

# Fast and robust approach to long-distance quantum communication with atomic ensembles

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Quantum repeaters create long-distance entanglement between quantum systems while overcoming difficulties such as the attenuation of single photons in a fiber. Recently, an implementation of a repeater protocol based on single qubits in atomic ensembles and linear optics has been proposed [Duan *et al.*, *Nature (London)* **414**, 413 (2001)]. Motivated by rapid experimental progress towards implementing that protocol, here we develop a more efficient scheme compatible with active purification of arbitrary errors. Using similar resources as the earlier protocol, our approach intrinsically purifies leakage out of the logical subspace and all errors within the logical subspace, leading to greatly improved performance in the presence of experimental inefficiencies. Our analysis indicates that our scheme could generate approximately one pair per 3 min over 1280 km distance with fidelity ( $F \geq 78\%$ ) sufficient to violate Bell's inequality.

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## I. INTRODUCTION

Quantum communication holds promise for the secret transfer of classical messages as well as forming an essential element of quantum networks, allowing for teleportation of arbitrary quantum states and violations of Bell's inequalities over long distances [1]. While experimental and even commercial implementation of simple quantum communication protocols are well-established [2,3], extending these techniques to distances much longer than the attenuation length of optical fiber remains a challenging goal due to exponential attenuation of transmitted signals. Quantum repeaters [4–6] overcome the exponential time overhead associated with fiber attenuation and other errors by using a quantum memory and local quantum computation.

Several promising avenues for quantum repeater implementation include both atomic ensembles [7] and using few qubit quantum computers, such as neutral atoms in cavity QED [8,9], ion traps [10], and solid-state single photon emitters [11]. Experimental progress [12–14] towards realization of the Duan-Lukin-Cirac-Zoller (DLCZ) protocol [7] has been especially rapid, with many building blocks demonstrated in the laboratory. The experimental challenge is now shifting towards the realization of scalable quantum repeater systems which could yield a reasonable communication rate at continental distances ( $\geq 1000$  km). Thus the DLCZ protocol should be examined and adapted to practical experimental considerations, allowing one to remove imperfections such as the finite efficiency of retrieval and single-photon detection and fiber length fluctuations. Our approach extends the DLCZ protocol, keeping the experimental simplicity of the original scheme while avoiding fundamental difficulties due to these expected experimental imperfections.

This paper is organized as follows. In Sec. II we will review the DLCZ protocol and describe our approach which uses a basis to encode each qubit. Section III compares both the DLCZ protocol and our approach in the presence of imperfections. Section IV estimates the time scaling of our approach and compares three specific implementations. Section V summarizes our results.

## II. ATOMIC-ENSEMBLE-BASED QUANTUM REPEATERS

### A. DLCZ protocol: Review

The DLCZ protocol [7] starts with entanglement generation (ENG) by counting the interfering Stokes photons scattered from a pair of distant atomic cells  $x$  and  $y$ . This generates an entangled state

$$|\xi_\phi\rangle_{x,y} = (\hat{S}_x^\dagger + e^{i\phi}\hat{S}_y^\dagger)/\sqrt{2}|\text{vac}\rangle_{x,y}, \quad (1)$$

with  $\hat{S}_x^\dagger$  and  $\hat{S}_y^\dagger$  the creation operators of spin-wave modes in the two cells, respectively, and  $\phi$  the phase difference between left and right channels for Stokes photons [15]. Then, entanglement connection (ENC) is performed on two pairs of entangled atomic cells  $|\xi_{\phi_1}\rangle_{x_L,y_C}$  and  $|\xi_{\phi_2}\rangle_{x_C,y_R}$ , obtaining a further separated entangled pair  $|\xi_{\phi_1+\phi_2}\rangle_{x_L,y_R}$  probabilistically. The ENC step provides built-in purification against many imperfections—photon loss, atomic excitation loss, and dark counts. In the final step, postselection is used to obtain an effectively *polarization entangled state*

$$|\Psi^{PME}\rangle = e^{i\phi}(\hat{S}_{x_1}^\dagger\hat{S}_{y_2}^\dagger + \hat{S}_{x_2}^\dagger\hat{S}_{y_1}^\dagger)/\sqrt{2}|\text{vac}\rangle \quad (2)$$

from two parallel pairs  $|\xi_\phi\rangle_{x_1,y_1}|\xi_\phi\rangle_{x_2,y_2}$ , which overcome static phase errors (time independent  $\phi$ 's).

There are two important merits of the DLCZ protocol. First, it has intrinsic purification of errors due to photon loss (in the fiber, the quantum memory, and the photon detector) and significantly relaxes the experimental requirement for quantum repeater. In addition, the time scaling of the DLCZ protocol is always subexponential and very close to polynomial when the retrieval and detection efficiency is high. However, the DLCZ protocol does not purify all kinds of errors. For example, time dependent  $\phi$ 's (due to fiber length fluctuation) induce phase error, which cannot be taken out as a common factor in Eq. (2), since the two pairs of entangled atomic cells are not produced at the same time. Such a phase error is accumulated and doubled after each level of ENC. In addition, combined photon loss during ENG and ENC may also induce a phase error not purified by the DLCZ protocol.

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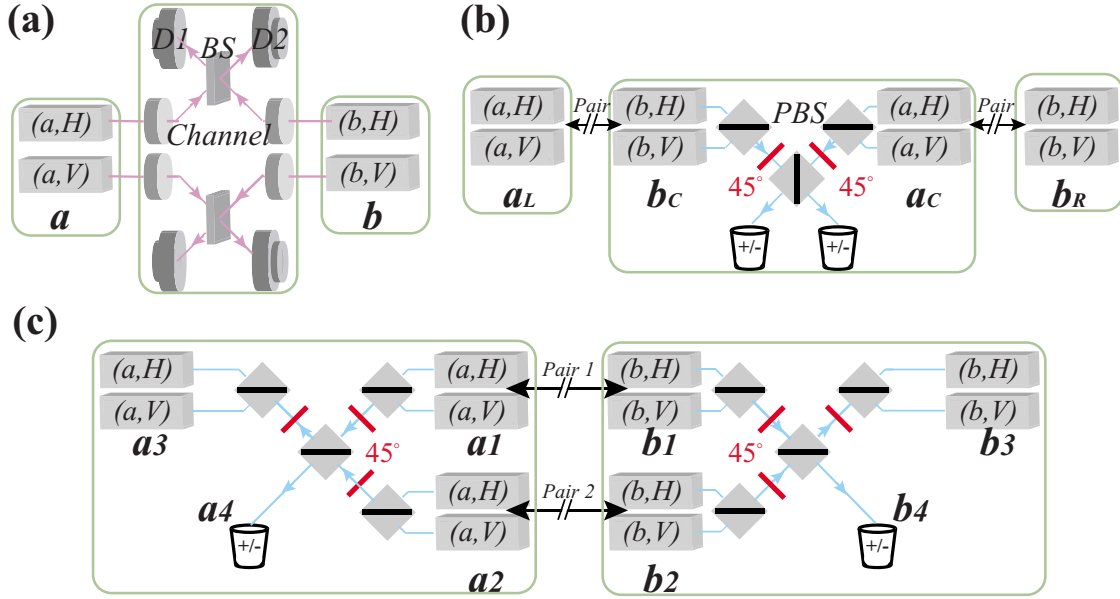


FIG. 1. (Color online) Repeater components: (a) entanglement generation (ENG) and (b) entanglement connection (ENC); indicated operations: retrieve  $b_C$  and  $a_C$  (additional  $45^\circ$  rotations only for the first level), join on polarizing beam splitter (PBS), detect in  $\pm$  basis conditioned on one photon per output, and finally adjust the phase. (c) Entanglement purification (ENP); indicated operations: retrieve  $a_1, b_1$  and  $a_2, b_2$  (additional  $45^\circ$  rotations to purify phase error), interfere  $a_1, a_2$  on PBS (same with  $b_1, b_2$ ), restore  $a_3, b_3$  conditioned on single photon at  $a_4$  and  $b_4$  respectively, and finally adjust the phase.

Furthermore, the DLCZ protocol (dashed line in Fig. 2) still has a significant time overhead for long distances because of the superpolynomial scaling in the presence of realistic imperfections. For instance, nonideal retrieval and detection efficiency ( $\eta \equiv \eta_{\text{retrieval}} \times \eta_{\text{detection}} < 1$ ) during ENC introduces a large vacuum component, suppresses the success probability of later ENC, and consequently slows down the protocol. Motivated by these issues, we will extend the DLCZ protocol, mitigating the above errors.

### B. Different approach

We now consider a different approach in which two atomic cells are used at each node  $a$ , labeled  $(a, H)$  and  $(a, V)$ , to store one qubit,  $a$ . The qubit is defined as one single spin-wave excitation shared between two cells:

$$\{|H\rangle_a = S_{a,H}^\dagger |\text{vac}\rangle, |V\rangle_a = S_{a,V}^\dagger |\text{vac}\rangle\}. \quad (3)$$

When the stored spin waves are converted back into photons, the photons have a polarization ( $H$  or  $V$ ) consistent with that stored in the originating cell. This qubit basis allows projective measurements along any qubit states, e.g.,  $|\pm\rangle \equiv (|H\rangle_a \pm |V\rangle_a) / \sqrt{2}$ , using linear optical operations and photon counting [16]. We will show that in this logical basis it is possible to perform entanglement purification (ENP) [6] to reduce errors within the logical subspace, including phase fluctuation. Since ENP can suppress errors within the logical subspace which occur with probability  $q$  to  $O(q^2)$ , only a few ENP levels are needed to obtain high fidelity entanglement.

We now describe our procedures for ENG, ENC, and ENP. ENG [Fig. 1(a)] is similar to that of the DLCZ protocol, but here *two* parallel entangled pairs are generated between  $a$  and  $b$ :

$$\begin{aligned} |\Psi^{ENG}\rangle_{a,b} &= |\xi_\phi\rangle_{(a,H)(b,H)}^\dagger |\xi_\phi\rangle_{(a,V)(b,V)}^\dagger \\ &= e^{i\phi} (|H\rangle_a |V\rangle_b + |V\rangle_a |H\rangle_b) + |HV\rangle_a |\text{vac}\rangle_b \\ &\quad + e^{2i\phi} |\text{vac}\rangle_a |HV\rangle_b. \end{aligned} \quad (4)$$

The entangled states are prepared in the quantum memory, so no simultaneity is required for creating the two states comprising  $|\Psi^{ENG}\rangle$ . For small excitation probability  $p_c$ , the whole generation only takes time  $O(1/p_c)$ , in contrast to  $O(1/p_c^2)$  for schemes requiring simultaneity, e.g., coupling between a trapped atom and photon [10] or parametric down conversion [17]. Errors from multiphoton events occur only with probability  $p_c^2$ , and are considered in a later analysis of imperfections.

The first level of ENC converts two  $|\Psi^{ENG}\rangle$  states (one between  $a_L$  and  $b_C$ , the other between  $a_C$  and  $b_R$ ) into polarization entangled states  $|\Phi^\pm\rangle_{ab} = |H\rangle_{a_L} |H\rangle_{b_R} + |V\rangle_{a_L} |V\rangle_{b_R}$ . Only 4 out of the 16 terms in the Schmidt decomposition of  $|\Psi^{ENG}\rangle_{a_L b_C} |\Psi^{ENG}\rangle_{a_C b_R}$  have any contribution to the output state; the remainder are eliminated by projective measurement during ENC, reducing the probability of success for ENC from 1/2 to 1/8. At higher levels of ENC, the operations correspond to standard entanglement swapping [4,5], where

$$|\Phi^\pm\rangle_{a_L b_C} \otimes |\Phi^\pm\rangle_{a_C b_R} \rightarrow |\Phi^\pm\rangle_{a_L b_R}$$

leads to an entangled pair between  $L$  and  $R$  with probability 1/2, as detailed below.

The procedure for ENC is illustrated in Fig. 1(b). First, the spin waves stored in qubit  $b_C$  and  $a_C$  are retrieved into photons. At the lowest level of ENC, the polarization of the

TABLE I. Entanglement connection procedure applied to  $|\Phi^\pm\rangle$  inputs for entangled pairs between  $a_L$  and  $b_C$ , and  $a_C$  and  $b_R$ . For clarity, we introduce  $|0\rangle \equiv |H\rangle$  and  $|1\rangle \equiv |V\rangle$  to represent logical states (i.e., states with exactly one excitation),  $|HV\rangle$  for nonlogical states with two excitations, and  $|\text{vac}\rangle$  for states with no excitation (sometimes omitted). We assume  $H$  photons pass through and  $V$  photons are reflected at the middle PBS.

| Operation                             | Transform of $ \Phi^\pm\rangle_{a_L b_C}  \Phi^\pm\rangle_{a_C b_R}$  |
|---------------------------------------|---|
| Retrieve<br>$b_C, a_C$                | $ 0000\rangle \pm  0011\rangle \pm  1100\rangle +  1111\rangle$   |
| Transform<br>$b_C, a_C$ at PBS        | $ 0000\rangle +  1111\rangle$<br>$\pm  0\rangle_{a_L} ( HV\rangle_{a_C})  1\rangle_{b_R}$<br>$\pm  1\rangle_{a_L} ( HV\rangle_{b_C})  0\rangle_{b_R}$ |
| One photon<br>per mode<br>( $p=0.5$ ) | $ 0000\rangle +  1111\rangle$   |
| Detect in $\pm$ ,<br>results $m, m'$  | $ 00\rangle_{a_L b_R} + mm'  11\rangle_{a_L b_R}$   |
| Phase shift<br>$mm'$                  | $ \Phi^\pm\rangle_{a_L b_R}$  |

photons is rotated  $45^\circ$ . The rotations transform  $|HV\rangle_{a_C(\text{or } b_C)}$  into  $(|HH\rangle - |VV\rangle)_{a_C(\text{or } b_C)}$ , because for bosonic fields [18]

$$S_H^\dagger S_V^\dagger \xrightarrow{45^\circ} (S_H^\dagger + S_V^\dagger)(S_H^\dagger - S_V^\dagger) = (S_H^\dagger S_H^\dagger - S_V^\dagger S_V^\dagger).$$

Thus after the polarizing beam splitter (PBS) there will be at least two photons at one output. For incoming state  $|\Psi^{ENG}\rangle_{a_L b_C} \otimes |\Psi^{ENG}\rangle_{a_C b_R}$ , all seven terms containing two excitations in at least one pair of cells in the center repeater node (such as  $|HV\rangle_{a_C(\text{or } b_C)}$ ) do not contribute to the click patterns with one photon at each output. Five terms containing two excitations in one of the left or right repeater nodes [e.g.,  $|HV\rangle_{a_L(\text{or } b_R)}$ ] have at most one excitation retrieved from  $b_C$  and  $a_C$ , which is insufficient to give two clicks. Therefore only the four terms remaining can give the correct photon detector click patterns.

For all levels of ENC, the photons are then joined on the middle PBS and the number of photons at two outputs are counted in the  $\{|+\rangle, |-\rangle\}$  basis. With probability 50%, there is one photon at each output, and the connection is successful; otherwise the process is repeated. If the two photons have orthogonal polarizations, a bit flip  $\alpha|H\rangle + \beta|V\rangle \rightarrow \alpha|V\rangle + \beta|H\rangle$  is applied to  $a_L$  [19]. At higher levels of ENC, where the  $45^\circ$  rotations are not necessary, the bit flip is replaced by the phase flip  $\alpha|H\rangle + \beta|V\rangle \rightarrow \alpha|H\rangle - \beta|V\rangle$ , as detailed in Table I [20].

The third component is ENP [Fig. 1(c)] which obtains a high fidelity entangled pair from two pairs. Our procedure uses polarization entangled photons and is similar to recent experimental investigations [17]. During entanglement puri-

TABLE II. Bit entanglement purification acting on  $|\Phi^\pm\rangle|\Psi^\pm\rangle$ . The same notation as Table I is used. For such given input states, the click pattern never matches the right pattern, and bit-error of a single input qubit can be filtered completely. The remaining steps to preserve the desired Bell states are detection of  $a_4, b_4$  in  $\pm$  basis, a phase shift  $n \cdot n'$  based on the measurement results, and storing of the traveling photons ( $a_3, b_3$ ) into atomic ensembles.

| Operation   | Transform of $ \Phi^n\rangle_{a_1 b_1}  \Psi^{n'}\rangle_{a_2 b_2}$   |
|---|---|
| Retrieve<br>$a_1 b_1, a_2 b_2$                          | $ 0001\rangle + n  1101\rangle + n'  0010\rangle + nn'  1110\rangle$  |
| Interfere $a_1, a_2$<br>on PBS; same<br>with $b_1, b_2$ | $ 00\rangle_{a_3 a_4} ( HV\rangle_{b_4})$<br>$+ n ( HV\rangle_{a_3})  11\rangle_{b_3 b_4}$<br>$+ n' ( HV\rangle_{a_4})  00\rangle_{b_3 b_4}$<br>$+ nn'  11\rangle_{a_3 a_4} ( HV\rangle_{b_3})$ |
| One photon<br>per lower<br>output                       | <b>0</b>  |

fication of bit errors (bit-ENP), the qubits from two parallel pairs  $\rho_{a_1, b_1}$  and  $\rho_{a_2, b_2}$  are retrieved from the quantum memory and joined at PBSs. The photons for two upper outputs are stored into quantum memory  $a_3$  and  $b_3$ . The photons for the lower outputs  $a_4$  and  $b_4$  are counted in  $\{|+\rangle, |-\rangle\}$  basis. With probability 50%, there is exactly one photon at each lower output, and the purification is successful; otherwise two new pairs are created by restarting the process. If the two photons have orthogonal polarizations, a phase flip is applied to  $a_3$ . An example of purification of bit-error is presented in Table II. During purification of phase errors (phase-ENP), additional  $45^\circ$  rotations are applied to the retrieved qubits and the bit flip is replaced by the phase flip. The addition of  $45^\circ$  rotations effects the basis transform  $|\Phi^-\rangle \leftrightarrow |\Psi^+\rangle$ , leading to purification of errors of the other type. The truth table of phase-ENP is listed in Table III. Bit (or phase) errors can be nonlinearly suppressed to the second order during bit-ENP (or phase-ENP) [21].

The three components described above for the quantum repeater protocol only use atomic cells, linear optics, and photon number counting. We remark that the duration of the retrieved anti-Stokes pulse can be made long ( $\geq 1 \mu\text{s}$ ) compared to the detector recovery time by adjusting the intensity and duration of the retrieval pulse. This enables photon number counting of the anti-Stokes pulse [22].

TABLE III. Truth table for phase-ENP. Each element gives the possible output state after the purification operation. (“—” for cases with no outputs.)

| $\rho_{a_1, b_1} \setminus \rho_{a_2, b_2}$ | $\Phi^+$ | $\Phi^-$ | $\Psi^+$ | $\Psi^-$ |
|---|----------|----------|----------|----------|
| $\Phi^+$                                    | $\Phi^+$ | —        | $\Psi^+$ | —        |
| $\Phi^-$                                    | —        | $\Phi^-$ | —        | $\Psi^-$ |
| $\Psi^+$                                    | $\Psi^+$ | —        | $\Phi^+$ | —        |
| $\Psi^-$                                    | —        | $\Psi^-$ | —        | $\Phi^-$ |

### III. NOISE AND IMPERFECTIONS

#### A. Nonlogical errors

We now examine the performance of our new scheme by considering the role of errors, starting with how imperfections due to inefficiency limit the protocols. Primarily, we find that inefficiency takes logical states into two types of nonlogical states—those with too few excitations (*vacuum* type) and those with too many excitations (*multiexcitation* type). We represent these errors by density matrix  $\pi_{vac}$  (a mixed state with at most one excitation between both pairs of cells) or  $\pi_{multi}$  (a mixed state with at least one pair of cells with more than one excitation). The normalized density matrix after  $m$ th ENC [Fig. 1(b)] can be written as

$$\rho_{a_L, b_R}^{(m)} = p_{logic}^{(m)} \rho_{logic}^{(m)} + p_{vac}^{(m)} \pi_{vac}^{(m)} + p_{multi}^{(m)} \pi_{multi}^{(m)}, \quad (5)$$

where the  $m$ -dependent operator  $\rho_{logic}^{(m)}$  is the density matrix within logical subspace;  $\pi_{vac}^{(m)}$  and  $\pi_{multi}^{(m)}$  also depend on  $m$ ; and the coefficients  $p_{logic}^{(m)}$ ,  $p_{vac}^{(m)}$ , and  $p_{multi}^{(m)}$  are the probabilities for the logical, vacuum, and multiexcitation types, respectively.

After the first level of ENC,  $p_{vac}^{(1)} \sim 1 - \eta$  and  $p_{multi}^{(1)} \sim p_c \ll 1$ . We can demonstrate that these three probabilities remain stable (see Appendix B) for all higher levels of ENC, by considering the unnormalized state after  $(m+1)$ th ENC for the new approach:  $\tilde{\rho}_{a,b}^{(m+1)} = \tilde{p}_{logic}^{(m+1)} \rho_{logic}^{(m+1)} + \tilde{p}_{vac}^{(m+1)} \pi_{vac}^{(m+1)} + \tilde{p}_{multi}^{(m+1)} \pi_{multi}^{(m+1)}$ , with

$$\tilde{p}_{logic}^{(m+1)} \approx \frac{1}{2} \eta p_{logic}^{(m)} p_{logic}^{(m)} [1 + p_{err, new}^{(m+1)} + O(p_c)],$$

$$\tilde{p}_{vac}^{(m+1)} \approx \frac{1}{2} \eta p_{logic}^{(m)} p_{vac}^{(m)} [1 + O(p_c)],$$

$$\tilde{p}_{multi}^{(m+1)} \approx \frac{1}{2} \eta p_{logic}^{(m)} p_{multi}^{(m)} [1 + O(p_c)],$$

where the probability for the new logical error from the multiexcitation states (accompanied by photon loss) is

$$p_{err, new}^{(m+1)} \sim (1 - \eta) p_c.$$

The total logical error probability  $p_{err}^{(m+1)}$  has two contributions: the accumulated logical errors from both input pairs for ENC,  $p_{err}^{(m)}$ , and the new logical error

$$p_{err}^{(m+1)} - 2p_{err}^{(m)} \sim (1 - \eta) p_c. \quad (6)$$

We can calculate for the new scheme,

$$p_{err}^{(m)} \sim (2^m - 1)(1 - \eta) p_c. \quad (7)$$

A more detailed calculation (see Appendix B), in which  $\pi_{vac}$  and  $\pi_{multi}$  are further divided into subspaces with a different number of excitations (e.g.,  $\pi_{vac}$  is subdivided into zero-excitation and one-excitation subspaces) verifies the stability of the probability distribution of  $p_{logic}^{(m)}$ ,  $p_{vac}^{(m)}$ , and  $p_{multi}^{(m)}$ . [Similarly, dark count can also induce errors in logical subspace with probability  $\sim p_{dark}(1 - \eta_s)$ , which is, however, negligible due to very low dark count probability  $p_{dark}$ .]

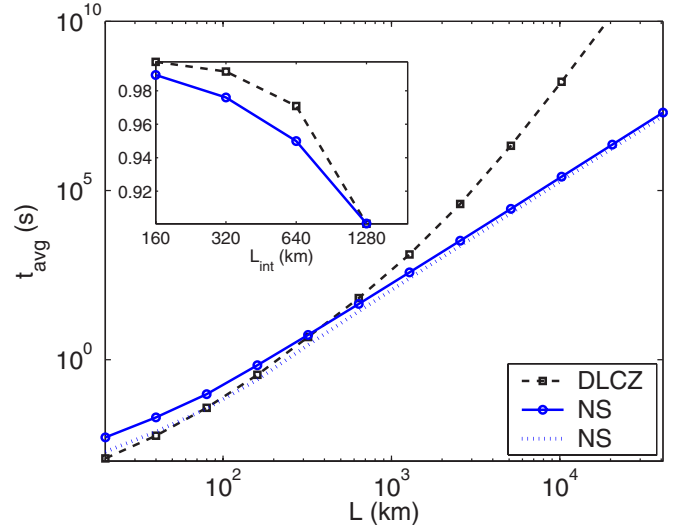


FIG. 2. (Color online) Comparison between the DLCZ protocol and the new scheme (NS) [without active entanglement purification (ENP)]. For each distance, we optimize over the choice of the control parameters (the half distance between neighboring repeater stations,  $L_0$ , and the elementary pair generation probability,  $p_c$ ). With efficiency  $\eta=90\%$  and targeting fidelity  $F=90\%$ , we find the most efficient implementations to create the polarization entangled state [Eq. (2)] for both the DLCZ (circled black dashed line) and the new scheme (squared blue solid line). The fiber attenuation length is  $L_{att}=20$  km, with no dynamical phase error. The main plot: we show the relationship between the (optimized) average creation time  $t_{avg}$  and the final distance  $L$  for both schemes, and the empirical estimate [Eq. (11)] of the time scaling for the new scheme (blue dotted line). Over long distances ( $L \geq 320$  km), the polynomial scaling of the new scheme is more favorable than the superpolynomial scaling of the DLCZ protocol. Inset: we plot the fidelities of the intermediate distances ( $L_{int}=160, 320, 640,$  and  $1280$  km) to create polarization entangled states ( $L=1280, F=90\%$ ), with the optimized choice of the control parameters  $(L_0, p_c)=(80, 0.0027)$  and  $(40, 0.0081)$  for the DLCZ ( $t_{avg} \approx 1900$  s) and the new scheme ( $t_{avg} \approx 380$  s), respectively. The optimized choices of the control parameters are detailed in Tables IV and V.

For the DLCZ protocol, only two cells are used to store entanglement. Besides the logical states (single excitation in two cells), we can similarly define the vacuum states (with no excitation) and multiexcitation states (with two or more excitations). Contrary to our approach, the probability distribution is not stable—both vacuum and multiexcitation probabilities increase with distance (see Appendix A). The vacuum probability soon becomes the dominant term, which reduces the success probability of ENC significantly, resulting in superpolynomial (but still subexponential) time scaling (Fig. 2). The logical error probability for the DLCZ protocol has the same form as Eq. (6) up to the coefficient, but the ratio  $p_{multi}^{(m)}/p_{logic}^{(m)}$  (thus  $p_{err}^{(m)}$ ) grows with distance (see Appendix A), which accounts for the sharp decrease of fidelity for the DLCZ protocol (see inset of Fig. 2). To maintain good final fidelity, the initial error  $p_{multi}^{(1)}$  (and  $p_c$ ) should be very small, which demands longer generation time of an elementary pair for the DLCZ protocol.

In essence, by requiring at least one excitation in the ensemble, our qubit subspace is automatically purified of

TABLE IV. This table provides detailed information for Fig. 2. With efficiency  $\eta=90\%$ , targeting fidelity  $F=90\%$ , and fiber attenuation length  $L_{att}=20$  km, the minimized average time  $t_{avg}$  and optimized control parameters  $(L_0, p_c)$  are listed with respect to various final distances for the DLCZ protocol.

|               |        |        |       |       |       |       |                      |                      |                      |                      |
|---------------|--------|--------|-------|-------|-------|-------|----------------------|----------------------|----------------------|----------------------|
| $L$ (km)      | 20     | 40     | 80    | 160   | 320   | 640   | 1280                 | 2560                 | 5120                 | 10240                |
| $t_{avg}$ (s) | 0.0013 | 0.0065 | 0.046 | 0.44  | 5.8   | 95    | 1900                 | $5.7 \times 10^4$    | $3.0 \times 10^6$    | $3.0 \times 10^8$    |
| $L_0$ (km)    | 10     | 20     | 40    | 40    | 40    | 80    | 80                   | 80                   | 80                   | 80                   |
| $p_c$         | 0.26   | 0.18   | 0.13  | 0.040 | 0.011 | 0.010 | $2.7 \times 10^{-3}$ | $7.1 \times 10^{-4}$ | $1.8 \times 10^{-4}$ | $4.6 \times 10^{-5}$ |
| $F_{fin}$     | 90%    | 90%    | 90%   | 90%   | 90%   | 90%   | 90%                  | 90%                  | 90%                  | 90%                  |

vacuum and multiexcitation type errors during ENC. The closest analog to the DLCZ protocol is our new scheme without ENP, i.e., only ENC. At longer distances, our approach is further improved in comparison to the DLCZ protocol due to the reduced amplitude of vacuum terms.

### B. Logical errors

So far, we have only considered the effects of inefficiency that maps states between logical and nonlogical subspace by changing the number of excitations. Besides inefficiency, there are other imperfections which preserve the number of excitations but induce errors within the logical subspace, such as interferometric path length fluctuation and linear optical misalignment. For example, the interferometric path length fluctuation leads to a phase difference  $\delta$ , which changes  $|\Psi^{ENG}\rangle_{a,b}$  into a mixture:

$$|\Psi^{ENG}\rangle_{a,b} \rightarrow e^{i\phi}(|H\rangle_a|V\rangle_b + e^{i\delta}|V\rangle_a|H\rangle_b) + |HV\rangle_a|\text{vac}\rangle_b + e^{2i\phi+i\delta}|\text{vac}\rangle_a|HV\rangle_b, \quad (8)$$

where  $\phi$  is the static phase difference between the left and right channels. Since the last two terms with  $|HV\rangle$  will be removed during the first level of ENC, the static phase  $\phi$  has no effect. However, the probability of being in an undesired logical state  $|\Psi^-\rangle$  is  $\sin^2 \frac{\delta}{2}$ . The first level of ENC with the combined two inputs of  $\Psi^-$  and  $\Psi^+$  gives  $\Phi^-$ , producing a phase error with probability  $2p_{\text{phase-err}} = 2\langle \sin^2 \frac{\delta}{2} \rangle$ , proportional to the variance of the interferometric phase fluctuation. This error will be amplified during subsequent ENCs because the survival probability of the state  $\Phi^-$  (the logical error) is twice as much as that of  $\Phi^+$  (the desired component).

We expect that there is little correlation in phase fluctuation between different sections of the fiber, and the variance of the phase fluctuation is proportional to the length of the fiber

TABLE V. This table provides detailed information for Fig. 2. With efficiency  $\eta=90\%$ , targeting fidelity  $F=90\%$ , and fiber attenuation length  $L_{att}=20$  km, the minimized average time  $t_{avg}$  and optimized control parameters  $(L_0, p_c)$  are listed with respect to various final distances for the new scheme.

|               |        |       |      |       |       |       |                      |                      |                      |                      |
|---------------|--------|-------|------|-------|-------|-------|----------------------|----------------------|----------------------|----------------------|
| $L$ (km)      | 20     | 40    | 80   | 160   | 320   | 640   | 1280                 | 2560                 | 5120                 | 10240                |
| $t_{avg}$ (s) | 0.0051 | 0.020 | 0.10 | 0.68  | 5.4   | 45    | 380                  | $3.3 \times 10^3$    | $2.9 \times 10^4$    | $2.6 \times 10^5$    |
| $L_0$ (km)    | 5      | 10    | 20   | 40    | 40    | 40    | 40                   | 40                   | 40                   | 40                   |
| $p_c$         | 0.26   | 0.17  | 0.11 | 0.087 | 0.037 | 0.017 | $8.1 \times 10^{-3}$ | $4.0 \times 10^{-3}$ | $2.0 \times 10^{-3}$ | $9.7 \times 10^{-4}$ |
| $F_{fin}$     | 90%    | 90%   | 90%  | 90%   | 90%   | 90%   | 90%                  | 90%                  | 90%                  | 90%                  |

$$\langle \delta^2 \rangle = 2DL_0, \quad (9)$$

where  $D$  is the phase diffusion coefficient of the fiber. If the phase fluctuation satisfies Gaussian distribution, the phase error probability

$$p_{\text{phase-err}} = \left\langle \sin^2 \frac{\delta}{2} \right\rangle = \frac{1}{2}(1 - e^{-DL_0}). \quad (10)$$

For example,  $D=10^{-3}$  rad<sup>2</sup>/km,  $L_0=10$  km, and  $p_{\text{phase-err}} \approx 0.5\%$ .

Also, a small probability ( $p_{\text{err}}$ ) of linear optical misalignment per ENC or ENP step is modeled as depolarizing errors. Later, we will demonstrate that errors within the logical subspace restrict the final fidelity of the DLCZ protocol, while for our new approach additional active purification can correct such logical errors to achieve high fidelity.

## IV. SCALING AND TIME OVERHEAD FOR QUANTUM REPEATER

### A. Scaling analysis

Based on the calculation of the success probability at each level of connection-purification, we can obtain the estimated average time for various schemes. In Fig. 2, we compare our approach to the DLCZ protocol (see Tables IV and V). For the DLCZ protocol, the average creation time for a distant pair contains a superpolynomial contribution (but still subexponentially) with distance, due to instability of the vacuum component. For our new scheme, the scaling is strictly polynomial with distance  $t_{avg} \propto L^\alpha$ , where the exponent  $\alpha = \alpha(\eta)$  explicitly depends on the efficiency.

We remark that the DLCZ protocol is slightly more efficient for short final distances ( $L \leq 160$  km). The DLCZ protocol can skip the entanglement connection and exploits postselection to create the polarization entangled state, while the new scheme requires the first level of ENC to eliminate

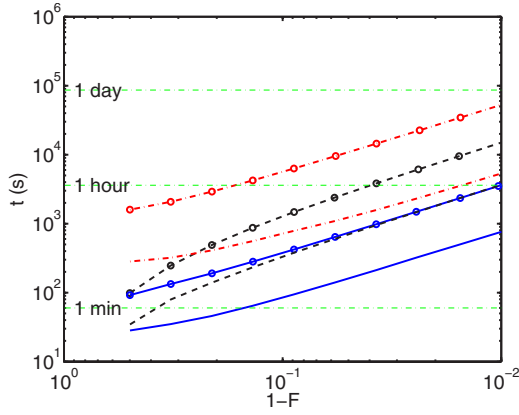


FIG. 3. (Color online) Average time versus final fidelity with no phase errors. For fixed final distance  $L=1280$ , we plot the (final) fidelity dependence of the (optimized) average pair creation time, for the DLCZ protocol (black dashed lines), new scheme without ENP (blue solid lines), and new scheme with ENP (red dashdotted lines), with efficiency  $\eta$  to be 90% (circles), and 95% (no circles).

those unwanted components and prepare the polarization entangled state. The postselection has success probability  $1/2$ , two times more efficient than the success probability  $1/4$  for the first level of ENC of the new scheme.

For the new scheme (without ENP), we can use the stable probability distribution to estimate the average time:

$$t_{avg} = t_0(L/L_0)^{\log_2\{1.5[2(2-\eta)^4/\eta^2(3-2\eta)]\}}, \quad (11)$$

where  $t_0 = \frac{1}{p_c \eta} \frac{L_0}{c} e^{L_0/L_{att}}$  is the elementary pair generation time,  $p_c$  is the elementary pair generation probability,  $L_0$  is half the distance between neighboring repeater stations, and  $L$  is the final distance. The exponent can be understood as an overhead from the finite success probability for ENC,  $p_{ENC} \approx \frac{\eta^2(3-2\eta)}{2(2-\eta)^4}$ . The constant 1.5 in Eq. (11) is the empirical estimate of the overhead from the waiting time to obtain two independent pairs versus the single pair. In Fig. 2, the differences between the simulated data and Eq. (11) are attributed to the empirical factor (1.5) and an overall factor from the overestimate of the success probability for the first level of ENC. According to Eq. (7), one can always reach good final fidelity if the elementary pair generation probability  $p_c$  scales as  $L_0/L$ . Therefore the average distant pair generation time scales *exactly polynomially* with distance  $t_{avg} \propto L^\alpha$ , with  $\alpha = 1 + \log_2(1.5) + \log_2\left(\frac{2(2-\eta)^4}{\eta^2(3-2\eta)}\right)$ .

### B. Comparison between different schemes

Besides the DLCZ protocol and our new approach without ENP, we now consider a scheme with ENP, which has one phase-ENP after the second level of ENC. We may compare these schemes by using  $t$ - $F$  plots—a parametric plot of  $t_{avg}$  and  $F$  as a function of excitation probability  $p_c$ . For given noise model and efficiency  $\eta$ , a repeater scheme corresponds to a curve on the  $t$ - $F$  plane.

In the absence of interferometric path length fluctuation (Fig. 3), the new approach without ENP is about five times

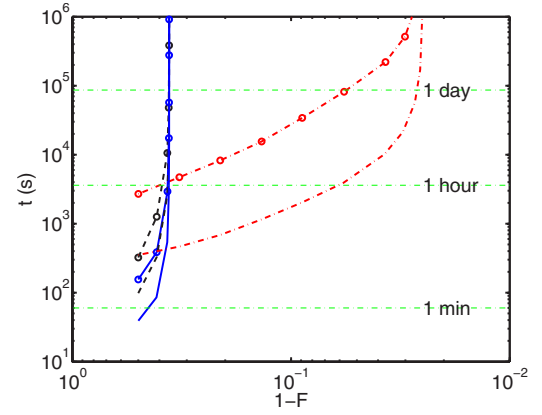


FIG. 4. (Color online) Average time versus final fidelity with phase errors. This shows the same optimized approaches as Fig. 3 but with finite interferometric path length fluctuation characterized by the phase diffusion coefficient  $D=10^{-3}$  rad<sup>2</sup>/km. Inclusion of ENP (red dash-dotted lines) yields a dramatic improvement in time for high fidelity operations.

faster than the DLCZ protocol, for  $\eta=90\%$ . As given by the previous discussion, this improvement is due to better control of inefficiency-induced imperfections. There is a time overhead for the new approach (with ENP) as compared to the new approach (without ENP). Within each implementation, the higher the efficiency  $\eta$ , the faster the quantum repeater. For high final fidelity ( $1-F \leq 10\%$ ), the curves approach straight lines with slope  $-1$  because  $t \propto p_c^{-1} \propto (1-F)^{-1}$ .

When interferometric path length fluctuation (leading to initial phase error) is non-negligible, active ENP is needed. We use a diffusion model for the path length fluctuation, as detailed in Sec. III B. In Fig. 4,  $t$ - $F$  curves are plotted, assuming the phase diffusion coefficient  $D=10^{-3}$  rad<sup>2</sup>/km, corresponding to  $p_{phase-err} \approx 0.5\%$  over  $L_0=10$  km. Unlike Fig. 3 where only inefficiency is considered, there is an upper bound in final fidelity for each implementation. Both the DLCZ protocol and new approach (without ENP) suffer from the initial phase error, with final fidelity no more than 65%, while the new approach with ENP maintains high final fidelity up to 97%. For high retrieval and detection efficiency ( $\eta=95\%$ ), the new approach (with ENP) can produce 1280 km entangled pairs with fidelity 90% at a rate of 2 pairs/h, even in the presence of substantial dynamical phase errors.

### V. OUTLOOK

In summary, our new approach to long distance quantum communication uses a different qubit basis which prevents the growth of vacuum and multiexcitation probabilities. This keeps the ENC success probability high and error probability low, and leads to true polynomial scaling even in the presence of realistic inefficiencies. We can achieve a bandwidth of 1 (or 2) entangled pair(s) per 6 min for  $F \approx 90\%$  (or 78%) and negligible initial phase error. The new approach also allows active entanglement purification, which combined

with built-in purification of transmission loss errors allows purification of arbitrary errors in quantum communication.

Although the present approach shows a dramatic improvement in communication rates and robustness compared to the original DLCZ protocol, the bandwidth remains relatively slow, even when very high efficiencies and very long-lived quantum memory are assumed. While such high efficiencies might ultimately be achievable (see Ref. [23] for recent progress), other approaches need to be considered that can further improve the effective communication bandwidth. For example, we can use many cells per node to improve the bandwidth. In this case, the improvement is at least linear with the number of cells, making it possible to realize long distance (1280 km) entangled state generation bandwidth of the order of one pair per second.

A simple Monte Carlo optimization of efficient use of the cells shows that we can increase the bandwidth by a factor of  $r=M^{1.12}$ , where  $M$  is the increment of the factor of physical resources. Recently, it has also been suggested that multiple cells can be used to further facilitate the quantum repeater, in the presence of memory errors from the quantum memory [24,25].

*Note added.* Since completion of this work, a work by Zhao *et al.* [26] describing a similar approach to improve the DLCZ protocol has appeared.

#### ACKNOWLEDGMENT

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#### APPENDIX

We now justify two main claims used in the previous discussion. (1) For the DLCZ protocol, the probability ratios  $p_{vac}^{(m)}/p_{logic}^{(m)}$  and  $p_{multi}^{(m)}/p_{logic}^{(m)}$  increase with the nesting level  $m$ . (2) For the new scheme (without ENP), the probability ratios  $p_{vac}^{(m)}/p_{logic}^{(m)}$  and  $p_{multi}^{(m)}/p_{logic}^{(m)}$  remain almost independent of the nesting level  $m$ . The states of logical, vacuum, and multiexcitation types depend on the repeater protocol. For example, the entangled logical state for the DLCZ protocol has a total of one excitation stored in two remotely entangled cells [e.g., Eq. (1)], while the entangled logical state for the new scheme has two excitations stored in four cells, with one excitation and two cells on each side [e.g., Eq. (2)]. Thus the definitions of  $p_{logic}^{(m)}$ ,  $p_{vac}^{(m)}$ , and  $p_{multi}^{(m)}$  are different for the two schemes.

#### APPENDIX A: NONLOGICAL STATES FOR DLCZ PROTOCOL

We start with the DLCZ protocol. First, we decompose the density matrix (for a pair of distant atomic cells  $x$  and  $y$ ) into components with different excitation patterns, neglecting the interpattern coherence

$$\rho_{x,y} = p_{00}\pi_{00} + p_{10}\pi_{10} + p_{11}\pi_{11} + p_{20}i_{20} + \dots, \quad (\text{A1})$$

where  $p_{ij}\pi_{ij}$  is the projected density matrix to the subspace spanned by the Fock states of the cells  $\{|i\rangle_x|j\rangle_y, |j\rangle_x|i\rangle_y\}$ , with

probability  $p_{ij}$  and normalized density matrix  $\pi_{ij}$ . For the DLCZ protocol, the vacuum type of state is  $\pi_{00}$ , the logical type of state is  $\pi_{10}$ , and the rest belong to the multiexcitation type. We may also introduce the notation corresponding to Eq. (5),

$$\rho_{x,y} = p_{logic}p_{logic} + p_{vac}\pi_{vac} + p_{multi}\pi_{multi} \quad (\text{A2})$$

with  $p_{vac}=p_{00}$ ,  $p_{logic}=p_{10}$ , and  $p_{multi}=p_{11}+p_{20}+\dots$ .

Since we are only interested in the coherence properties for the logical type  $\pi_{10}$ , we only keep track of the probabilities for the vacuum and multiexcitation types and neglect their coherences. From the symmetry for the two cells, we have

$$\pi_{ij} = \pi_{ji} \equiv \frac{1}{2}(|i\rangle_x\langle i| \otimes |j\rangle_y\langle j| + |j\rangle_x\langle j| \otimes |i\rangle_y\langle i|). \quad (\text{A3})$$

In the rest of this appendix, we will add a superscript to  $\pi_{ij}$  only when we want to keep track of the coherence for that specific term. For example,  $\pi_{10}^{(m)}$  indicates that there is coherence between the states  $|1\rangle_x|0\rangle_y$  and  $|0\rangle_x|1\rangle_y$  after the  $m$ th level of ENC.

Since the DLCZ protocol requires that the probability for the multiexcitation states should always be much smaller than the probability for the logical states (otherwise, a large fraction of multiexcitation states, accompanied by photon loss, can induce significant logical errors), we regard  $p_{11}^{(m)}$ ,  $p_{20}^{(m)}$  ( $\ll p_{10}^{(m)}$ ) as perturbations.

We denote the entangled state after the  $m$ th ENC as

$$\rho_{x,y}^{(m)} = p_{00}^{(m)}\pi_{00} + p_{10}^{(m)}\pi_{10} + p_{11}^{(m)}\pi_{11} + p_{20}^{(m)}\pi_{20} + \dots \quad (\text{A4})$$

We now connect two such entangled states  $\rho_{x_L,y_L}^{(m)}$  and  $\rho_{x_R,y_R}^{(m)}$  for the  $(m+1)$ th ENC via the superoperator  $\mathcal{E}_{ENC}$ ,

$$\tilde{\rho}_{x_L,y_R}^{(m+1)} = \mathcal{E}_{ENC}[\rho_{x_L,y_L}^{(m)}, \rho_{x_R,y_R}^{(m)}], \quad (\text{A5})$$

where  $\tilde{\rho}_{x_L,y_R}^{(m+1)}$  is the unnormalized density matrix for the entangled state after the  $(m+1)$ th ENC. Since  $\mathcal{E}_{ENC}$  is a linear operator and two inputs have the same state,

$$\mathcal{E}_{ENC}\left[\sum_{\alpha} p_{\alpha}\pi_{\alpha}, \sum_{\beta} p_{\beta}\pi_{\beta}\right] = \sum_{\alpha,\beta} p_{\alpha}p_{\beta}\mathcal{E}_{ENC}^{\text{sym}}[\pi_{\alpha}, \pi_{\beta}], \quad (\text{A6})$$

where  $\mathcal{E}_{ENC}^{\text{sym}}[\pi_{\alpha}, \pi_{\beta}] \equiv \frac{1}{2}\mathcal{E}_{ENC}[\pi_{\alpha}, \pi_{\beta}] + \frac{1}{2}\mathcal{E}_{ENC}[\pi_{\beta}, \pi_{\alpha}]$ . Now we calculate

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{\alpha}, \pi_{\beta}]$$

for

$$\pi_{\alpha}, \pi_{\beta} \in \{\pi_{00}, \pi_{10}^{(m)}, \pi_{11}, \pi_{20}, \dots\}.$$

For example,

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{10}^{(m)}, \pi_{10}^{(m)}] = \frac{\eta}{2}\pi_{10}^{(m+1)} + \frac{\eta(1-\eta)}{2}\pi_{00}, \quad (\text{A7a})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{10}^{(m)}, \pi_{00}] = \frac{\eta}{2}\pi_{00}, \quad (\text{A7b})$$



$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{10}^{(m)}, \pi_{11}] = \frac{\eta}{2} \pi_{11} + \eta(1-\eta) \pi_{10}, \quad (\text{A7c})$$

$$\begin{aligned} \mathcal{E}_{ENC}^{\text{sym}}[\pi_{10}^{(m)}, \pi_{20}] &= \frac{\eta}{4} \pi_{20} + \frac{\eta(1-\eta)}{2} \pi_{10} \\ &+ \frac{3\eta(1-\eta)^2}{4} \pi_{00}, \end{aligned} \quad (\text{A7d})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{00}, \pi_{00}] = 0, \quad (\text{A7e})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{00}, \pi_{11}] = \eta \pi_{10}, \quad (\text{A7f})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_0, \pi_{20}] = \eta(1-\eta) \pi_{00}. \quad (\text{A7g})$$

The logical type of state after the  $(m+1)$ th ENC,  $\pi_{10}^{(m+1)}$ , is the average of the states  $\pi_{10}^{(m+1)'}$  and  $\pi_{10}$ , with relative weights  $\frac{\eta}{2} p_{10}^{(m)} p_{10}^{(m)}$  and  $2\eta(1-\eta) p_{10}^{(m)} p_{11}^{(m)} + \eta(1-\eta) p_{10}^{(m)} p_{20}^{(m)} + 2\eta p_{00}^{(m)} p_{11}^{(m)}$ , respectively.

Then we calculate the (unnormalized) density matrix after the  $(m+1)$ th ENC,

$$\begin{aligned} \tilde{\rho}_{x_L, y_R}^{(m+1)} &= \tilde{p}_{00}^{(m+1)} \pi_{00} + \tilde{p}_{10}^{(m+1)} \pi_{10}^{(m+1)} + \tilde{p}_{11}^{(m+1)} \pi_{11} \\ &+ \tilde{p}_{20}^{(m+1)} \pi_{20} + \dots, \end{aligned} \quad (\text{A8})$$

with the probability coefficients

$$\tilde{p}_{00}^{(m+1)} \approx \eta p_{10}^{(m)} \left( p_{00}^{(m)} + \frac{(1-\eta)}{2} p_{10}^{(m)} \right), \quad (\text{A9a})$$

$$\tilde{p}_{10}^{(m+1)} \approx \frac{\eta}{2} p_{10}^{(m)} p_{10}^{(m)}, \quad (\text{A9b})$$

$$\tilde{p}_{11}^{(m+1)} \approx \eta p_{10}^{(m)} p_{11}^{(m+1)}, \quad (\text{A9c})$$

$$\tilde{p}_{20}^{(m+1)} \approx \frac{\eta}{2} p_{10}^{(m)} p_{20}^{(m+1)}, \quad (\text{A9d})$$

to the leading order with respect to the perturbations of  $p_{11}^{(m)}$  and  $p_{20}^{(m)}$ .

Finally, we divide these probabilities by  $\tilde{p}_{10}^{(m+1)}$ , and obtain

$$\frac{\tilde{p}_{00}^{(m+1)}}{\tilde{p}_{10}^{(m+1)}} \approx 2 \left( \frac{p_{00}^{(m)}}{p_{10}^{(m)}} + \frac{(1-\eta)}{2} \right) > 2 \frac{p_{00}^{(m)}}{p_{10}^{(m)}}, \quad (\text{A10a})$$

$$\frac{\tilde{p}_{11}^{(m+1)}}{\tilde{p}_{10}^{(m+1)}} \approx 2 \frac{p_{11}^{(m)}}{p_{10}^{(m)}}, \quad (\text{A10b})$$

$$\frac{\tilde{p}_{20}^{(m+1)}}{\tilde{p}_{10}^{(m+1)}} \approx \frac{p_{20}^{(m)}}{p_{10}^{(m)}}. \quad (\text{A10c})$$

Since the normalization does not change the relative ratio between the probabilities, the above perturbative estimate tells us that the fractions for both the vacuum state ( $\pi_{00}$ ) and

the multiexcitation state ( $\pi_{11}$ ) are at least doubled, relative to the logical state  $\pi_{10}^{(m+1)}$ , after each ENC.

In terms of the notation corresponding to Eq. (5) ( $p_{vac} = p_{00}$ ,  $p_{logic} = p_{10}$ , and  $p_{multi} = p_{11} + p_{20} + \dots$ ), we have

$$\frac{p_{vac}^{(m+1)}}{p_{logic}^{(m+1)}} = \frac{\tilde{p}_{00}^{(m+1)}}{\tilde{p}_{10}^{(m+1)}} > 2 \frac{p_{vac}^{(m)}}{p_{logic}^{(m)}}, \quad (\text{A11a})$$

$$\frac{\tilde{p}_{multi}^{(m+1)}}{\tilde{p}_{logic}^{(m+1)}} \approx 2 \frac{p_{multi}^{(m)}}{p_{logic}^{(m)}}. \quad (\text{A11b})$$

The ratio of nonlogical states to logical states is at least doubling with distance. As discussed in the main text, it is these unstable nonlogical states that leads to the superpolynomial scaling for the DLCZ protocol.

## APPENDIX B: NONLOGICAL STATES FOR NEW SCHEME

For the new scheme, we can similarly decompose the density matrix [following Eq. (5)]

$$\rho = p_{00} \pi_{00} + p_{10} \pi_{10} + p_{11} \pi_{11} + p_{20} \pi_{20} + p_{21} \pi_{21} + p_{30} \pi_{30} \dots, \quad (\text{B1})$$

where  $p_{ij} \pi_{ij}$  is the projected density matrix to the subspace spanned by the Fock states with  $i$  (or  $j$ ) photons in  $a$  cell-pair and  $j$  (or  $i$ ) photons in  $b$  cell-pair, with probability  $p_{ij}$  and normalized density matrix  $\pi_{ij}$ . For the new scheme, the vacuum type of states consists of  $\pi_{00}$  and  $\pi_{10}$ , the logical type of state is  $\pi_{11}$ , and the rest belong to the multiexcitation type.

We use a perturbative approach, by assuming  $p_{00} \pi_{00}$ ,  $p_{10} \pi_{10}$ , and  $p_{11} \pi_{11}$  are the dominant terms, and the rest terms are perturbations of order  $p_c$  (terms not listed are of order  $p_c^2$ ). We eliminate those irrelevant perturbation terms (e.g.,  $p_{30} \pi_{30}$ ) because after one level of ENC, they are suppressed to  $O(p_c^2)$ .

Suppose the entangled state after the  $m$ th ENC is

$$\begin{aligned} \rho_{a,b}^{(m)} &= p_{00}^{(m)} \pi_{00} + p_{10}^{(m)} \pi_{10} + p_{11}^{(m)} \pi_{11} + p_{20,\parallel}^{(m)} \pi_{20,\parallel} + p_{20,\perp}^{(m)} \pi_{20,\perp} \\ &+ p_{21,\parallel}^{(m)} \pi_{21,\parallel} + p_{21,\perp}^{(m)} \pi_{21,\perp} + \dots \end{aligned} \quad (\text{B2})$$

Notice that we need to distinguish two possible types of states for  $\pi_{20}$  because they behave differently during ENC. The first type of states (denoted as  $\pi_{20,\parallel}$ ) has both photons stored in the same cell, and after retrieval the photons will have the same polarization, follow the same path way, and trigger the photon detector(s) on the same side of the PBS [Fig. 1(b)]. The second type of state (denoted as  $\pi_{20,\perp}$ ) has two photons stored in different cells, and after the retrieval the photons will have orthogonal polarization, split at the PBS, and trigger photon detectors on both sides of the PBS [Fig. 1(b)]. Thus the second type of state is more likely to give the correct click pattern and thus propagate the error to the next level of ENC. Similarly, we introduce  $\pi_{21,\parallel}$  and  $\pi_{21,\perp}$ .

In the rest of the discussion, we still follow the convention from the previous appendix that  $\pi_{ij} = \pi_{ji}$  and we will add a superscript  $m$  to  $\pi_{ij}$  only when we want to keep track of the coherence for that specific term.

We now connect two such entangled states  $\rho_{a_L b_C}^{(m)}$  and  $\rho_{a_C b_R}^{(m)}$  for the  $(m+1)$ th ENC,

$$\tilde{\rho}_{a_L b_R}^{(m+1)} = \mathcal{E}_{ENC}[\rho_{a_L b_C}^{(m)} \rho_{a_C b_R}^{(m)}], \quad (\text{B3})$$

where  $\tilde{\rho}_{a_L b_R}^{(m+1)}$  is the unnormalized density matrix for the entangled state after the  $(m+1)$ th ENC.

Now we calculate

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_\alpha, \pi_\beta] \equiv \frac{1}{2} \mathcal{E}_{ENC}[\pi_\alpha, \pi_\beta] + \frac{1}{2} \mathcal{E}_{ENC}[\pi_\beta, \pi_\alpha]$$

for

$$\pi_\alpha, \pi_\beta \in \{\pi_{00}, \pi_{10}, \pi_{11}^{(m)}, \pi_{20, \parallel}(\text{or } \perp), \pi_{21, \parallel}(\text{or } \perp), \dots\}.$$

For example,

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{11}^{(m)}, \pi_{11}^{(m)}] = \frac{\eta^2}{2} \pi_{11}^{(m+1)}, \quad (\text{B4a})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{11}^{(m)}, \pi_{10}] = \frac{\eta^2}{4} \pi_{10}, \quad (\text{B4b})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{11}^{(m)}, \pi_{00}] = 0, \quad (\text{B4c})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{11}^{(m)}, \pi_{20, \delta}] = \eta^2(1 - \eta) \pi_{10}, \quad (\text{B4d})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{11}^{(m)}, \pi_{21, \delta}] = \frac{\eta^2}{4} \pi_{21, \delta} + \frac{\eta^2(1 - \eta)}{2} \pi_{11}, \quad (\text{B4e})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{10}, \pi_{10}] = \frac{\eta^2}{8} \pi_{00}, \quad (\text{B4f})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{10}, \pi_{00}] = 0, \quad (\text{B4g})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{10}, \pi_{21, \parallel}] = \frac{\eta^2(1 - \eta)}{4} \pi_{10} + \frac{\eta^2}{8} \pi_{20, \parallel}, \quad (\text{B4h})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{10}, \pi_{21, \perp}] = \frac{\eta^2}{4} \pi_{1, \perp} + \frac{\eta^2(1 - \eta)}{4} \pi_{10} + \frac{\eta^2}{8} \pi_{20, \perp}, \quad (\text{B4i})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{00}, \pi_{21, \parallel}] = 0, \quad (\text{B4j})$$

$$\mathcal{E}_{ENC}^{\text{sym}}[\pi_{00}, \pi_{21, \perp}] = \frac{\eta^2}{2} \pi_{10}. \quad (\text{B4k})$$

The logical type of state after the  $(m+1)$ th ENC,  $\pi_{11}^{(m+1)}$ , is the average of the states  $\pi_{11}^{(m+1) \prime}$  and  $\pi_{11}$ , with relative weights  $\frac{\eta^2}{2} p_{11}^{(m)} p_{11}^{(m)}$  and  $\eta^2(1 - \eta) p_{11}^{(m)} \sum_{\delta=\parallel, \perp} p_{21, \delta}^{(m)} + \frac{\eta^2}{2} p_{10}^{(m)} p_{21, \perp}^{(m)}$ , respectively.

Then we calculate the (unnormalized) density matrix after the  $(m+1)$ th ENC,

$$\begin{aligned} \tilde{\rho}_{a_L b_R}^{(m+1)} = & \tilde{p}_{00}^{(m+1)} \pi_{00} + \tilde{p}_{10}^{(m+1)} \pi_{10} + \tilde{p}_{11}^{(m+1)} \pi_{11}^{(m+1)} + \tilde{p}_{20, \parallel}^{(m+1)} \pi_{20, \parallel} \\ & + p_{20, \perp}^{(m+1)} \pi_{20, \perp} + p_{21, \parallel}^{(m+1)} \pi_{21, \parallel} + p_{21, \perp}^{(m+1)} \pi_{21, \perp} + \dots, \end{aligned} \quad (\text{B5})$$

with the probability coefficients

$$\tilde{p}_{00}^{(m+1)} \approx \frac{\eta^2}{8} p_{10}^{(m)} p_{10}^{(m)}, \quad (\text{B6a})$$

$$\tilde{p}_{10}^{(m+1)} \approx \frac{\eta^2}{2} p_{11}^{(m)} p_{10}^{(m)} [1 + O(p_c)], \quad (\text{B6b})$$

$$\tilde{p}_{11}^{(m+1)} \approx \frac{\eta^2}{2} \left( p_{11}^{(m)} p_{11}^{(m)} + p_{10}^{(m)} p_{21, \perp}^{(m)} + 2(1 - \eta) p_{11}^{(m)} (p_{21, \parallel}^{(m)} + p_{21, \perp}^{(m)}) \right), \quad (\text{B6c})$$

$$\tilde{p}_{20, \delta}^{(m+1)} \approx \frac{\eta^2}{4} p_{10}^{(m)} p_{21, \delta}^{(m)}, \quad (\text{B6d})$$

$$\tilde{p}_{21, \delta}^{(m+1)} \approx \frac{\eta^2}{2} p_{11}^{(m)} p_{21, \delta}^{(m)}. \quad (\text{B6e})$$

Finally, we divide these probabilities by  $\tilde{p}_{11}^{(m+1)}$ , and to the leading order (i.e., the zeroth order of  $p_c$ ) we obtain

$$\frac{\tilde{p}_{00}^{(m+1)}}{\tilde{p}_{11}^{(m+1)}} \approx \frac{1}{4} \left( \frac{p_{10}^{(m)}}{p_{11}^{(m)}} \right)^2, \quad (\text{B7})$$

$$\frac{\tilde{p}_{10}^{(m+1)}}{\tilde{p}_{11}^{(m+1)}} \approx \frac{p_{10}^{(m)}}{p_{11}^{(m)}}, \quad (\text{B8})$$

$$\frac{\tilde{p}_{20, \delta}^{(m+1)}}{\tilde{p}_{11}^{(m+1)}} \approx \frac{1}{2} \frac{p_{10}^{(m)} p_{21, \delta}^{(m)}}{p_{11}^{(m)} p_{11}^{(m)}}, \quad (\text{B9})$$

$$\frac{\tilde{p}_{21, \delta}^{(m+1)}}{\tilde{p}_{11}^{(m+1)}} \approx \frac{p_{21, \delta}^{(m)}}{p_{11}^{(m)}}. \quad (\text{B10})$$

Furthermore, all these ratios remain constant (to order  $p_c$ ), which justifies the claim that the probabilities for different types of states remain stable for all higher levels of ENC.

If we further introduce  $\tilde{p}_{vac}^{(m+1)} = \tilde{p}_{00}^{(m+1)} + \tilde{p}_{10}^{(m+1)}$ ,  $\tilde{p}_{logic}^{(m+1)} = \tilde{p}_{11}^{(m+1)}$ , and  $\tilde{p}_{multi}^{(m+1)} = \sum_{\delta=\parallel, \perp} \tilde{p}_{20, \delta}^{(m+1)} + \tilde{p}_{21, \delta}^{(m+1)}$ , we have

$$\tilde{p}_{logic}^{(m+1)} \approx \frac{\eta^2}{2} p_{logic}^{(m)} p_{logic}^{(m)} [1 + p_{err, new}^{(m+1)} + O(p_c)], \quad (\text{B11a})$$

$$\tilde{p}_{vac}^{(m+1)} \approx \frac{\eta^2}{2} p_{logic}^{(m)} p_{vac}^{(m)} [1 + O(p_c)], \quad (\text{B11b})$$

$$\tilde{p}_{multi}^{(m+1)} \approx \frac{\eta^2}{2} p_{logic}^{(m)} p_{multi}^{(m)} [1 + O(p_c)], \quad (\text{B11c})$$

where  $p_{err,new}^{(m+1)}$  is the probability for the new logical error from the multiexcitation states (accompanied by photon loss)

$$p_{err,new}^{(m+1)} \approx \frac{2(1-\eta)p_{11}^{(m)}(p_{21,\parallel}^{(m)} + p_{21,\perp}^{(m)}) + p_{10}^{(m)}p_{21,\perp}^{(m)}}{p_{11}^{(m)}p_{11}^{(m)}} \\ \sim (1-\eta)p_{multi}^{(m)}/p_{logic}^{(m)} \sim (1-\eta)p_c. \quad (\text{B12})$$

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[21] ENP can be summarized as  $\Theta_{ENP}^{m,m'} |x\rangle_{a_1} |y\rangle_{b_1} |u\rangle_{a_2} |v\rangle_{b_2} \rightarrow (x \oplus u \oplus 1)(y \oplus v \oplus 1)(-1)^{x(mm'+1)} |x\rangle_{a_4} |y\rangle_{b_4}$  with binary basis  $\{|0\rangle, |1\rangle\}$  for  $\{|H\rangle, |V\rangle\}$  during bit-ENP and  $\{|+\rangle, |-\rangle\}$  during phase-ENP, and  $mm'$  represents the parity of two detected photons  
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