Atomic quantum state transferring and swapping via quantum Zeno dynamics

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In this paper, we first demonstrate how to realize quantum state transferring (QST) from one atom to another based on quantum Zeno dynamics. Then, the QST protocol is generalized to realize the quantum state swapping (QSS) between two arbitrary atoms with the help of a third one. Furthermore, we also consider the QSS within a quantum network. The influence of decoherence is analyzed by numerical calculation. The results demonstrate that the protocols are robust against cavity decay.

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I. INTRODUCTION

Quantum information processing (QIP) \cite{1, 2} has demonstrated an important development in recent years. Many protocols for QIP have been proposed in different quantum systems, such as cavity QED \cite{3}, trapped-ion systems \cite{4}, quantum-dot systems \cite{5}, superconducting quantum systems \cite{6, 7}, and linear optical systems \cite{8, 9, 10}. The significant advances in implementing various protocols for QIP can, in the future, lead to long-distance quantum communication or creation of a quantum computer.

Quantum information transferring (QIT) from one to another place is an important goal in the field of quantum information science. So far, a lot of substantial efforts have been

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devoted to the field of QIT and much important progresses have been made [11–20]. An important element of many QIP operations is the transfer of a quantum state from one to another qubit [21], such as $|0\rangle_A \otimes (a|0\rangle + b|1\rangle)_B \rightarrow (a|0\rangle + b|1\rangle)_A|0\rangle_B$, where $|a|^2 + |b|^2 = 1$, $A$ and $B$ denote atom $A$ and atom $B$, respectively. From this expression, we can notice that the problem about the quantum information transfer (QIT) can be reduced to the issue of quantum state transfer (QST) in some sense if the quantum information is encoded in the states of atoms. There are many methods that can implement the QST, such as making use of quantum teleportation original proposed by Bennett et al. [22], which has been experimentally realized in optical and liquid-state nuclear magnetic resonance (NMR) systems [23–25]. In addition, atomic systems in the context of cavity QED are suitable to act as qubits because moderate internal electronic states can coherently store information over very long time scale. In 2010, Yang [26] have proposed a way of implementing QST with two superconducting flux qubits by coupling them to a resonator. This proposal does not require adjustment of the level spacings or uniformity in the device parameters.

On the other hand, Facchi et al. [27–29] found the quantum Zeno dynamics which is a broader formulation of the quantum Zeno effect [30], since the system will evolve away from its initial state and remains in the Zeno subspace determined by the measurement when frequently projected onto a multi-dimensional subspace and the quantum Zeno effect can be reformulated in terms of a continuous coupling to obtain the same effect without making use of von Neumann’s projections and non-unitary dynamics. Until now, the new finding has enlightened numerous schemes to implement quantum computation and prepare quantum entanglement [31–39].

In this paper, we will first demonstrate how to implement the QST based on quantum Zeno dynamics. Then, the QST protocol will be generalized to realize the quantum state swapping (QSS) between two arbitrary atom. Moreover, the QSS within in a quantum network will be also considered in present paper. The setup is composed of cavity QEDs, optical fibers, and A-type atoms, which make the scheme feasible with the current technology. We will show that the protocols are robust against cavity decay and a relatively high fidelity can be obtained even in the presence of atomic spontaneous emission and optical fiber decay.

Before elaborating on our protocols, we first give an elementary introduction to the quantum Zeno dynamics induced by continuous coupling [40]. We assume that a system whose dynamical evolution governed by a generical Hamiltonian $H_K = H + KH_c$, where $H$ is
the Hamiltonian of the system to be investigated and $H_c$ can be regarded as an additional interaction Hamiltonian, which perform the “measurement”. $K$ is a coupling constant. For the infinitely strong coupling limit $K \to \infty$, the system is dominated by the limiting evolution operator $U_K(t) = \lim_{K \to \infty} \exp(-iKH_c t)\mathcal{U}(t)$, where $\mathcal{U}(t) = \exp(-iH_z t)$ [41].

$H_z = \sum_n P_n HP_n$ is viewed as the Zeno Hamiltonian and $P_n$ is the eigenprojection of $H_c$ correspondence to the eigenvalue $\eta_n$ ($H_c = \sum_n \eta_n P_n$. ($\eta_n \neq \eta_m$, for $n \neq m$)). Therefore, the limiting evolution operator of the system can be depicted as $U_K(t) \sim \exp(-iKH_c t)\mathcal{U}(t) = \exp(-i\sum_n K\eta_n P_n t + P_n HP_n t)$. Thus, we can derive the expression of the effective Hamiltonian of the system: $H_{eff} = \sum_n (K\eta_n P_n + P_n HP_n)$, which is an important result to the following works that are based on.

II. THE QST FROM ATOM 2 TO ATOM 1

As depicted in Fig. 1, we consider that two identical atoms (1, 2), which have one excited state $|e\rangle$ and two ground states $|0\rangle$ and $|1\rangle$ with a Λ-type three-level configuration, are trapped in distant cavities ($c_1$, $c_2$) connected by one optical fiber $f$, respectively. Suppose that the transition $|e\rangle_k \leftrightarrow |0\rangle_k$ ($k=1,2$) is resonantly coupled to the cavity mode with the coupling strength $g_k$ while the transition $|e\rangle_k \leftrightarrow |1\rangle_k$ is resonantly driven by a classical laser field with the Rabi frequency $\Omega_k$. Let $L$ be the length of fiber, $C$ be the speed of light, and $\bar{\nu}$ be the decay rate of the cavity fields into a continuum of fiber modes. The length $L$ of the fiber means a quantization of the modes of the fiber with frequency spacing given by $2\pi C/L$. Then we can have that the number of modes which would significantly interact with the cavities modes is of the order of $n = L\bar{\nu}/2\pi C$ [42]. In the short fiber limit $L\bar{\nu}/2\pi C$ [43], which focuses on the case $n \leq 1$, only one fiber mode is essentially excited and coupled to the cavity mode with coupling strength $\lambda$. Notice that such a regime applies in most realistic experimental situations: for instance, $L \leq 1$ m and $\bar{\nu} \simeq 1$ GHz (natural units are adopted with $\hbar = 1$) are in the proper range. In the interaction picture, the Hamiltonian...
for the whole system can be written as \((\hbar = 1)\)

\[
\begin{align*}
H_{\text{tot}} &= H_l + H_c + H_{cf}, \\
H_l &= \sum_{k=1}^{2} \Omega_k (|e\rangle_k \langle 1| + |1\rangle_k \langle e|), \\
H_c &= \sum_{k=1}^{2} g_k (a_k |e\rangle_k \langle 0| + a_k^\dagger |0\rangle_k \langle e|), \\
H_{cf} &= \lambda b (a_1^\dagger + a_2^\dagger) + H.c.,
\end{align*}
\]

where \(a_k^\dagger\) and \(a_k\) are the creation and annihilation operators for the \(k\)th cavity mode and \(b^\dagger\) and \(b\) are the creation and annihilation operators for the fiber mode. We assumed \(g_k = g \in R\) for simplicity.

If the initial state of the system is \(|0\rangle_1 |1\rangle_2 |0\rangle_{c_2} |0\rangle_f |0\rangle_{c_1}\), it will evolve in a closed subspace spanned by \(\{|\phi_1\rangle, |\phi_2\rangle, |\phi_3\rangle, |\phi_4\rangle, |\phi_5\rangle, |\phi_6\rangle, |\phi_7\rangle\}\), where

\[
\begin{align*}
|\phi_1\rangle &= |0\rangle_1 |1\rangle_2 |0\rangle_{c_2} |0\rangle_f |0\rangle_{c_1}, \\
|\phi_2\rangle &= |0\rangle_1 |e\rangle_2 |0\rangle_{c_2} |0\rangle_f |0\rangle_{c_1}, \\
|\phi_3\rangle &= |0\rangle_1 |0\rangle_2 |1\rangle_{c_2} |0\rangle_f |0\rangle_{c_1}, \\
|\phi_4\rangle &= |0\rangle_1 |0\rangle_2 |0\rangle_{c_2} |1\rangle_f |0\rangle_{c_1}, \\
|\phi_5\rangle &= |0\rangle_1 |0\rangle_2 |0\rangle_{c_2} |0\rangle_f |1\rangle_{c_1}, \\
|\phi_6\rangle &= |e\rangle_1 |0\rangle_2 |0\rangle_{c_2} |0\rangle_f |0\rangle_{c_1}, \\
|\phi_7\rangle &= |1\rangle_1 |0\rangle_2 |0\rangle_{c_2} |0\rangle_f |0\rangle_{c_1}.
\end{align*}
\]

The subscripts 1, 2, \(c_1, f\) and \(c_2\) represent the atom 1, atom 2, cavity 1, optical fiber and cavity 2, respectively.

On the condition that \(\Omega_1, \Omega_2 \ll g, \lambda\), the Hilbert subspace is split into five invariant Zeno subspaces \([40, 41]\):

\[
\begin{align*}
H_{P_1} &= \{ |\phi_1\rangle, |\phi_7\rangle, |\phi_1\rangle \},
H_{P_2} &= \{ |\phi_2\rangle \},
H_{P_3} &= \{ |\phi_3\rangle \},
H_{P_4} &= \{ |\phi_4\rangle \},
H_{P_5} &= \{ |\phi_5\rangle \},
\end{align*}
\]
As the initial state is corresponding to eigenvalues \( \eta \) to \( \eta \), therefore, the Hamiltonian of the current system is approximately governed by:

\[
|\varphi_1\rangle = \frac{1}{\sqrt{2\lambda^2 + g^2}} (\lambda|\phi_2\rangle - g|\phi_4\rangle + \lambda|\phi_6\rangle),
\]

\[
|\varphi_2\rangle = \frac{1}{2} (-|\phi_2\rangle + |\phi_3\rangle - |\phi_5\rangle + |\phi_6\rangle),
\]

\[
|\varphi_3\rangle = \frac{1}{2} (-|\phi_2\rangle - |\phi_3\rangle + |\phi_5\rangle + |\phi_6\rangle),
\]

\[
|\varphi_4\rangle = \frac{1}{2\sqrt{2\lambda^2 + g^2}} (g|\phi_2\rangle - \sqrt{2\lambda^2 + g^2}|\phi_3\rangle + 2\lambda|\phi_4\rangle - \sqrt{2\lambda^2 + g^2}|\phi_5\rangle + g|\phi_6\rangle),
\]

\[
|\varphi_5\rangle = \frac{1}{2\sqrt{2\lambda^2 + g^2}} (g|\phi_2\rangle + \sqrt{2\lambda^2 + g^2}|\phi_3\rangle + 2\lambda|\phi_4\rangle + \sqrt{2\lambda^2 + g^2}|\phi_5\rangle + g|\phi_6\rangle),
\]

(4)

Corresponding to eigenvalues \( \eta_1 = 0, \eta_2 = -g, \eta_3 = g, \eta_2 = -\sqrt{2\lambda^2 + g^2}, \eta_3 = \sqrt{2\lambda^2 + g^2} \) with the projections:

\[
P_n = \sum_j |\beta_{n,j}\rangle \langle \beta_{n,j}|, (|\beta_{n,j}\rangle \in H_{P_n}).
\]

(5)

Therefore, the Hamiltonian of the current system is approximately governed by:

\[
H_{\text{total}} \approx \sum_n (\eta_n P_n + P_n H_{\text{laser}} P_n)
\]

\[
= -g|\varphi_2\rangle \langle \varphi_2| + g|\varphi_3\rangle \langle \varphi_3| - \sqrt{2\lambda^2 + g^2}|\varphi_4\rangle \langle \varphi_4| + \sqrt{2\lambda^2 + g^2}|\varphi_5\rangle \langle \varphi_5| + \frac{\lambda}{\sqrt{2\lambda^2 + g^2}} (\Omega_1|\phi_1\rangle \langle \varphi_1| + \Omega_2|\phi_7\rangle \langle \varphi_1|) + H.c..
\]

(6)

As the initial state is \( |0\rangle_1|1\rangle_2|0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1} \), thus the effective Hamiltonian of the system reduces to:

\[
H_{\text{eff}} = \frac{\lambda}{\sqrt{2\lambda^2 + g^2}} (\Omega_1|\phi_1\rangle \langle \varphi_1| + \Omega_2|\phi_7\rangle \langle \varphi_1|) + H.c..
\]

(7)

On the other hand, it is easily checked that the evolution of initial state \( |0\rangle_1|0\rangle_2|0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1} \) is frozen due to \( H_{\text{tot}}|0\rangle_1|0\rangle_2|0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1} = 0 \).

As the initial state of the whole system is \( |\Phi(0)\rangle = |0\rangle_1 \otimes (a|0\rangle + b|1\rangle)_2 \otimes |0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1} \), where \( |a|^2 + |b|^2 = 1 \), it will evolve with respect to the effective Hamiltonian in Eq. (7). Set \( \Omega_1 = -\Omega_2 = \Omega \in R \). For an interaction time \( t \), the final state of the system becomes:

\[
|\Phi(t)\rangle = a|0\rangle_1|0\rangle_2|0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1} + b\left[ \frac{1}{2}(1 + \cos \frac{\sqrt{2\lambda\Omega t}}{\sqrt{2\lambda^2 + g^2}})|\phi_1\rangle + \frac{1}{2}(1 - \cos \frac{\sqrt{2\lambda\Omega t}}{\sqrt{2\lambda^2 + g^2}})|\phi_7\rangle - i\frac{\sqrt{2}}{2} \sin \frac{\sqrt{2\lambda\Omega t}}{\sqrt{2\lambda^2 + g^2}}|\varphi_1\rangle \right].
\]

(8)
By selecting the interaction time to satisfy $\frac{2\lambda \Omega t}{\sqrt{2\lambda^2 + g^2}} = \pi$, one will obtain

$$|\Phi(\frac{\sqrt{2\lambda^2 + g^2}\pi}{\sqrt{2\lambda\Omega}})| = a|0\rangle_1|0\rangle_2|0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1} + b|\phi_7\rangle$$

$$= a|0\rangle_1|0\rangle_2|0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1} + b|1\rangle_1|0\rangle_2|0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1}$$

$$= (a|0\rangle + b|1\rangle)_1 \otimes |0\rangle_2 \otimes |0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1},$$

where the QST from atom 2 to atom 1 has been realized.

III. THE QSS BETWEEN ATOMS 2 AND 3 WITH THE HELP OF ATOM 1

Now, we will demonstrate that how to swap the quantum states between atom 2 and atom 3 with the help of the auxiliary atom 1, as shown in Fig. 2. Assume that the initial arbitrary states of atom 2 and atom 3 are $(a|0\rangle + b|1\rangle)_2$ and $(c|0\rangle + d|1\rangle)_3$ $(|a|^2 + |b|^2 = 1, |c|^2 + |d|^2 = 1)$, respectively. In addition, all the optical switches are closed in the initial time. During the swapping operations, we will introduce a auxiliary atom 1 with the initial state $|0\rangle$.

A. The QST From Atom 2 To Atom 1

First, we turn on the optical switches 1 and 2 to let the optical fiber mediate the cavities 1 and 2. The initial state of the system is $|\Phi(0)\rangle = |0\rangle_1 \otimes (a|0\rangle + b|1\rangle)_2 \otimes |0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1}$. A analogue analysis is utilized with the Eq. (2) - Eq. (8), then set Rabi frequency $\Omega_1 = -\Omega_2 = \Omega \in R$ and an interaction time $\frac{\sqrt{2\lambda^2 + g^2}\pi}{\sqrt{2\lambda\Omega}}$. We will realize the QST from atom 2 to atom 1. Next, we turn off the optical switches 1 and 2 to inhibit the interaction between atom 1 and atom 2. As a consequence, the quantum state of atom 1 becomes $(a|0\rangle + b|1\rangle)_1$ while the final state of atom 2 becomes $|0\rangle_2$.

B. The QST From Atom 3 To Atom 2

Then, we turn on the optical switches 2 and 3 to let the optical fiber mediate the cavities 2 and 3. The initial state of the system is $|\Phi'(0)\rangle = |0\rangle_2 \otimes (c|0\rangle + d|1\rangle)_3 \otimes |0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1}$. A analogue analysis is utilized with the Eq. (2) - Eq. (8), then set Rabi frequency $\Omega_2 =
\(-\Omega_3 = \Omega \in R\) and an interaction time \(\sqrt{\frac{2\lambda + g^2\pi}{2\lambda\Omega}}\). We will realize the QST from atom 3 to atom 2. Next, we turn off the optical switches 2 and 3 to inhibit the interaction between atom 2 and atom 3. As a consequence, the quantum state of atom 2 becomes \((c|0\rangle + d|1\rangle)_2\) while the final state of atom 3 becomes \(|0\rangle_3\).

C. The QST From Atom 1 To Atom 3

Finally, we turn on the optical switches 1 and 3 to let the optical fiber mediate the cavities 1 and 3. The initial state of the system is \(|\Phi''(0)\rangle = |0\rangle_3 \otimes (a|0\rangle + b|1\rangle)_1 \otimes |0\rangle_e |0\rangle_f |0\rangle_c_1\). A analogue analysis is utilized with the Eq. (2) - Eq. (8), then set Rabi frequency \(\Omega_3 = -\Omega_1 = \Omega \in R\) and an interaction time \(\sqrt{\frac{2\lambda + g^2\pi}{2\lambda\Omega}}\). We will realize the QST from atom 1 to atom 3. Next, we turn off the optical switches 1 and 3 to inhibit the interaction between atom 1 and atom 3. As a consequence, the quantum state of atom 3 becomes \((a|0\rangle + b|1\rangle)_3\) while the final state of the auxiliary atom 1 becomes \(|0\rangle_1\).

After above operations, we have realized the QSS between atom 2 and atom 3, which become \((c|0\rangle + d|1\rangle)_2\) and \((a|0\rangle + b|1\rangle)_3\) now, while the final state of auxiliary atom 1 remains \(|0\rangle_1\).

IV. THE QSS FOR TWO ARBITRARY ATOMS AMONG \(N\) ATOMS WITHIN THE QUANTUM NETWORK

From above analysis, we can find that the state of auxiliary atom 1 remains unchange after two other atoms 2 and 3 have realized the QSS. Thus, it provides a scalable way to realize the QSS for two arbitrary atoms among \(N\) atoms within the quantum network.

As shown in Fig. 3, \(N\) atoms are trapped in \(N\) separate cavities, respectively. The \(N\) cavities are connected by the fibers and \(N\) optical switches within the quantum network. Now we briefly demonstrate how to realize one QSS. For example, if we want to swap the arbitrary two atomic quantum state within the quantum network, for example, atom 4 and arbitrary atom \(N\), the first step we must do is to turn off all the optical switches in quantum network. Next, we turn on the optical switches 1 and 4 to realize the QST from atom 4 to atom 1. Then we turn off the optical switch 1 and turn on the optical switch \(N\) to realize the QST from atom \(N\) to atom 4. Finally, we turn off the optical switch 4 and turn on the
optical switch 1 to realize the QST from atom 1 to atom N. Until now, we have realize the QSS between atom 4 and atom N and turn off the optical switches 1 and N.

V. NUMERICAL ANALYSIS AND CONCLUSIONS

All the above results are based on the condition that $\Omega_1, \Omega_2 \ll g, \lambda$. Thus we shall analyze the influence of the ratio $\Omega/g$ on the fidelity of QST. On the other hand, the ratio $\lambda/g$ will also affect the fidelity of QST. We depict the relation between the fidelity of QST and the ratio $\lambda/g$ and $\Omega/g$ by numerical calculation in the FIG. 4. Obviously, the smaller $\Omega$ we set, the better behavior we will get. However, small $\Omega$ implies that long operation times should be required. We can also see that the fidelity is above 96% even though the ratio $\lambda/g = 0.1$. Thus the large cavity-fiber coupling is not necessary needed in an experiment.

As we can see from the above analysis, the time evolution of the initial state $|0\rangle_1|0\rangle_2|0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1}$ will freeze during the operations. Thus it will transfer with 100%. the only factor that will affect the fidelity of QST is the time evolution of the initial state $|0\rangle_1|1\rangle_2|0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1}$. Therefore we will emphasize on discussion about the fidelity of QST in the presence of the decoherence induced by cavity decay, optical fiber decay, and atomic spontaneous emission while the initial state is $|0\rangle_1|1\rangle_2|0\rangle_{c_2}|0\rangle_f|0\rangle_{c_1}$ as follows. When we consider about the decoherence, the master equation of motion for the density matrix of the whole system can be express as

$$
\dot{\rho} = -i[H_{tot}, \rho] - \sum_{j=1}^{2} \frac{\kappa_j}{2}(a_j^\dagger a_j\rho - 2a_j\rho a_j^\dagger + \rho a_j^\dagger a_j) - \frac{\kappa_f}{2}(b^\dagger b\rho - 2b b^\dagger + \rho b^\dagger b) \\
- \sum_{k=1}^{1} \sum_{m=0}^{1} \frac{\Gamma_{em}^k}{2}(\sigma_{em}^k\sigma_{me}^k\rho - 2\sigma_{me}^k\rho\sigma_{em}^k + \rho\sigma_{em}^k\sigma_{me}^k),
$$

(10)

where $\Gamma_{em}^k$ is the spontaneous emission rate of the $k$th atom from the excited state $|e\rangle$ to the ground state $|m\rangle$ ($m = 0, 1$). $\kappa_j$ is the decay rate of the $j$th cavity mode and $\kappa_f$ is the decay rate of the optical fiber mode between two cavities, such as the cavity 1 and cavity 2. For the sake of simplicity, we assume $\Gamma_{em}^k = \Gamma/2$ and $\kappa_j = \kappa$. In Fig. 5 (Fig. 6), we plot the relation of the fidelity $F$ versus $\kappa/g$ and $\Gamma/g$ ($\kappa_f/\lambda$) by solving the master equation numerically. One can find from Fig. 5 (Fig. 6) that with the increasing of cavity decay and atomic spontaneous emission (optical fiber decay), the fidelity $F$ of the QST will decrease. In addition, the results indicate that the QST is robust against the decay of cavity,
since for a large cavity decay $\kappa/g = 0.1$, $\Gamma/g = 0$ and $\kappa_f/\lambda = 0$, the fidelity is still about 97.21%. Therefore it can be considered as a decoherence-free QST with respect to cavity decay. The dominant decoherence is the atomic spontaneous emission and the optical fiber decay due to the excited states and the state of fiber with one photon are included during the evolution. However, the effect of optical fiber decay is weaker than the effect of atomic spontaneous emission, which we can account for in this way that the population probability for one photon in fiber is nearly one-half of the population probability for excited atoms while $g$ and $\lambda$ are kept in the same magnitude.

Finally we bring forward the basic elements that may be candidates for the intended experiment. The requirements of our protocols are $\Lambda$-type three-level configuration atoms and resonant cavities connected by optical fibers. The atomic configuration involved in our proposal can be achieved with a cesium. The state $|0\rangle$ corresponds to $F = 3, m = 2$ hyperfine state of $6^2S_{1/2}$ electronic ground state, the state $|1\rangle$ corresponds to $F = 4, m = 4$ hyperfine state of $6^2S_{1/2}$ electronic ground state, and the excited state $|e\rangle$ corresponds to $F = 3, m = 3$ hyperfine state of $6^2P_{1/2}$ electronic ground state, respectively. In recent experiments [44, 45], it is achievable with the parameters $\lambda = 2\pi \times 750$ MHz, $\Gamma = 2\pi \times 2.62$ MHz, $\kappa = 2\pi \times 3.5$ MHz in an optical cavity with the wavelength in the region 630 - 850 nm. A near-perfect fiber-cavity coupling with an efficiency larger than 99.9% can be realized using fiber-taper coupling to high-Q silica microspheres [46]. The optical fiber decay at a 852 nm wavelength is about 2.2 dB/km [47], which corresponds to the fiber decay rate 0.152 MHz, lower than the cavity decay rate. By substituting these typical parameters into Eq. (10), we will obtain a high fidelity about 97.54%, which shows the QST in our protocols are relative robust against realistic one.

In summary, we have proposed a set of protocols for quantum state transferring and swapping based on quantum Zeno dynamics. The protocols are robust against cavity decay since it keeps in a closed subspace without exciting the cavity field during the whole system evolution. In addition, we have also discussed the influence of atomic spontaneous emission and optical fiber decay by a straightforward numerical calculation. The results demonstrate that a relatively high fidelity can be obtained even in the presence of atomic spontaneous emission and fiber decay. Therefore, we hope that it may be possible to realize it in this paper with the current experimental technology.
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[1] M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information (Cambridge University Press, Cambridge, 2000).
[2] H. J. Kimble, “The quantum internet,” Nature (London) 453, 1023-1030 (2008).
[3] S. B. Zheng and G. C. Guo, “Efficient scheme for two-atom entanglement and quantum information processing in cavity QED,” Phys. Rev. Lett. 85, 2392-2395 (2000).
[4] D. Kielpinski, C. Monroe, and D. J. Wineland, “Architecture for a large-scale ion-trap quantum computer,” Nature (London) 417, 709-711 (2002).
[5] M. Bayer, P. Hawrylak, K. Hinzer, S. Fafard, M. Korkusinski, Z. R. Wasilewski, O. Stern, and A. Forchel, “Coupling and entangling of quantum states in quantum dot molecules,” Science 291, 451-453 (2001).
[6] J. Q. You and F. Nori, “Quantum information processing with superconducting qubits in a microwave field,” Phys. Rev. B 68, 064509 (2003).
[7] Z. R. Lin, G. P. Guo, T. Tu, F. Y. Zhu, and G. C. Guo, “Generation of quantum-dot cluster states with a superconducting transmission line resonator,” Phys. Rev. Lett. 101, 230501 (2008).
[8] E. Knill, R. Laflamme, and G. J. Milburn, “A scheme for efficient quantum computation with linear optics,” Nature (London) 409, 46-52 (2001).
[9] J. W. Pan, S. Gasparoni, R. Ursin, G. Weihs, and A. Zeilinger, “Experimental entanglement purification of arbitrary unknown states,” Nature (London) 423, 417-422 (2003).
[10] Y. Xia, J. Song, and H. S. Song, “Linear optical protocol for preparation of N-photon
Greenberger-Horne-Zeilinger state with conventional photon detectors,” Appl. Phys. Lett. 92, 021127 (2008); J. Song, Y. Xia, an H. S. Song, “Quantum nodes for W-state generation in noisy channels,” Phys. Rev. A 78, 024302 (2008).

[11] A. Kuzmich and E. S. Polzik, “Atomic quantum state teleportation and swapping,” Phys. Rev. Lett. 85, 5639-5642 (2000).

[12] A. Biswas and G. S. Agarwal, “Transfer of an unknown quantum state, quantum networks, and memory,” Phys. Rev. A 70, 022323 (2004).

[13] J. F. Zhang, X. H. Peng, and D. Suter, “Speedup of quantum-state transfer by three-qubit interactions: Implementation by nuclear magnetic resonance,” Phys. Rev. A 73, 062325 (2006).

[14] H. Wei, Z. J. Deng, X. L. Zhang, and M. Feng, “Transfer and teleportation of quantum states encoded in decoherence-free subspace,” Phys. Rev. A 76, 054304 (2007).

[15] A. Bayat and V. Karimipour, “Transfer of d-level quantum states through spin chains by random swapping,” Phys. Rev. A 75, 022321 (2007).

[16] C. D. Franco, M. Paternostro, and M. S. Kim, “Quantum state transfer via temporal kicking of information,” Phys. Rev. A 81, 022319 (2010).

[17] B. Chen, W. Fan, and Y. Xu, “Adiabatic quantum state transfer in a nonuniform triple-quantum-dot system,” Phys. Rev. A 83, 014301 (2011).

[18] P. B. Li, Y. Gu, Q. H. Gong, and G. C. Guo, “Quantum-information transfer in a coupled resonator waveguide,” Phys. Rev. A 79, 042339 (2009).

[19] J. I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi, “Quantum state transfer and entanglement distribution among distant nodes in a quantum network,” Phys. Rev. Lett. 78, 3221-3224 (1997).

[20] A. D. Boozer, A. Boca, R. Miller, T. E. Northup, and H. J. Kimble, “Reversible state transfer between light and a single trapped atom,” Phys. Rev. Lett. 98, 193601 (2007).

[21] S. Bose, “Quantum communication through an unmodulated spin chain,” Phys. Rev. Lett. 91, 207901 (2003).

[22] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, “Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels,” Phys. Rev. Lett. 70, 1895-1899 (1993).

[23] D. Bouwmeester, J. W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, “Experimental quantum teleportation,” Nature (London) 390, 575-579 (1997).
[24] D. Boschi, S. Branca1, F. D. Martini, L. Hardy, and S. Popescu, “Experimental realization of teleporting an unknown pure quantum state via dual classical and einstein-podolsky-rosen channels,” Phys. Rev. Lett. 80, 1121-1125 (1998).

[25] M. A. Nielsen, E. Knill, and R. Laflamme, “Complete quantum teleportation using nuclear magnetic resonance,” Nature (London) 396, 52-55 (1998).

[26] C. P. Yang, “Quantum information transfer with superconducting flux qubits coupled to a resonator,” Phys. Rev. A 82, 054303 (2010).

[27] P. Facchi, V. Gorini, G. Marmo, S. Pascazio, and E. C. G. Sudarshan, “Quantum Zeno dynamics,” Phys. Lett. A 275, 12-19 (2000).

[28] P. Facchi, S. Pascazio, A. Scardicchio, and L. S. Schulman, “Zeno dynamics yields ordinary constraints,” Phys. Rev. A 65, 012108 (2001).

[29] P. Facchi and S. Pascazio, “Quantum Zeno and inverse quantum Zeno effects,” Progress in Optics, 42, 147-217 (2001).

[30] B. Misra and E. C. G. Sudarshan, “The Zeno’s paradox in quantum theory,” J. Math. Phys. 18, 756-763 (1977).

[31] P. Jiannis and W. Herbert, “Quantum computation with trapped ions in an optical cavity,” Phys. Rev. Lett. 89, 187903 (2002).

[32] K. P. Jiannis and B. Almut, “Decoherence-free dynamical and geometrical entangling phase gates,” Phys. Rev. A 69, 033817 (2004).

[33] X. Q. Shao, H. F. Wang, L. Chen, S. Zhang, and K. H. Yeon, “One-step implementation of the Toffoli gate via quantum Zeno dynamics,” Phys. Lett. A 374, 28-33 (2009).

[34] S. Zhang, X. Q. Shao, L. Chen, Y. F. Zhao, and K. H. Yeon, “Robust √\text{swap} gate on nitrogen-vacancy centres via quantum Zeno dynamics,” J. Phys. B: At. Mol. Opt. Phys. 44, 075505 (2011).

[35] X. B. Wang, J. Q. You, and F. Nori, “Quantum entanglement via two-qubit quantum Zeno dynamics,” Phys. Rev. A 77, 062339 (2008).

[36] X. Q. Shao, L. Chen, S. Zhang, Y. F. Zhao, and K. H. Yeon, “Deterministic generation of arbitrary multi-atom symmetric Dicke states by a combination of quantum Zeno dynamics and adiabatic passage,” Europhys. Lett. 90, 50003 (2010).

[37] X. Q. Shao, H. F. Wang, L. Chen, S. Zhang, Y. F. Zhao, and K. H. Yeon, “Converting two-atom singlet state into three-atom singlet state via quantum Zeno dynamics,” New J. Phys.
[38] A. L. Wen, “Distributed qutrit-qutrit entanglement via quantum Zeno dynamics,” Opt. Commun. 284, 2245-2249 (2011).

[39] A. L. Wen and Y. H. Guang, “Deterministic generation of a three-dimensional entangled state via quantum Zeno dynamics,” Phys. Rev. A 83, 022322 (2011).

[40] P. Facchi, G. Marmo, and S. Pascazio, “Quantum Zeno dynamics and quantum Zeno subspaces,” J. Phys: Conf. Ser. 196, 012017 (2009).

[41] P. Facchi, S. Pascazio, “Quantum Zeno subspaces,” Phys. Rev. Lett. 89, 080401 (2002).

[42] T. Pellizzari, “Quantum networking with optical fibres,” Phys. Rev. Lett. 79, 5242 (1997).

[43] A. Serafini, S. Mancini, and S. Bose, “Distributed quantum computation via optical fibers,” Phys. Rev. Lett. 96, 010503 (2006).

[44] S. M. Spillane, T. J. Kippenberg, K. J. Vahala, K. W. Goh, E. Wilcut, and H. J. Kimble, “Ultra-high-Q toroidal microresonators for cavity quantum electrodynamics,” Phys. Rev. A 71, 013817 (2005).

[45] J. R. Buck and H. J. Kimble, “Optimal sizes of dielectric microspheres for cavity QED with strong coupling,” Phys. Rev. A 67, 033806 (2003).

[46] K. J. Gordon, V. Fernandez, P. D. Townsend, and G. S. Buller, “A short wavelength gigahertz clocked fiber optic quantum key distribution system,” IEEE J. Quantum Electron. 40, 900-908 (2004).

[47] F. Dimer, B. Estienne, A. S. Parkins, and H. J. Carmichael, “Proposed realization of the Dicke-model quantum phase transition in an optical cavity QED system,” Phys. Rev. A 75, 013804 (2007).
FIG. 1. The experimental setup for realizing the QST from atom 2 to atom 1. Those atoms have the identical Λ-type three-level configuration.

FIG. 2. The experimental setup for realizing the QSS between atom 2 and atom 3 while atom 1 is an auxiliary atom. The cavities are connected by optical fibers. The optical switches 1, 2 and 3 can control two cavities whether have interaction or not.

FIG. 3. The experimental setup for realizing the QSS for two arbitrary atom among $N$ atoms in the quantum network.

FIG. 4. The fidelity $F$ of QST as a function of the ratio $\lambda/g$ and $\Omega/g$.

FIG. 5. The fidelity $F$ of QST as a function of cavity decay $\kappa/g$ and atomic spontaneous emission $\Gamma/g$ in the case of $\Omega_1 = 0.1g$ and $\kappa_f/\lambda = 0$.

FIG. 6. The fidelity $F$ of QST as a function of cavity decay $\kappa/g$ and optical fiber decay $\kappa_f/\lambda$ in the case of $\Omega_1 = 0.1g$, $\Gamma/g = 0$ and $g = \lambda$. 
FIG. 1:

FIG. 2:

FIG. 3:
FIG. 4:

FIG. 5:
FIG. 6: