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The Development and Application of Quantum Teleportation

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Abstract: Quantum teleportation is one of the most important protocols in quantum information, which is based on quantum entanglement. This paper provides an overview of the basic theory behind the original quantum teleportation protocol and explores its advanced variations. We validate these protocols' effectiveness by constructing simple quantum circuits. Following this, we delve into deeper theoretical aspects, experimental realizations, and applications of quantum teleportation, including quantum state exchange experiments and weak measurement techniques, as well as environment-assisted measurements. Finally, we briefly discussed its current limitations and the future prospects of quantum teleportation.

Keywords: quantum teleportation, entanglement, quantum circuit, Bell state.

1. Introduction

Quantum teleportation is a novel communication method. It no longer transmits classical information but rather quantum information. Utilizing quantum entanglement, quantum teleportation offers significant advantages, including long-distance quantum communication, enhanced security in quantum information transfer, and the capability to transmit quantum information between different quantum systems. Proposed by Einstein, Podolski, and Rosen in 1935, quantum entanglement describes a "mysterious" relationship between particles, where the state of one particle can instantaneously affect the state of another, regardless of the distance between them.

The concept of quantum teleportation was further developed by Bennett et al. in 1993, who proposed a scheme for teleporting an unknown quantum state (i.e., an unknown quantum bit) from one location to another without physically moving the particle itself, thereby achieving quantum information transfer. In 1997, the Austrian scientist Zeilinger's research group conducted experiments on the quantum teleportation of photon polarization states[1]. Most of the above studies were conducted under ideal conditions without noise or decoherence. However, in any practical implementation of the transmission protocol, noise is inevitably present and affects the entanglement state during transmission to the transmitting party.

To address this, entanglement purification techniques are employed to enhance the entanglement of a pair of qubits by using a large number of entangled qubits and combining local operations with classical communication [6].

Quantum error correction is another method used to protect quantum bits from noise during transmission, although it requires a large number of redundant quantum bits for encoding logical quantum information.

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Therefore, in the pursuit of quantum network implementation, finding a solution to overcome the inherent quantum noise with a limited number of quantum bits is a major challenge. In recent years, a decoherence control strategy based on weak measurement has been widely applied and verified in theoretically and experimentally[6].

2. The process and basic theory of quantum teleportation

2.1. The conditions before experiment[2][3]

Assuming that A and B are in two different locations. A possesses qubits 1 and 2, while B has qubit 3. Qubit 1 is in the following quantum state:

$$|\varphi\rangle_1=\alpha|0\rangle_1+\beta|1\rangle_1$$

where α and β are two arbitrary, unknown complex coefficients, satisfying:

$$|\alpha|^2+|\beta|^2=1$$

Qubits 2 and 3 are entangled to form a Bell state, which serves as a quantum channel between A and B:

$$|\varphi\rangle_{23}=\frac{1}{\sqrt{2}}(|0\rangle_{23}|1\rangle_{23}-|1\rangle_{23}|0\rangle_{23})$$

The overall state of the system composed of these three qubits is:

$$|\varphi\rangle_{123}=\frac{1}{\sqrt{2}}\{\alpha(|0\rangle_1|0\rangle_2|1\rangle_3-|0\rangle_1|1\rangle_2|0\rangle_3)+\beta(|1\rangle_1|0\rangle_2|1\rangle_3-|1\rangle_1|1\rangle_2|0\rangle_3)\}$$

The Bell states for qubits 1 and 2 are defined as:

$$|\varphi^{\pm}\rangle_{12}=\frac{1}{\sqrt{2}}(|0\rangle_1|1\rangle_2\pm|1\rangle_1|0\rangle_2)$$

$$|\varphi^{\pm}\rangle_{12}=\frac{1}{\sqrt{2}}(|0\rangle_1|0\rangle_2\pm|1\rangle_1|1\rangle_2)$$

Expanding the qubit 1 and 2 into equivalent forms of these Bell states:

$$|\varphi\rangle_{123}=\frac{1}{\sqrt{2}}[|\varphi^-\rangle_{12}(-\alpha|0\rangle_3)-\beta|1\rangle_3)+|\varphi^+\rangle_{12}(-\alpha|0\rangle_3)+\beta|1\rangle_3)]+\frac{1}{\sqrt{2}}[|\varphi^-\rangle_{12}(\alpha|1\rangle_3)+\beta|0\rangle_3)+|\varphi^+\rangle_{12}(\alpha|1\rangle_3)-\beta|0\rangle_3)]$$

2.2. The process of experiment

A transfers the information state of bit 1 $|\varphi\rangle_1$ to bit 3 owned by B, changing the information state of bit 3 to $|\varphi\rangle_3$. In this way, α,β is transmitt from bit 1 to bit 3.

Operating principle:

①A performs a Bell state measurement on qubits 1 and 2.

②Alice communicates the measurement results to Bob via classical communication.

③According to the information from A, B transforms bit 3 to achieve:

$$|\phi\rangle_1\rightarrow|\phi\rangle_3$$

If A gets the message |φ- ﹥12(|φ ﹥123 collapsed into the first item of the expansion), the bit3 belonging to B collapsed into: |φ ﹥3=α|0 ﹥3+β|1 ﹥3, on this condition, B can obtain the information state without any operation.

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If A gets the message $|\varphi+\rangle_{12}(|\varphi\rangle_{123}$ collapsed into the second item of the expansion), the state of bit3:$|\varphi\rangle_3$=-α$|0\rangle_3$+β$|1\rangle_3$,B can obtain the information state by applying a transformation δz to bit3.

$$\delta z\ (-\alpha|0\rangle_3+\beta|1\rangle_3)=\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\begin{pmatrix}\beta\\ -\alpha\end{pmatrix}=\alpha|0\rangle_3+\beta|1\rangle_3$$

If A gets the message $|\varphi+\rangle_{12}(|\varphi\rangle_{123}$ collapsed into the third item of the expansion), the state of bit3:$|\varphi\rangle_3$=α$|1\rangle_3$+β$|0\rangle_3$,B can obtain the information state by applying a transformation δx to bit3.

$$\delta z\ (\alpha|1\rangle_3+\beta|0\rangle_3)=\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\begin{pmatrix}\alpha\\ \beta\end{pmatrix}=\alpha|0\rangle_3+\beta|1\rangle_3$$

If A gets the message $|\varphi+\rangle_{12}(|\varphi\rangle_{123}$ collapsed into the fourth item of the expansion), the state of bit3:$|\varphi\rangle_3$=α$|1\rangle_3$-β$|0\rangle_3$,B can obtain the information state by applying a transformation δx to bit3.

$$\delta z\ (\alpha|1\rangle_3-\beta|0\rangle_3)=\begin{pmatrix}0 & i\\ -i & 0\end{pmatrix}\begin{pmatrix}\alpha\\ -\beta\end{pmatrix}=i(\alpha|0\rangle_3+\beta|1\rangle_3)$$

2.3. Building a quantum gate circuit to verify the effectiveness of the quantum teleportation[5]

Step1 A applies CNOT to the first two qubits.
Step2 A applies Hadamard to the first qubit.
Step3 A measures the first two qubits.
Step4 A sends the results to B who applies correction.

2.4. The quantum teleportation circuit is illustrated as follows

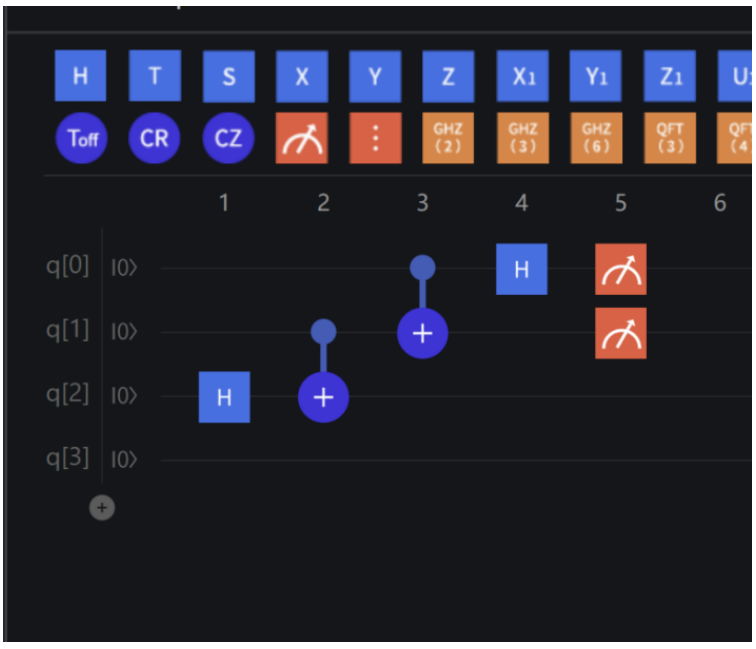

Figure 1: The circuit of quantum teleportation

3. Quantum exchange experiment

In 1998, the quantum exchange experiment - the hyperspace teleportation experiment of quantum entanglement - was first realized.

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Previously, it was believed that quantum entanglement could only be established through direct interaction.

This experiment demonstrated that quantum entanglement could be created indirectly and remotely[4].

Before the experiment, Photons 1 and 2 are in an entangled state $|0\rangle_{12}$,while photons 3 and 4 are in another entangled state$|0\rangle_{34}$. At this point, there is no entanglement between the two pairs of photons.

Photons 1 and 4 are with Bob, while Photons 2 and 3 are with Alice.

Initial state of the entire system is given by:

$$|\varphi\rangle_{1234}=\frac{1}{2}(|0\rangle_1|1\rangle_2-|1\rangle_1|0\rangle_2)\otimes(|0\rangle_3|1\rangle_4-|1\rangle_3|0\rangle_4)$$

This can be decomposed as:

$$|\varphi\rangle_{1234}=\frac{1}{2}(|\varphi^+\rangle_{14}|\varphi^+\rangle_{23}-|\varphi^-\rangle_{14}|\varphi^-\rangle_{23}-|\Psi^+\rangle_{14}|\Psi^+\rangle_{23}+|\Psi^-\rangle_{14}|\Psi^-\rangle_{23})$$

In the experiment, Alice performs Bell measurements on photon 2,3 in her hand, generating corresponding entanglement decomposition and collapse.

For example, if Alice measures the state $|\varphi^+\rangle_{23}$, she would communicate this result to Bob. Consequently, Bob can determine the outcome and apply the necessary corrections.

4. Non local storage of hyperspace transfer

Consider photon 1# is in an unknown information state.

$$|\psi\rangle_1=\frac{1}{\sqrt{2}}(\alpha|0\rangle_1+\beta|1\rangle_1)$$

Photons 2#,3#,4#and 5# were prepared in advance on a 4-photon GHZ state.

$$|\varphi\rangle_{2345}=\frac{1}{\sqrt{2}}(|0\rangle_2|0\rangle_3|0\rangle_4|0\rangle_5+|1\rangle_2|1\rangle_3|1\rangle_4|1\rangle_5)$$

Decompose this state:

$$|\phi\rangle_{12345}=|\varphi\rangle_1|\phi\rangle_{2345}=\frac{1}{2}\{|\varphi^+\rangle_{12[}\alpha|0\rangle_3|0\rangle_4|0\rangle_5+\beta|1\rangle_3|1\rangle_4|1\rangle_{5]}$$
$$+|\varphi^-\rangle_{12[}\alpha|0\rangle_3|0\rangle_4|0\rangle_5-\beta|1\rangle_3|1\rangle_4|1\rangle_{5]}$$
$$+|\psi^+\rangle_{12[}\alpha|1\rangle_3|1\rangle_4|1\rangle_5+\beta|0\rangle_3|0\rangle_4|0_{5]}$$
$$+|\psi^-\rangle_{12[}\alpha|1\rangle_3|1\rangle_4|1\rangle_5-\beta|0\rangle_3|0\rangle_4|0\rangle_{5]}\}$$

Alice measures the photons 1#and2#, photons 3#, 4#, 5# are transformed to

$$|\psi\rangle_{345}=\frac{1}{\sqrt{2}}(\alpha|0\rangle_3|0\rangle_4|1\rangle_{5+}\beta|1\rangle_3|1\rangle_4|1\rangle_5)$$

Finally, they obtained the information $\alpha\ and\ \beta$.

The information $\alpha\ and\ \beta$ are carried by photons 3#, 4# and 5# which are located in different places and controlled jointly by three parties.

Without prior consultation and collaborative operation, no single party can extract the information. It embodies the "non local storage" of quantum information. Quantum teleportation demonstrates the nonlocality of quantum entanglement, where the correlations between entangled particles are not limited by spatial distance. This concept holds significant importance in theoretical research and quantum information processing, such as in the construction of quantum computing, quantum communication, and quantum networks. However, practical implementation of quantum teleportation

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requires precise quantum state preparation, entanglement generation, quantum manipulation, and measurement techniques, which remain significant challenges in the field of quantum technology.

5. Weak measurement and environment-assisted measurement

In the presence of inevitable noise interference, entanglement purification and quantum error correction require a large number of redundant quantum bits to encode logical quantum information. In this article, we introduce a stealth teleportation protocol that utilizes environment assisted measurement (EAM) and weak measurement (TP-EW) to transmit unknown quantum bits through a noisy channel via a single copy of the entangled state. It should be emphasized that the proposed teleportation protocol is applicable to any type of entanglement[6][7].

5.1. Environment-assisted measurement

In this section, we would briefly explain the basic concept of Environmental Aided Measurement (EAM), which is a key component of our transmission protocol[6].

According to the Schr ö dinger equation, the evolution of the total density matrix (system+environment) is given by the following equation:

$$\rho_{tot}(t)=U(t)(\rho_s(0)\otimes\rho_E)U^{+}(t),\ U(t)=\exp(-iH_{tot}\,t)$$

where U(t) is the total evolution operator with the total Hamiltonian H_{tot} including the interaction between system and environment.

Assume that the environment is in a vacuum state. Then, by tracking the degrees of freedom of the environment, the evolution of the system's reduced density matrix can be obtained as

$$\rho_s(t)=\mathrm{Tr}_E(\rho_{tot}(t))$$

$$=\Sigma_n E\langle\Psi^{+}|U(t)|0\rangle_E\rho_s(0)_E\langle 0|U^{+}(t)\ |\psi_n\rangle_E$$

$$=\Sigma_n K_n\ \rho_s(0)\ K_n^{+}$$

And $K_{n=E}|\psi_n\rangle U(t)|0\rangle_E$ is the so-called Kraus operator, it depends on the basic state of the environment and the selection of the complete foundation

of the environment$\{|\psi_n\rangle_E\}$[6]. Therefore, changing the foundation of the environment$\{|\psi_n\rangle_E\}$ to $\{|\psi_m\rangle_E\}$. For example, $E|\psi_m\rangle=\Sigma_m\langle\psi_m|V_{n,m}$ will cause the other Kraus operator $L_m=E\langle\psi_m|U(t)|0\rangle_E$,where $V_{n,m}$ is a unitary matrix. The relationship between two sets of Kraus operators is described as

$$K_n=\Sigma_m V_{n,m}E|\psi_m\rangle U(t)|0\rangle_E$$

$$=\Sigma_m V_{n,m}L_m\,.$$

After measuring the environment, it collapses into the eigenstate of the observable being measured. The system would also project to states corresponding to each environmental state[6]. After measuring the environment, only quantum trajectories corresponding to the reversible Kraus operator are considered, while others are discarded[6][8] . Finally, use a weak measurement operator to restore the initial state of the system and this measurement operator is defined as the reciprocal of the reversible Kraus operator as

$$R_n=N_nK_n^{-1}$$

Where N_n is Normalization Factor, given by the following equation:

$N_n=\min\{\sqrt{\lambda_i}\}$, λ_i is the eigenvalues of a matrix $K_nK_n^{+}$.

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5.2. Transmission protocol using weak measurement and EAM over noisy channels.

In this part, I would introduce a stealth quantum teleportation protocol that utilizes EAM and weak measurements through noisy channels. EAM acts on quantum entanglement partitioning process and weak measurement is applied in the final step of the invisible transmission state of the receiver[6][9].

First, Alice prepares entangled states, retaining part of the system and sending a qubit to Bob through an Amplitude Damping Channel (ADC).

Secondly, Bob performs measurements on a noisy audio channel, preserving the system state corresponding to the reversible Kraus operator of the channel, discarding other states corresponding to the irreversible Kraus operator[6][10][11].

Finally, based on successful EAM, weak measurement operators are designed to mitigate noise effects and recover the transmitted input state at the receiving end. The teleportation protocol is applicable to various quantum teleportation protocols that share entanglement[6].

6. Compared to traditional communication

6.1. Larger information capacity

Compared to classical particles that can only exist in two states, 0 or 1, microscopic particles allow for simultaneous superposition of 0 and 1.This property allows quantum systems to carry significantly more information than classical systems.

6.2. Enhanced Security

Quantum No-Cloning Theorem: This principle states that it is impossible to perfectly replicate an unknown quantum state, and any attempt to measure or replicate a quantum state would change its state and be detected by the sender. This means that if someone attempts to steal information, the sender can immediately detect and take corresponding security measures[12].

Quantum entanglement: By utilizing entangled particles for information transmission, the security of the information transmission process can be ensured. During the transmission process, if there are eavesdroppers, they cannot obtain information without leaving traces, because any measurement of entangled particles would destroy their entangled state and be detected by the sender and receiver[13].

So can quantum teleportation achieve superluminal communication? Unfortunately, quantum teleportation cannot achieve superluminal communication.

A closer look at the process reveals the limitation: classical communication between Alice and Bob is still required. Through this classical channel, Alice informs Bob of the Bell state measurement results of qubits 1 and 2, allowing Bob to apply the correct transformation to bit 3 and achieve:

$$|\phi\rangle_1 \rightarrow |\phi\rangle_3$$

7. The prospect of quantum teleportation

Quantum teleportation represents a major advancement in future communication technologies, offering high efficiency, strong security, and robust resistance to interference.

Compared with traditional communication methods, quantum communication is unparalleled and irreplaceable in terms of security. Quantum secure communication based on quantum key distribution would become a very promising technological means to ensure network information security in the future. In the environment of complex electromagnetic information confrontation, quantum hidden states to transmit information ensures the timeliness, integrity, and security of communication. Quantum communication would demonstrate its power in the increasingly complex international information war[14].

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Quantum communication, applied in the unpredictable information warfare and cyber warfare, undoubtedly greatly improves communication security and is conducive to ensuring the stability of our command and control system, and controlling the information initiative in intelligent warfare.

Quantum communication can break through the military blind spots of deep water communication. By utilizing entangled photon pairs, a secure channel connection can be achieved, and the communication range can be extended through repeaters. This not only enhances the communication capabilities of submarines but also allows for quieter operations, improving underwater communication effectiveness.

By using quantum communication technology to connect ghost submarines hidden in the deep sea, on the one hand, it can greatly improve the communication capabilities of submarines; On the other hand, strategic decisions can be made more effectively based on the information available, enabling submarines to closely engage, detect, and strike the enemy, thereby enhancing their combat capabilities.

8. Conclusion

Quantum communication enable full coverage of military battlefields, offering long-range, highly secure communication. In the future, with the deployment of quantum communication satellites, global networking could be achieved, significantly reducing the risk of information interception. Once a fully developed space-based quantum communication system is established, it will drastically upgrade military command and control capabilities.

With its large channel capacity and high communication speed, quantum communication networks will become indispensable in future information warfare, reshaping the landscape of military conflict.

However, the measurement and determination of quantum state information also require the assistance of existing communication technologies. The key technologies for the preparation, distribution, and measurement of entangled pairs in quantum teleportation still need further breakthroughs. Quantum teleportation remains in the realm of theoretical research and experimental exploration, with practical applications still some distance away.

Quantum teleportation has undergone a long period of debate and development, and has now been preliminarily applied in the field of signal transmission. Compared with traditional communication technology, it has advantages such as efficient transmission and good confidentiality. But there are also many difficulties that have not yet been overcome in practical applications. However, regardless, quantum communication is a promising technological direction for the future.

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