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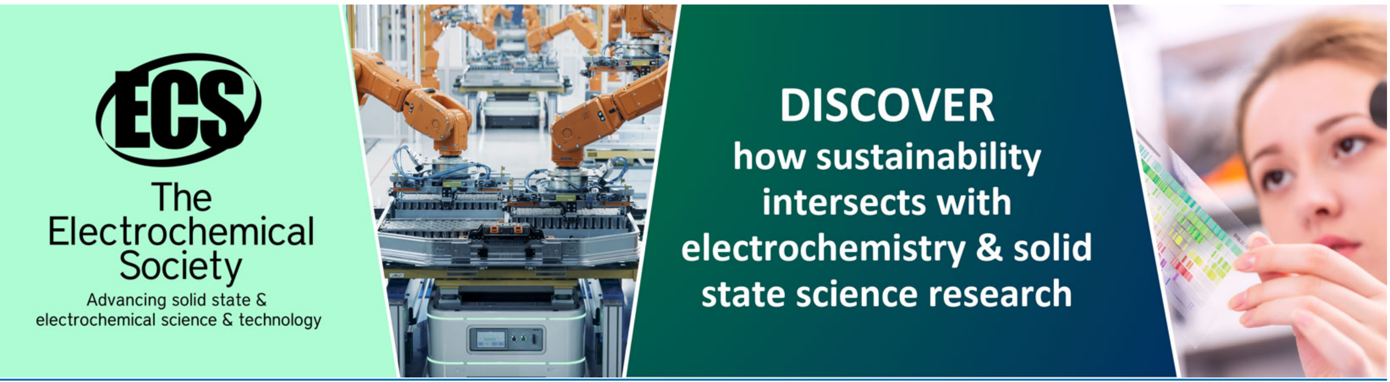

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Research Progress Of Quantum Repeaters

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Abstract. At present, the main components of quantum communication channels are optical fibers and free space. However, whether it is a fiber channel or a free-space channel, the channel in which it propagates is affected by noise, resulting in loss or absorption of photons. Experimental studies have shown that the quantum key can basically meet the requirements of the local area network, and the safety distance is about 100km. However, if you want to achieve longer distance distribution, you can't do without quantum repeaters. The quantum repeater can divide the long-distance communication distance into several segments, and then perform quantum key distribution in several segments respectively; then establish a longer-distance EPR pair between adjacent nodes, and establish an EPR pair to utilize entanglement switching and Entanglement purification technology; finally repeat the above steps, and finally achieve long-distance information transmission. The development of quantum repeaters can solve the communication problems facing the world and promote the replacement of global communication methods.

1. Quantum Communication

Quantum communication is a perfect combination of the classical communication principle and the basic principle of quantum mechanics. It uses the physical essence of quantum mechanics combined with classical information theory to realize the characteristics of high-security information processing that classical communication cannot overcome. Since the introduction of BB84, the way of quantum communication has been mainly quantum key distribution. It is an expert in the field of quantum communications that predicts the quantum communication technology that is most likely to be the first to enter the practical path. Quantum key distribution has amazing results both experimentally and theoretically. Quantum communication best embodies the idea that "information is physical reality." The most basic of quantum communication is quantum bits. A quantum bit is a quantum system that can be encoded by various physical quantities. For example, the polarization state of a photon, the spin state of an atom, and the like. Because of the single qubit non-cloning theorem, any manipulation of the quantum key will change the quantum state or destroy the information carrier itself, so that the information obtained by the eavesdropper is meaningless. We can use the quantum state as the communication key to achieve "absolutely safe" information transmission.

The intrinsic decoherence effect of photons in the process of transmission in vacuum is small. In order for quantum bits to come into use in actual communication, we must avoid their random coupling with the external environment (decoherence effect). When transmitted in an optical fiber, the intensity of the photon is exponentially attenuated with the transmission distance. For classic

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communication, the repeater acts to amplify the compensation signal and can supplement the energy lost during the carrier transmission. However, the classical repeater cannot be applied to quantum communication. Because of the non-cloning theorem of the quantum state, the noise generated by it is too large, so that the bit error rate is high in communication, and more error qubits are generated, eventually leading to communication failure. Quantum repeaters primarily have the ability to manipulate qubits, including operations such as storing qubits and measuring qubits. At the same time, it also guarantees high fidelity reproduction of the transmitted quantum state, so that the next communication user can safely and efficiently extract quantum information on the transmission line.

Usually, the nodes (relay stations) of the quantum communication network are composed of quantum memories, and the connection between stations and stations needs to extend the communication distance by means of quantum entanglement switching technology. Quantum entanglement switching and quantum entanglement purification are the two most important technologies of quantum repeaters. Together with quantum memories, they form the main components of quantum repeaters.

2. Quantum Repeater And Its Development Status

Quantum key distribution has gradually moved from the laboratory to the path of practical commercialization. At present, the security distance of key distribution is about one hundred kilometers, which can basically meet the needs of quantum key distribution in the metropolitan area. However, the global quantum key distribution to realize the concept of the global village is also urgent for the development of human society. Therefore, we need to study how to realize the quantum key distribution in this long distance. The key to solving this problem must be to quantum.The transmission efficiency of a state in a fiber channel changes from exponential decay to polynomial attenuation.

The theoretical model of the quantum repeater is gradually established. In principle, the quantum repeater can be used to make the distributed quantum entanglement pair polynomial decay with the channel length. The quantum key distribution is then completed by a long-range quantum entanglement pair. Only quantum multiplexer-based quantum cryptography can truly realize long-distance quantum communication. We know that photons are currently the only viable quantum bit transfer particles, because photons have the advantage of moving fast and not easily interacting with other substances. However, the channel still has absorption and scattering effects on photons, and the efficiency of photon propagation in the channel decreases with the length of the transmission. It is this exponential level of attenuation that makes remote quantum key distribution impossible. In quantum communication, information is encoded in the quantum state of the photon, and we will establish a series of quantum relay stations to extract information from the transmitted quantum state. The main function of the quantum repeater is to extract the transmitted quantum state information, enhance the fidelity of the quantum state and transfer the measured quantum state to the next user. It is well known that measuring the inevitable quantum collapse effect on quantum ensembles is determined by the fundamental principles of quantum mechanics. Moreover, the more information obtained by measuring the quantum state, the greater the amount of disturbance to the transmitted quantum state. Therefore, it is of great significance to study the information disturbance balance of quantum repeaters.

In 2003, Pan Jianwei published an article on the entanglement and purification scheme in nature. The main idea came from Bennett's control-based non-gate entanglement purification scheme, which uses the PBS polarizing beam splitter to transmit nearly parallel polarized polarized light and transmits parallel polarized incident photons. In fact, it has overcome the shortcomings of the difficulty of controlling the non-door implementation. His example is not the Werner state in the Bennett scheme, but a more special two-state system, so the purification is more efficient.To lay the foundation for long-range quantum communication, it is expected to realize global quantum communication by using quantum repeaters. In 2006, Klein et al. proposed a quantum repeater based on noise-free subspace, which utilizes the noise-free subspace without the influence of collective noise to realize a quantum repeater that preserves quantum states for a long time. In January 2008, W. Dur et al. proposed an embedded quantum repeater based on entanglement purification and entanglement exchange, which enables parallel computing between stages, and the required physical resources only logarithmically increase with channel length, while time is Polynomial growth. In December 2008, Yan Changxing et al. proposed a quantum repeater communication system based on entangled state, which mainly uses quantum entanglement as the basic resource and quantum teleportation principle to transmit quantum information.

In quantum noisy channels, when the transmission distance is greater than the coherence length, standard purification schemes are usually not available. Instead, the channel is divided into multiple segments, and each segment is separately purified, and finally each segment is connected by entanglement switching. This scheme is more efficient than a quantum error correction scheme. Therefore, the quantum repeater can fully realize the great dream of global quantum communication.

3. The Basic Principle Of Quantum Repeater

Our goal is to create an entangled quantum state with high entanglement between two legitimate communication parties that are far apart. Since the entangled state of spatial separation is established, it is not possible to rely solely on local operations, and a quantum channel is also required, and in general, it is noisy. One bottleneck of quantum communication is that as the communication distance increases, the bit error rate becomes higher and higher. For example, when we use fiber and single photon as the quantum channel, the absorption loss and depolarization error of the photon increase exponentially with the increase of the channel. The photon state or the photon itself is destroyed, causing communication to fail. Quantum repeaters are a good solution to this problem.

Below we introduce the basic principles of quantum repeaters. In order to overcome the bottleneck of quantum information exponential decay, we divide the long-distance channel into N smaller-distance channels and establish EPR pairs between adjacent channels. This is the basic principle of quantum repeaters. The original quantum repeater concept was proposed by Briegel and Zoller et al. The principle is as follows:

- The quantum channel between the legal communication parties Alice and Bob is divided into segments. Under the current technical conditions, the attenuation of the quantum information in this relatively short channel is very small, and we can successfully complete the entanglement pair. Allocate and make the fidelity of the entangled state reach the communication threshold requirement.
- Two nodes at each end of each segment are distributed in parallel to distribute quantum entangled pairs (such as Alice and N1 ends, N1 right end and N2 left end), and are stored by their quantum memories, respectively, and the quantum states are purified using entanglement purification techniques. Entanglement purification techniques bring the degree of entanglement between them to communication threshold requirements.Note: The above entanglement distribution and entanglement purification are completely probabilistic, and may be successful or impossible. The higher the probability of success, the better, so the time spent will be less. If it fails, we only need to repeat this process until it succeeds, and then store the entangled state in the corresponding quantum memory.
- After the entanglement is established between two adjacent nodes (each segmented channel), the entanglement switching technique is used at the quantum relay station to extend the communication distance so that non-adjacent nodes (such as Alice and N2) Quantum states are also in entangled states and use entanglement switching techniques to increase the entanglement of quantum states between them.
- Repeat the above operations until the final quantum states between Alice and Bob are entangled and have a high degree of entanglement, and we can use them for quantum communication.

In summary, the whole process is the basic process of the quantum relay scheme. The process can be as described as follows: Each black dot represents a qubit, and the lines between them indicate an entanglement relationship between them. The circle of the relay station indicates the entanglement exchange operation, and the downward arrow indicates the entanglement purification operation.

Assuming that the length of each channel is l0, the total length of the channel is the relationship of the number of relay stations N: $S_n = Nl_0$

The total length of the channel has a simple linear relationship with the number of relay stations. The entangled state distribution of each channel in the above quantum relay scheme is performed independently, and the successful distribution of the entangled pair has nothing to do with the success of the entangled state distribution of other segments. After successfully distributing the entangled pair between a channel, it is immediately stored by the quantum memory at both ends of the channel, waiting for other nodes to successfully distribute.

The embedded quantum repeater mainly uses the quantum entanglement switching technology and quantum entanglement purification to realize the relay function. Each black dot represents a qubit, and the lines between them indicate their entanglement. Since we divide the entire channel into 2n segments, the highest number of n-generation quantum repeaters, parallel operations can be performed between the peers.

In Figure 1, we simply assume that each relay station operates at the same time, including quantum entanglement switching operations, quantum entanglement purification operations, and quantum measurements. After this simplification, we can roughly compare the advantages and disadvantages of these two different relaying schemes. In the case where the communication distance is the same, that is, the number of relay stations is the same. The time required for the embedded relay scheme increases logarithmically with the number of relay stations, and the general relay scheme has a simple linear relationship with the number of relay stations. As can be seen from Fig.4, the embedded relay scheme requires less time. In particular, this advantage is more pronounced in ultra-long-haul communications.

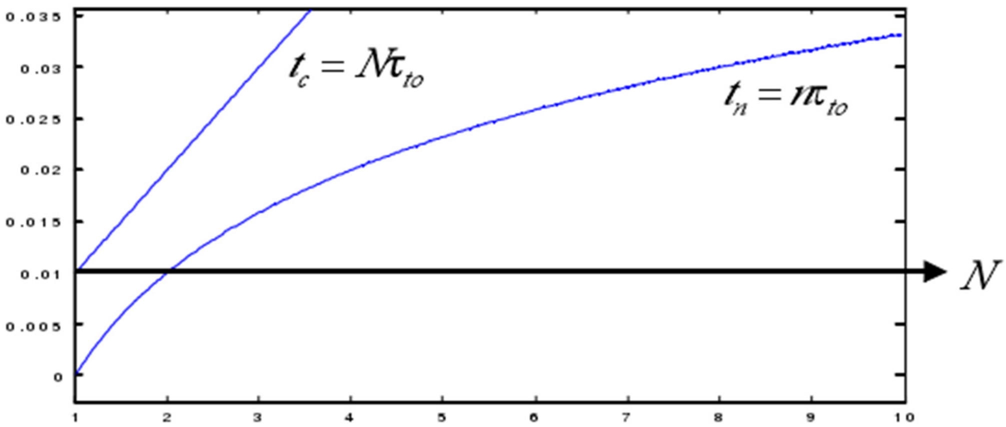

Figure 1.The relationship between the time required to successfully establish EPR and the number of quantum relay stations.

The bit error rate during communication directly limits the length of each channel, so it is important to divide the entire channel to get the best solution. We mainly analyze the performance of the quantum repeater from two physical quantities: the particle pair M and the required T time required to successfully establish the EPR pair at the legal communication home. In fact, each entanglement and purification step utilizes two pairs of entangled particles (the next purification operation utilizes the results of the last purification). Therefore, we can obtain a total of $M = \prod_{k}^{k_{\max}} \frac{2}{p_k}$ pairs of particles required for the entanglement purification operation. Of these, $k_{\max}$ indicates the total number of successful purification operations required, and p_k indicates the probability of success at step k. Molecule 2 uses two pairs of entangled particles for each purification.

The required physical resources are quite different under different purification schemes, so the expression is not unique. M represents the physical resources of the embedded quantum relay scheme, and each purification operation utilizes two pairs of entangled particles of the same confidence. There are already many entanglement purification schemes, and the physical resources they need are not listed. Next, we discuss in detail the time T used to establish an EPR pair over the entire channel, which contains at least three parameters: local operating time τ_{op}, preparation of basic entanglement pair time τ_{pair} and classic communication time τ_{class}. Local operation time τ_{op}, which includes single qubits, double qubits, and time required for measurement operations. In general, the local operation time is relatively small. To prepare the time of the basic entanglement pair τ_{pair}, we consider the fiber to be a lossless channel model (AFC), which can be expressed as $\tau_{pair} = \tau_{AFC} = \left(5\tau_{op} + 2\tau_{class}\right) e^{\frac{l_s}{l_0}}$

Where l_o represents half the length of the fiber and l_s represents the length of each channel.

The time τ_{class} of the classical communication is the time required to check the measurement result, which is $\tau_{class} = \frac{l_s}{c}$ with respect to the length of each channel and the speed of light. For the sake of discussion, we assume that the entangled photon pair between each quantum repeater is an exponent of 2, $L=2^l$, in which case the join process can be performed in parallel. Each connection process includes three basic operations (control non-operation, measurement operation, and operation after checking the measurement results) and classic communication. For an embedded quantum relay scheme, the purification operation time of the mth quantum repeater can be expressed as $t_{top}\left(m\right) = 3l\tau_{op} + f\left(m\right)\left(2^l - 1\right)\tau_{class} + k_{\max}\left[3l\tau_{op} + f\left(m\right)2^l\tau_{class}\right]$

where the length of $f\left(m\right) = \left(2^l\right)^m$ depends on the distance between the basic entangled pairs (the length of each channel). In order to calculate the time of the whole process, we use the following iterative formula $t_{tot}\left(m\right) = t_{tot}\left(m-1\right) + t_{loop}\left(m\right)$

M to represent the m-level embedded quantum repeater. The initial value $t_{tot}\left(0\right) = \tau_{pair}$ of this formula, that is, the initial preparation of the basic entanglement pair, then the time required to establish an EPR pair between Alice and Bob is $T = n\left(3l + 3k_{\max}\right)\tau_{op} + \left[2^l - 1 + k_{\max}2^l\left(\frac{\left(2^l\right)^n - 1}{2^l - 1}\right)\right]\tau_{class} + \tau_{pair}$.

Thus, the total time T increases polynomically with the increase of the communication distance L, and Not exponential growth.

4. Conclusion

The current quantum communication channels are mainly optical fibers and free space. However, information transmitted in any channel will be affected by channel noise, and photon loss (absorption) will increase exponentially with channel length. Experimentally, the safety distance of the quantum key distribution system is about 100 km, which can basically meet the needs of the local area network. However, for quantum key distribution over longer distances, and even quantum key distribution worldwide, we need quantum repeaters to implement them. The basic idea of a quantum repeater is to divide the long communication distance into several segments, each of which can be separately distributed with quantum key; and then use an entanglement exchange and entanglement purification technique to establish a longer-distance EPR between adjacent nodes. Yes; these steps are continually repeated, and finally a quantum entangled state with long distance and high fidelity is obtained. Once the quantum repeater can truly implement the relay function, the quantum communication network covers the entire earth, and the classic communication method will be challenged as never before. Maybe the communication method will be completely updated.

References

[1] Wu D.(2012) Research on quantum information network architecture and routing technology based on quantum repeater. http://www.cnki.net.
[2] Liu Z.J. (2015)Research on Switching Technology in Quantum Multiuser Communication Network . http://www.cnki.net.
[3] Wu Z.B. (2009)Analysis of Quantum Key Distribution Network. Optical Communication Research, 2: 22-24.
[4] Hou B.G. (2013)Research on Topology Structure and Routing Algorithm of Quantum Key Distribution Network. http://www.cnki.net..
[5] Peng H.(2014)Research on Grover routing algorithm in wireless self-organizing quantum communication network. Journal of Zhejiang University of Technology, 6: 612-615.
[6] Wang Z. (2015)Research on security of quantum key distribution system under detection efficiency mismatch. http://www.cnki.net.