\cos \theta = \frac{\delta\omega_{i}^{(1)} - \delta\omega_{i}^{(2)}}{\sqrt{(\delta\omega_{i}^{(1)} - \delta\omega_{i}^{(2)})^{2} + 4g^{2}}} \quad (8)
\]

\[
\sin \theta = \frac{2g}{\sqrt{(\delta\omega_{i}^{(1)} - \delta\omega_{i}^{(2)})^{2} + 4g^{2}}} \quad (9)
\]

In our paper, we assume \( |\delta\omega_{i}^{(1)} - \delta\omega_{i}^{(2)}| \gg g > 0 \), and so we have \( \cos \frac{\pi}{2} \approx 1 \) and \( \sin \frac{\pi}{2} \approx \frac{2g}{\delta\omega_{i}^{(1)} \delta\omega_{i}^{(2)}} \leq 1 \). Also, the eigenvalues are as follows:

\[
E_{1} = \frac{\hbar\delta\omega_{i}^{(1)} + \hbar\delta\omega_{i}^{(2)}}{2} \quad (10)
\]

\[
E_{2} = \frac{\hbar\sqrt{(\delta\omega_{i}^{(1)} - \delta\omega_{i}^{(2)})^{2} + 4g^{2}}}{2} \quad (11)
\]

\[
E_{3} = \frac{-\hbar\sqrt{(\delta\omega_{i}^{(1)} - \delta\omega_{i}^{(2)})^{2} + 4g^{2}}}{2} \quad (12)
\]

\[
E_{4} = \frac{-\hbar\delta\omega_{i}^{(1)} + \hbar\delta\omega_{i}^{(2)}}{2} \quad (13)
\]

It is worth mentioning that, if we have a uniform interaction between the qubits and cavity such as \( J_{1} = J_{2} \), the interaction Hamiltonian \( H_{I} \) commutes with \( H_{\text{qubit}} \), and the cavity does not induce the energy transfer as shown in the Fig. 2. So we consider a case of an inhomogeneous coupling (\( J_{1} \neq J_{2} \))
with the cavity. Importantly, due to the small but a finite effect of the coupling strength $g$, the interaction from the cavity induces a transition between $|E_2\rangle$ and $|E_3\rangle$ where we have $\langle E_2 | H_{1} | E_3 \rangle \neq 0$. This means that, when the resonant frequency $\omega_{c}$ of the cavity is closer to the energy difference between $|E_2\rangle$ and $|E_3\rangle$, there is an efficient energy exchange between the cavity and qubits. Actually, this explains why the transfer becomes more efficient as the cavity frequency becomes closer to the qubit-qubit detuning $(\delta \omega^{(1)}_{q} - \delta \omega^{(2)}_{q})$ in the Fig. [2]. Moreover, due to the strong coupling of the cavity with the low-temperature environment, the cavity emits a photon immediately after catching the excitation from the qubit, and the cavity can approximately stay in a vacuum state. Therefore, the initial state $|E_2\rangle$ will irreversibly evolve into a steady state $|E_3\rangle$ in our system. On the other hand, although the energy of $|E_4\rangle$ is lower than that of $|E_3\rangle$, a transition from $|E_3\rangle$ to $|E_4\rangle$ is prohibited due to a zero transition matrix element of $\langle E_3 | H_{1} | E_4 \rangle = 0$. It is worth mentioning that, as the qubit-qubit coupling $g$ becomes larger, a deviation of the state $|E_2\rangle$ from $|\uparrow\downarrow\rangle_{12}$ becomes larger. With a large $g$, the irreversible transition from $|E_2\rangle$ to $|E_4\rangle$ does not correspond to our desired transition (from $|\uparrow\downarrow\rangle_{12}$ to $|\uparrow\downarrow\rangle_{12}$), which explains the reason why the excitation of the target qubit in the steady state becomes smaller with a larger coupling $g$ in the Fig. [2].

III. ONE-WAY QUANTUM STATE TRANSFER

Let us now describe the model of our system to implement a one-way coherent quantum state transfer. In the scheme explained in the Sec. [II] the decoherence from the environment will destroy the quantum coherence, and so only the energy of the initial state can be transferred to the target qubit. On the other hand, in this section, we will show that a quantum state can be directionally transferred in a qubit array. Here, we consider four qubits collectively coupled with a dissipative cavity, as shown in the Fig. [I] The Hamiltonian in the rotating frame is given as follows.

$$
\hat{H}_{\text{QIT}} = \hat{H}_{\text{qubit}} + \hat{H}_{\text{cavity}} + \hat{H}_1
$$

$$
\hat{H}_{\text{qubit}} = \sum_{j=1}^{4} \frac{\hbar \delta \omega_q^{(j)}}{2} \hat{\sigma}_z^{(j)} + \hbar g \sum_{j=1,3} \left( \hat{\sigma}_+^{(j)} \hat{\sigma}_-^{(j+1)} + \hat{\sigma}_-^{(j)} \hat{\sigma}_+^{(j+1)} \right)
$$

$$
\hat{H}_{\text{cavity}} = \hbar \omega_c \hat{a}^{\dagger} \hat{a}
$$

$$
\hat{H}_1 = \hbar \left( \hat{a} + \hat{a}^{\dagger} \right) \sum_{j=1}^{4} J_j \hat{\sigma}_z^{(j)}
$$

where the first (third) qubit has an energy-exchange interaction with the second (fourth) qubit. We assume $\delta \omega_{q}^{(1)} > \delta \omega_{q}^{(2)}$ ($\delta \omega_{q}^{(3)} > \delta \omega_{q}^{(4)}$). Also, we assume that the qubit 1 (2) and qubit 3 (4) has the same parameter such as $\delta \omega_{q}^{(1)} = \delta \omega_{q}^{(3)}$, $\delta \omega_{q}^{(2)} = \delta \omega_{q}^{(4)}$, $J_1 = J_3$, and $J_2 = J_4$. The key idea is to use a decoherence free subspace [45, 48]. By using the qubits 1 and 3, we can define a logical qubit $|\psi_{L}^{13}\rangle = |\uparrow\rangle_{13}$ and $|\psi_{L}^{13}\rangle = |\downarrow\rangle_{13}$. We can also define such a logical qubit by using the qubit 2 and 4. Since the qubit 1 (2) and 3 (4) are identical for the dissipative cavity, the environment cannot distinguish them, which makes it possible to implement a one-way transfer of quantum states as we will describe later. Similar to the case of the energy transfer in the Sec. [II], we consider a photon loss of the cavity, and so we will solve the following Lindblad master equation:

$$
\frac{d\hat{\rho}(t)}{dt} = -\frac{i}{\hbar} [\hat{H}_{\text{QIT}}, \hat{\rho}(t)] - \frac{\kappa}{2} (\hat{a}^{\dagger} \hat{\rho}(t) \hat{a} - \hat{a} \hat{a}^{\dagger} \hat{\rho}(t) - \hat{a}^{\dagger} \hat{a} \hat{\rho}(t) + \hat{\rho}(t) \hat{a}^{\dagger} \hat{a})
$$

We show the efficiency of our scheme to transfer the quantum state by solving the Lindblad master equation. Firstly, we set the initial state as $|\psi_{\text{Bell}}\rangle = |\uparrow\downarrow\rangle_{13} + |\downarrow\uparrow\rangle_{13} |\downarrow\downarrow\rangle_{24}$. Also, we define a fidelity with the target state $F = \text{Tr}[\hat{\rho}(t) |\psi_{\text{Bell}}\rangle \langle \psi_{\text{Bell}}|]$ where $|\psi_{\text{Bell}}\rangle = |\downarrow\downarrow\rangle_{13} |\uparrow\downarrow\rangle_{24} + |\uparrow\downarrow\rangle_{13} |\downarrow\downarrow\rangle_{24}$. In the Fig. [3] we plot the infidelity $1 - F$ against a time $t$. By choosing the parameters in the Fig. [3] the fidelity can be more than 99%, which is more than the threshold of the topological quantum error correction [51, 53]. Secondly, we numerically confirm that, for several other initial states described as $|\alpha \uparrow \downarrow\rangle_{13} + |\beta \downarrow \uparrow\rangle_{13} |\downarrow\downarrow\rangle_{24}$ where $\alpha$ and $\beta$ are coefficients, we can obtain a similar fidelity by using the same parameters. So these show that we can implement a directional transfer of 1 qubit information by using four qubits and a dissipative cavity.

We explain the reasons why we can send the quantum state in a directional way. Since the qubit 1 (2) and 3 (4) are identical, the dissipative cavity cannot distinguish whether the excitation is located at the qubit 1 (2) or at the qubit 3 (4). This means that the coherence between $|\psi_{L}^{13}\rangle = |\uparrow\rangle_{13}$ and $|\psi_{L}^{13}\rangle = |\downarrow\rangle_{13}$ is preserved in our scheme. On the other hand, as long as we set $J_1 > J_2$, the dissipative cavity still can distinguish whether the excitation is on the qubit 1 or on the qubit 2, which means that the directional excitation transfer...
can be performed similar to the mechanism described in the Sec. II. Similar to the Eqs. (4)-(11), we can diagonalize $H_{\text{qubit}}$. The second excited state and the third excited state are approximated as $|↓↑\rangle_{12}$ ($|↓↓\rangle_{34}$) and $|↑↓\rangle_{12}$ ($|↑↑\rangle_{34}$) for $H_{\text{qubit}}$, where the dissipative cavity can induce an irreversible transition between them as described in the Sec II, and this approximation becomes better for $(\delta \omega_{q}^{(1)} - \delta \omega_{q}^{(2)}) \gg (\delta \omega_{q}^{(3)} - \delta \omega_{q}^{(4)}) \gg g$. This explains why the infidelity can be smaller for a smaller $g$ in the Fig. [3].

IV. CONCLUSION

In conclusion, we have shown a scheme to implement a directional transfer of a quantum state by using a tailored environment. Since we use decoherence for the transfer, this is an irreversible process. Moreover, once we prepare an initial state, the transfer can be automatically implemented without any time dependent operations. To implement a one-way energy transfer, two qubits and a dissipative cavity are required, while we need four qubits and a dissipative cavity for a quantum state transfer with preserved coherence. Our scheme provides not only an alternative way to implement a quantum state transfer for quantum information processing but also a deep understanding of a non-reciprocal device for future superconducting circuit applications.

ACKNOWLEDGMENTS

We thank Keisuke Fujii, Emi Yokawa, and Ivan Iakoupov for helpful discussions. This work was supported by CREST (JPMJCR1774), JST, and in part by MEXT Grants-in-Aid for Scientific Research on Innovative Areas “Science of hybrid quantum systems” (Grant No. 15H05870).

Note added - While we are preparing our manuscript, a related paper appeared on arXiv, which shows another way to perform the directional quantum state transfer by dissipation [54].

[1] J. I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi, Phys. Rev. Lett. 78, 3221 (1997).
[2] M. Christandl, N. Datta, A. Ekert, and A. J. Landahl, Phys. Rev. Lett. 92, 187902 (2004).
[3] M. A. Sillanpää, J. I. Park, and R. W. Simmonds, Nature 449, 438 (2007).
[4] C. Cabrillo, J. Cirac, P. Garcia-Fernandez, and P. Zoller, Phys. Rev. A 59, 1025 (1999).
[5] S. Bose, P. Knight, M. Plenio, and V. Vedral, Phys. Rev. Lett. 83, 5158 (1999).
[6] L.-M. Liang and C.-Z. Li, Phys. Rev. A 72, 024303 (2005).
[7] Y. Lim, A. Beige, and L. Kwek, Phys. Rev. Lett. 95, 030505 (2005).
[8] S. D. Barrett and P. Kok, Phys. Rev. A 71, 060310(R) (2005).
[9] D. L. Moehring, P. Maunz, S. Olmschenk, K. C. Young, D. N. Matsukevich, L.-M. Duan, and C. Monroe, Nature 449, 68 (2007).
[10] D. N. Matsukevich, P. Maunz, D. L. Moehring, S. Olmschenk, and C. Monroe, Phys. Rev. Lett. 100, 150404 (2008).
[11] M. Tey, Z. Chen, S. Aljunid, B. Chng, F. Huber, G. Maslennikov, and C. Kurtsiefer, Nature Physics (2008).
[12] S. Bose, Phys. Rev. Lett. 91, 207901 (2003).
[13] V. Subrahmanyam, Phys. Rev. A 69, 034304 (2004).
[14] J. Shi, Y. Li, Z. Song, and C.-P. Sun, Phys. Rev. A 71, 032309 (2005).
[15] M. Christandl, N. Datta, T. C. Dorlas, A. Ekert, A. Kay, and A. J. Landahl, Phys. Rev. A 71, 032312 (2005).
[16] D. Burgarth and S. Bose, Phys. Rev. A 71, 052315 (2005).
[17] A. Lyakhov and C. Bruder, New journal of physics 7, 181 (2005).
[18] S. Bose, Contemporary Physics 48, 13 (2007).
[19] N. Y. Yao, L. Jiang, A. V. Gorshkov, P. C. Maurer, G. Giedke, J. I. Cirac, and M. D. Lukin, Nature communications 3, 800 (2012).
[20] N. Y. Yao, L. Jiang, A. V. Gorshkov, Z.-X. Gong, A. Zhai, L.-M. Duan, and M. D. Lukin, Phys. Rev. Lett. 106, 040505 (2011).
[21] Y. Ping, B. W. Lovett, S. C. Benjamin, and E. M. Gauger, Phys. Rev. Lett. 110, 100503 (2013).
[22] N. Schuch and J. Siewert, Phys. Rev. A 67, 032301 (2003).
[23] F. W. Strauch, P. R. Johnson, A. J. Dragt, C. Lobb, J. Anderson, and F. Wellstood, Phys. Rev. Lett. 91, 167005 (2003).
[24] C.-P. Yang, S.-I. Chu, and S. Han, Phys. Rev. A 67, 042311 (2003).
[25] R. Raussendorf and H. Briegel, Phys. Rev. Lett. 86, 5188 (2001).
[26] R. Raussendorf, D. E. Browne, and H. J. Briegel, Phys. Rev. A 68, 022312 (2003).
[27] G. S. Engel, T. R. Calhoun, E. L. Read, T.-K. Ahn, T. Mančal, Y.-C. Cheng, R. E. Blankenship, and G. R. Fleming, Nature 446, 782 (2007).
[28] H. Lee, Y.-C. Cheng, and G. R. Fleming, Science 316, 1462 (2007).
[29] M. B. Plenio and S. F. Huelga, New Journal of Physics 10, 113019 (2008).
[30] J. Gilmore and R. H. McKenzie, The Journal of Physical Chemistry A 112, 2162 (2008).
[31] P. Rebentrost, M. Mohseni, I. Kassal, S. Lloyd, and A. Aspuru-Guzik, New Journal of Physics 11, 033003 (2009).
[32] K. Fujii and K. Yamamoto, Phys. Rev. A 82, 042109 (2010).
[33] C. Uchiyama, W. J. Munro, and K. Nemoto, npj Quantum Information 4, 33 (2018).
[34] B. A. Auld, IRE Transactions on Microwave Theory and Techniques 7, 238 (1959).
[35] D. M. Pozar, Microwave engineering (John Wiley & Sons, 2009).
[36] A. Kamal, J. Clarke, and M. Devoret, Nat. Phys. 7, 311 (2011).
[37] C. Macklin, K. O’Brien, D. Hover, M. Schwartz, V. Bolkhovsky, X. Zhang, W. Oliver, and I. Siddiqi, Science 330, 307 (2010).
[38] S. Barzanjeh, M. Wulf, M. Peruzzo, M. Kalae, P. Dieterle, O. Painter, and J. Fink, Nature Communications 8, 953 (2017).
[39] J. Petersen, J. Volz, and A. Rauschenbeutel, Science 346, 67 (2014).
[40] A. Metelmann and A. A. Clerk, Phys. Rev. X 5, 021025 (2015).
[41] K. Sliwa, M. Hatridge, A. Narla, S. Shankar, L. Frunzio, R. Schoelkopf, and M. Devoret, Phys. Rev. X 5, 041020 (2015).
[42] P. Lodahl, S. Mahmoodian, S. Stobbe, A. Rauschenbeutel, P. Schneeweiss, J. Volz, H. Pichler, and P. Zoller, Nature 541, 473 (2017).
[43] M. Westig and T. Klapwijk, Physical Review Applied 9, 064010 (2018).
[44] A. R. Hamann, C. Müller, M. Jerger, M. Zanner, J. Combes, M. Pletyukhov, M. Weides, T. M. Stace, and A. Fedorov, Phys. Rev. Lett. 121, 123601 (2018).
[45] G. M. Palma, K.-A. Suominen, and A. K. Ekert, Proc. R. Soc. Lond. A 452, 567 (1996).
[46] A. Beige, D. Braun, B. Tregenna, and P. L. Knight, Phys. Rev. Lett. 85, 1762 (2000).
[47] L.-A. Wu and D. Lidar, Phys. Rev. Lett. 88, 207902 (2002).
[48] J. Altepeter, P. Hadley, S. Wendelken, A. Berglund, and P. Kwiat, Phys. Rev. Lett. 92, 147901 (2004).
[49] E. T. Jaynes and F. W. Cummings, Proc. IEEE 51, 89 (1963).
[50] C. W. Gardiner and H. Haken, Quantum noise, vol. 2 (Springer Berlin, 1991).
[51] R. Raussendorf, J. Harrington, and K. Goyal, New Journal of Physics 9, 199 (2007).
[52] R. Raussendorf and J. Harrington, Physical review letters 98, 190504 (2007).
[53] A. M. Stephens, W. J. Munro, and K. Nemoto, Phys. Rev. A 88, 060301 (2013).
[54] C. Wang and J. M. Gertler, arXiv preprint arXiv:1809.03571 (2018).