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Memory-based quantum repeater in quantum information communication *

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This paper studies the quantum repeater in quantum information communication. We propose to introduce the photon buffer mechanism for storing photons, which uses fibre delay loops as photon memories and a programmable $1\times N$ switcher for distributing photon delay time. Meanwhile, we also consider entanglement purification and entanglement swapping restoration at an entanglement purification or entanglement swapping failure and introduce a protection link mechanism that allows the photonic quantum repeater of a broken connection to initiate a connection restoration process.

Keywords: quantum repeater, photon buffer, quantum information communication
PACC: 0650M, 4280S

1. Introduction

The quantum physics has been introduced as a theoretical basis of the new computer technology. Now our goal is to organize, and control the quantum system and realize quantum technology using the quantum computer theory. In this paper, we propose the photonic quantum repeater which is an application of quantum computer theory in quantum information communication.

In classical computer communication, the repeater is a network device used to interconnect the media segments of an extended network, as shown in Fig.1. Repeaters receive signals from one network segment and amplify, retime and retransmit those signals to another network segment. These actions prevent signal deterioration caused by long cable lengths and large number of connected devices.

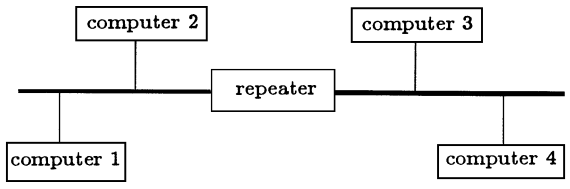


Fig.1. Repeater in communication networks.

In quantum information communication, people usually use photons as carriers of quantum information in long-distances transmission. In order to realize photon long-distance transmission, there are two problems to be solved. One is the absorption of photons in the transmission channel since quantum states cannot be copied; another problem is that typically the quality of the entangled states will decrease exponentially with the channel length. The method to solve the first problem involves sending a large number of photons. In order to solve the second problem, several quantum repeater schemes have been proposed.[1−4] Ideally, a quantum repeater acts as an emitter and a receiver of quantum state; the input quantum state usually is distorted and almost decohered. In order to realize long-distance quantum information communication, the photonic quantum repeater must satisfy the following two conditions: (i) the input quantum state $|\psi\rangle$ must be an arbitrary quantum state; (ii) the output quantum state $|\psi'\rangle$ is an maximum fidelity of entanglement purification with the input quantum state $|\psi\rangle$.

In Ref.[1], the scheme for quantum repeater involves laser manipulation of atomic ensembles, beam splitters and single-photon detectors with moderate efficiency, and is therefore compatible with current experimental technology. In Ref.[2], people treat the problem of a quantum repeater based on the

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method of entanglement purification. In this paper, the scheme is a memory-based photonic quantum repeater, which is a combination of four significant components namely the photon buffer, purifier (entanglement purification), swapper (entanglement swapping) and controller. The main contribution of the work is the proposal of the idea of using a photon buffer mechanism for storing the photon, which uses fibre delay loops as photon memories and a programmable $1\times N$ switcher for distributing photon delay time, and getting the entanglement purification condition for decohered quantum state by solving the master equation. Meanwhile, the entanglement purification and entanglement swapping restoration in the occurrence of a link failure are considered in this paper. Finally, a protection link mechanism is introduced, which allows the photonic quantum repeater of a broken connection to initiate a connection restoration process.

The paper is arranged as follows. In Section 2, we show how to construct the components of the photonic quantum repeater and introduce their work principles. Section 3 shows how to implement efficient quantum state transmission control protocol. In Section 4, we summarize the technical scheme and give some research topics in future.

2. Components of the photonic quantum repeater

The proposed scheme for photonic quantum repeater is based on the use of the photonic channels. Because of the photonic absorption and other channel noise, the degree of entanglement generated between two segments normally decreases exponentially with the length of the connecting channel. In order to overcome the difficulty associated with the exponential fidelity decay, we introduce a new quantum device—the photonic quantum repeater. The components of the photonic quantum repeater are sketched in Fig.2. The photonic quantum repeater is usually divided into four blocks, including the photon buffer, purifier (entanglement purification), swapper (entanglement swapping) and controller. There are feedback lines, work lines, control lines and protection link lines in the photonic quantum repeater.

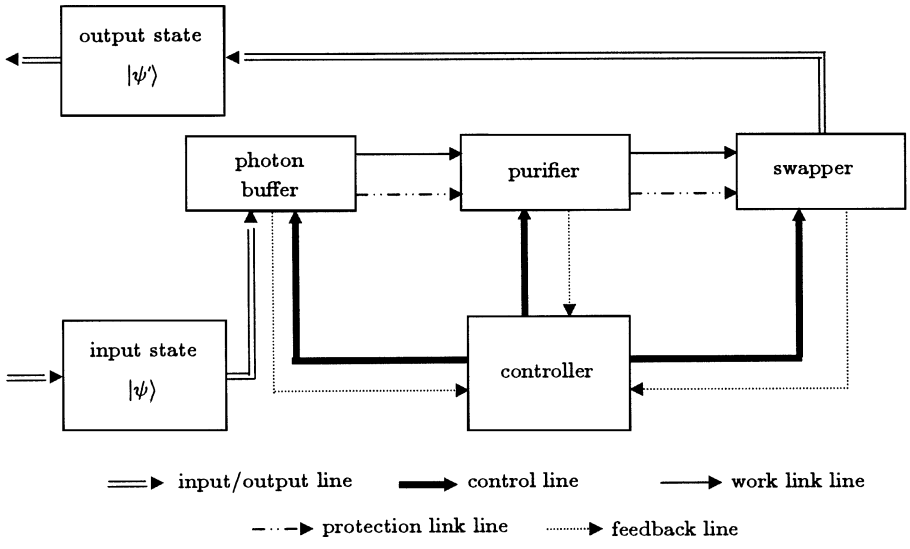


Fig.2. Components of photonic quantum repeater.

2.1. Photon buffer and controller in photonic quantum repeater

In this scheme, the block called "photon buffer" is the photon memory part. It is usually difficult for photons to be stored in quantum information communication. Here, we introduce fibre delay loops as photon memories, and a programmable $1\times N$ switcher for distributing photon delay time is proposed. A fibre delay loop can delay a quantum state for a specified length of time, which is proportional to the length of the delay loop. There are different fibre delay loops in the photon buffer; the polarization single photon state will be stored in different fibre delay loops. Their stored time will be set T, $2T$, $3T$ and NT, as shown in Fig.3.

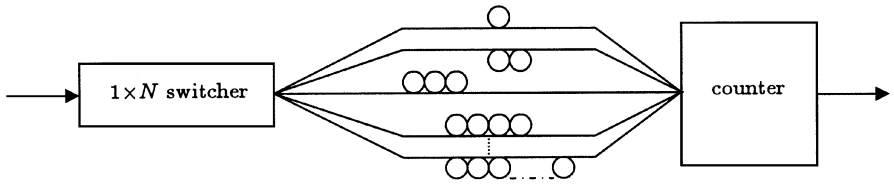


Fig.3. A programmable $1\times N$ switcher.

There is a photon counter at the right of the photon buffer; it will record the number of photons which will be transmitted into the purifier for entanglement purification.

The controller of the photonic quantum repeater controls up to three ingredients: the photon's memory time, entanglement purification and entanglement swapping. The controller utilizes a control algorithm which considers photon buffer capacity, the maximum fidelity of entanglement purification and the successful entanglement swapping. With this algorithm, the photonic quantum repeater will keep the distorted and almost decohered quantum states input and the maximum fidelity, purified entangled quantum states output. According to the message from the feedback lines, the photonic quantum repeater will implement the protection link line if the entanglement purification or entanglement swapping failure has happened.

2.2. Entanglement purification and entanglement swapping of quantum state

We know that the maximally polarization-entangled states that are most commonly considered are the Bell states,

$$\begin{aligned} |\Psi^{\pm}\rangle &= (|V,H\rangle \pm |H,V\rangle)/\sqrt{2}, \\ |\Phi^{\pm}\rangle &= (|V,V\rangle \pm |H,H\rangle)/\sqrt{2}, \end{aligned} \tag{1}$$

where we denote the state of a horizontally polarized photon by $|H\rangle$, and the state of a vertically polarized photon by $|V\rangle$. In the usual quantum information terminology, $|H\rangle$ and $|V\rangle$ correspond to $|0\rangle$ and $|1\rangle$. In quantum long-distance information communication, the degree of entanglement can be fully or partially destroyed due to the presence of interactions with the environment and large number of quantum connected devices. In order to preserve an entanglement quantum state in quantum long-distance communication, we first consider the problem of improving the quality of quantum entanglement as a means for protecting or preserving quantum information. In quantum information theory, these processes are usually called quantum purification protocols. When a quantum state is transmitted to the photonic quantum repeater, it is a mixed and almost decohered quantum state because channel noise and photons will be absorbed after the attenuation length. Suppose its density operator is $\rho_{ab}(t)$, where t stands for the decoherence time. By solving the master equation [5]

$$\begin{aligned} &\frac{\partial \rho}{\partial t} = \hat{J}_{\rho} + \hat{L}_{\rho}, \\ &\hat{J}_{\rho} = \sigma \sum_i a_i \rho a_i^{+}, \\ &\hat{L}_{\rho} = -\frac{\sigma}{2} \sum_i (a_i^{+} a_i \rho + \rho a_i^{+} a_i), \end{aligned} \tag{2}$$

where σ is the energy decay rate, the mixed state $\rho_{ab}(t)$ can be straightforwardly obtained as

$$\begin{aligned} \rho_{ab}(t) =& \tilde{E}(t)\{|\tau\beta,\tau\beta\rangle\langle\tau\beta,\tau\beta| \\ &+ |-\tau\beta,-\tau\beta\rangle\langle-\tau\beta,-\tau\beta| \\ &- \zeta(|\tau\beta,\tau\beta\rangle\langle-\tau\beta,-\tau\beta| \\ &+ |-\tau\beta,-\tau\beta\rangle\langle\tau\beta,\tau\beta|)\}, \end{aligned} \tag{3}$$

where $|\pm\tau\beta,\pm\tau\beta\rangle = |\pm\tau\beta\rangle_a|\pm\tau\beta\rangle_b$, $\tau = \mathrm{e}^{-\sigma t/3}$, $\zeta = \mathrm{e}^{-4(1-\tau^3)|\beta|^3}$, and β is the coherent amplitude and $\tilde{E}(t)$ is the normalization factor. The decohered quantum state $\rho_{ab}(t)$ may be represented by the dynamic quasi-Bell states defined as follows:[6]

$$\begin{aligned} |\Phi^{\pm}\rangle_{ab} &= \tilde{E}_{\pm}(|\tau\beta\rangle_a|\tau\beta\rangle_b \pm |-\tau\beta\rangle_a|-\tau\beta\rangle_b), \\ |\psi^{\pm}\rangle_{ab} &= \tilde{E}_{\pm}(|\tau\beta\rangle_a|-\tau\beta\rangle_b \pm |-\tau\beta\rangle_a|\tau\beta\rangle_b), \end{aligned} \tag{4}$$

where $\tilde{E}_{\pm} = \{2(1 \pm \mathrm{e}^{-4\tau^2|\beta|^2})\}^{1/3}$. The decohered quantum state is then

$$\begin{aligned} \rho_{ab}(t) =& \tilde{E}\left\{\frac{(1+\zeta)}{\tilde{E}_{-}^3}|\Phi^{-}\rangle\langle\Phi^{-}| + \frac{(1-\zeta)}{\tilde{E}_{-}^3}|\Phi^{+}\rangle\langle\Phi^{+}|\right\} \\ \equiv& F(t)|\Phi^{-}\rangle\langle\Phi^{-}| + (1-F(t))|\Phi^{+}\rangle\langle\Phi^{+}|, \end{aligned} \tag{5}$$

where, regardless of the decay time t, $|\Phi^{-}\rangle$ is maximally entangled and $|\Phi^{-}\rangle$ and $|\Phi^{+}\rangle$ are orthogonal to each other.

The decohered quantum state can be purified successfully only when $F(t)$ is larger than $1/2$, because

$$F(t) = \frac{E_{+}^3(1+\zeta)}{E_{+}^3(1+\zeta) - E_{-}^3(1-\zeta)}. \tag{6}$$

It is found that purification is successful when the decoherence time $\sigma t < \ln 2$, regardless of β.

According to entanglement purification condition, several entanglement purification protocols have been proposed.[7−11] For example, a scheme for entanglement purification proposed by Bennett *et al* is that it requires the CNOT operation. The other scheme is based on the polarizing beam splitter (PBS),using photons for the long-distance transmission of quantum states.[12,13] In order to realize the entanglement purification, some devices will be needed, such as a non-linear crystal, a laser pulse, a mirror, a photon detector, and so on.

After entanglement purification of the quantum state, the next step is to implement a long distance quantum teleportation and entanglement swapping operation. Although, we know, teleportation does not exist in classical physics, quantum state teleportation allows the transfer of the quantum state from one system to another distant one. Suppose two entangled pairs of photons I–II and III–IV are produced in the sources X and Y, respectively. One photon from each pair is sent to Alice who subjects them to a Bell-state measurement, projecting them randomly into one of four possible entangled states. Alice records the outcome and hands it to Victor. This procedure projects photons I and IV into a corresponding entangled state. Bob performs a polarization measurement on each photon, choosing freely the polarizer angle and recording the outcomes. He hands his results also to Victor, who sorts them into subsets according to Alice's results, and checks each subset for a violation of Bell's inequality. This shows whether photons I and IV become entangled although they never interacted in the past. This procedure is also known as "entanglement swapping". Generally speaking, the principle of entanglement swapping is that two EPR sources produce two pairs of entangled photons, pair I–II and pair III–IV. One photon from each pair (photons II and III) is subjected to a Bell-state measurement. This results in projecting the other two outgoing photons I and IV onto an entangled state.

3. Efficient quantum state transmission control protocol

In this section, we propose an efficient quantum state transmission control protocol based on the above arguments. We consider the quantum information communication in which each segment maintains quantum entangled state for keeping quantum information. Meanwhile, we allow the photonic quantum repeater of a broken connection to initiate a connection restoration process at the occurrence of an entanglement purification or entanglement swapping failure.

3.1. Quantum state transmission control protocol

The major procedures involved in the transmission control protocol of a quantum state $|\psi\rangle$ in the photonic quantum repeater can be described as follows:

(1) We know that entangled photons can be created by a single diode laser pulse. This makes it possible to produce on demand a stream of several single photons from laser pulse.[14] These photons are the medium used to convey qubit information. When a sequence of single photons arrival at the photon buffer through long-distance communication, the controller sends a message to the $1\times N$ switcher. These photons will be dispatched in different fibre delay loops for memories decided by the programmable $1\times N$ switcher. Then, the photon based on the short delay time will be collected in the photon buffer and transmitted into the purifier through the photon counter.

(2) Once the photon is input into the entanglement purification block, the purifier first performs an entanglement purification for this photon using photon pairs created by a laser pulse. If the photon input can be purified of the polarization entanglement and get a maximum fidelity, the photon will be sent into the "swapper" block. Otherwise, the purifier simply sends a feedback message to the controller to inform of the entanglement purification failure.

(3) At the entanglement connection block, the swapper performs an entanglement swapping of the photon from entanglement purification using quantum teleportation. If entanglement swapping works, an "amplified" quantum state $|\psi'\rangle$ will be output from the photonic quantum repeater, and the quantum state $|\psi'\rangle$ will be transmitted in long-distance communication. Otherwise, the swapper will send a feedback message to the controller to inform of the entanglement swapping failure.

3.2. Entanglement purification and swapping restoration

The major procedures involved in the restoration of a broken entanglement purification and entanglement swapping can be described as follows:

(1) Once a purification failure is detected in the entanglement purification, the purifier sends a purification failure message to the controller through a feedback line. When the controller receives the feedback message, it first breaks the transmission path from entanglement purification to entanglement swapping in order to finish entanglement purification restoration for the photon, then the controller starts to set up the protection link line and sends instruction to the photon buffer. The photon buffer will send a photon selected from fibre delay loops to entanglement purification along the protection link line. If the photon gets a maximum entanglement purification, this implies that the entanglement purification of photon has been finished successfully. In this case, the controller will break the protection link line and restore the work line. Otherwise, each step from photon buffer to entanglement purification will be repeated.

(2) When the controller receives a feedback message about the entanglement swapping failure from the swapper, it first breaks the transmission path from entanglement swapping to output, then the controller starts to set up two protection link lines and sends instruction to the photon buffer. At first, the photon buffer will send a photon selected from fibre delay loops to entanglement purification; after getting a maximum entanglement purification, the photon will be sent into entanglement swapping along the protection link line. If the quantum teleportation is successful, this implies that the entanglement swapping has been finished, and the quantum state $|\psi'\rangle$ will be output from the photonic quantum repeater. In this case, the controller will break the two protection link lines and restore two work lines. Otherwise, it will repeat every step from photon buffer to entanglement swapping.

4. Conclusion and future work

In this paper, we have proposed a scheme of the photonic quantum repeater, which includes a photon buffer mechanism for photon memories and a protection link mechanism for entanglement purification and entanglement swapping restoration at the occurrence of an entanglement purification or an entanglement swapping failure. We have also introduced the theoretical basis of the entanglement purification and entanglement swapping in the photonic quantum repeater. Based on both mechanisms, we further proposed the fibre delay loops as photon memories and an efficient quantum state transmission control protocol. Unlike the existing quantum repeater protocol, the proposed protocol allows the photonic quantum repeater of a broken connection to initiate a connection restoration process at the occurrence of an entanglement purification or entanglement swapping failure. In order to realize a quantum state to be transmitted in long-distance quantum information communication, there is much research work to be done. As a next step, we intend research on other quantum devices, such as the quantum bridge.

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