The Progress and the state-of-art approaches of Quantum Teleportation and Communication

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Abstract. Quantum teleportation is a new technique utilized dispersed quantum entanglement to transmit information (i.e., the quantum states). In this paper, the principles and the protocol will be introduced systematically. Specifically, the experimental setups and the state-of-art applications will be discussed. According to the analysis, one can better understand the working principle and current development of quantum teleportation. However, the limitation of further applying the quantum teleportation is obvious the cost of building the QT infrastructure and the superconducting technology. Besides, it is also too expensive to achieve large-scale use and commercial promotion. In the future, QT will expand its industrial scale and build a national or even global quantum communication network. These results shed light on guiding further development for quantum teleportation important.

Keywords: Quantum teleportation, progress, application.

1. Introduction

Traditional communication is a deterministic signal characterized by macroscopic physical quantities such as current, voltage, electromagnetic field and light wave [1]. It uses electrical signals, optical signals, microwave signals and other modulation transmission, channel transmission, and then demodulation acceptance. It is mainly based on stimulated radiation, frequency conversion, photoelectric effect, and other mechanisms to achieve the regulation and conversion of electrical, microwave, and optical signals. Connection objects are classical information processing terminals, e.g., computers and servers. Compared with optical quantum communication, classical communication is not safe or efficient. Quantum communication is a novel approach, mainly consists of quantum teleportation and quantum key distribution [2].

Compared with optical quantum communication, it possesses the advantages of security, which will know whether the information is be received by others, attributed to the random distribution of the key in terms of quantum encryption. In order to make quantum communication from theory to reality, scientists at home and abroad have done a lot of research work since the 1990s. Since the quantum communication theory was proposed by IBM researchers in the United States in 1993, both the National Science Foundation and the Defense Advanced Research Projects Agency have carried out in-depth research on this project. There are as many as 12 projects, and the Ministry of Posts of Japan regards quantum communication as a strategic project in the 21st century [3]. China has been engaged in research in the field of quantum optics since the 1980s. In recent years, the quantum research group of the University of Science and Technology of China has made outstanding achievements in quantum communication. To be more specific, Pan's research team successfully achieved the first quantum teleportation of degree of freedom in the world by using QT of spin and orbital angular momentum of single photon. Since 2016, the research team of Li, a member of the research group of the university, has used the path freedom coding of photons to prepare high-fidelity three-dimensional entanglement states, and realized the effective transmission of high-dimensional quantum entanglement states in the 11-kilometer optical fiber [4]. In 2021, Fedorov's group achieve unconditional quantum teleportation of propagating microwave using two-mode squeezing [5].

As more progress in QT has been made, a revolution in communication technology is within reach. At this point, collecting and reviewing some recent breakthroughs can help one quickly get familiar with contemporary development of QT. The rest part of the paper is organized as follows. The Section 2 will discuss the basic principle of Quantum teleportation. The Section 3 will elaborate on the protocol we use in quantum teleportation. The Section 4 will describe the recent experiment setups, and the Section 5 will introduce the applications which use quantum teleportation. The Section 6 will discuss the limitations and the Sec. 7 will summarize the whole paper.

2. Basic principle of Quantum teleportation

The process of quantum teleportation is referring to the group of Innsbruck who first achieve the quantum teleportation experimentally in 1997 [6]. A pair of entangled qubits, 2 and 3, created by an EPR source are sent to Alice and Bod, this pair of qubits are in the entangle state [7]. Therefore, we can write it as

$$\left|\Psi_{23}^{(-)}\right\rangle = \sqrt{\frac{1}{2}}(|0_2\rangle 1_3\rangle - 1_2\rangle|0_3\rangle) \tag{1}$$

Now the third particle, (particle 1), that in the initial state of what Alice wants to teleport is in the state of

$$|\phi_1\rangle = a|\,0\rangle + b|\,1\rangle \tag{2}$$

where the *a* and *b* are the probability amplitudes of the initial state *0* and *1* respectively. Then, Alice projects the particle 1 and 2 onto an entangle state and state will instantaneously be transferred to the particle 3[8].

$$|\Psi_{123}\rangle = \frac{a(|0\rangle_1|0\rangle_2|0\rangle_3 - |0\rangle_1|\,1\rangle_2|0\rangle_3)}{\sqrt{2}} + \frac{b(|1\rangle_1|0\rangle_2|1\rangle_3 - |1\rangle_1|1\rangle_2|0\rangle_3)}{\sqrt{2}} \tag{3}$$

Expressing this state using four maximally bell-state of the particle a and c, we derive

$$\left|\Phi_{12}^{\pm}\right\rangle = \frac{|0\rangle_1|0\rangle_0 \pm |1\rangle_0\,|1\rangle_1}{\sqrt{2}} \tag{4}$$

$$\left|\Psi_{12}^{\pm}\right\rangle = \frac{|0\rangle_1|1\rangle_2 \pm |1\rangle_1\,|0\rangle_2}{\sqrt{2}} \tag{5}$$

When Alice measures both particle 1 and 2, the particle b on the Bob side will has a 25 percent chance to collapse to the initial state of particle c. Hence, Alice is required to send Bob of her outcome through a classical channel. Once Bob knows the result of Alice's side, he can perform a unitary transformation on his particle to obtain the initial state of the teleported particle.

3. Protocol

We assume that the two parts of transmitting the information respectively are Alice and Bob [9]. The experimentalist Alice has a qubit in her laboratory in a quantum state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$. Alice wants to send her quantum state to a remote laboratory run by her colleague Bob. Bob should conduct the following quantum circuit in his lab.

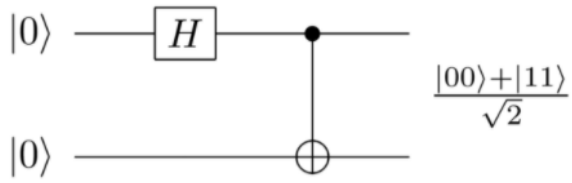


Figure 1. Bob's quantum circuit

After accomplishments, Bob sends one of the two qubits to Alice. It doesn't matter which qubit he sends, because the state is symmetrical. Now, we can describe the three qubits as given in Figs. 2 and 3.

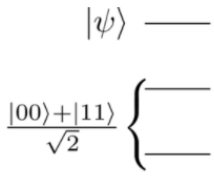


Figure 2. the three qubits

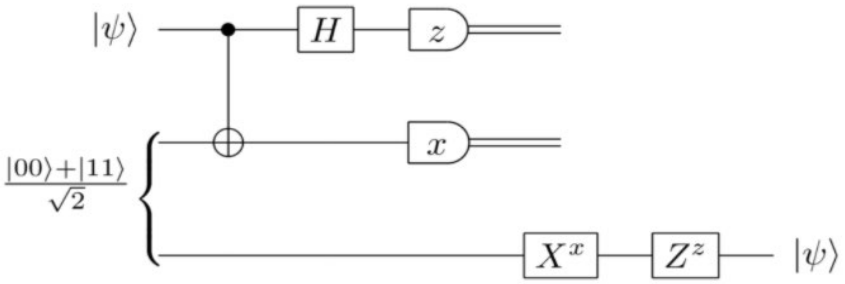


Figure 3. Quantum circuit and quantum state

Alice's work begins with an unknown quantum state |ψ⟩, which will be teleported. Alice and Bob share a quantum state: $|00\rangle + |11\rangle/\sqrt{2}$. Alice then performs two gate operations on her qubits and then, on a computational basis, measures both qubits, resulting in z and x. These are just regular classical bits, each taking a value of 0 or 1. After measuring her qubits, Alice sends Bob the classical z and x. Bob then applies a Pauli X gate (a quantum NOT gate) to his qubits if x = 1, and otherwise does nothing. Similarly, if z = 1, Bob applies a Pauli Z gate to his qubit, otherwise does nothing. The end result is that Bob's qubit is now in the same state ψ⟩ that Alice's started working on, i.e., Alice has successfully transmitted her status to Bob [9].

4. Setups of recent experiment

In 2017, Pan and his team experimentally achieved QT between ground station of satellite [10]. The transmitter (Ngari) on the Earth and the receiver (Micius) in the satellite forms an uplink implement. On the side of the transmitter as shown in Fig. 4, two pairs of photons are produced by ultraviolet pulses travel through two bismuth borate (BiBO) crystals. The process of collinear spontaneous parametric down-conversion (SPDC) generates the first pair of photons, and thus one of the photons shows the existence of the photon 1. The initial state of the photon1 is randomly prepared by utilizing half-wave plate (HWP) and quarter-wave plate (QWP). Polarizing beam splitter (PBS) overlaps photons 1 and 2 in the Bell-state measurement sector. Then, each state of the output that detects one photon is selected and the condition is that the two photons are having the same polarization. 3 and 8-nm narrowband filters play the role of eliminating the extra frequency correlation of the down-converted photon. The photon1 whose state is teleported is received by a single-mode fiber, then passed to the transmitting antenna. In the sector of transmitting antenna Figure 4c, fine and coarse tracking is done by a faster-steering mirror (FSM) and tow-axis gimbal mirrors. Signal and beacon light are distinguished by a dichroic mirror. This section also contains laser emitters emit 671nm continuous-wave laser and 1064nm, 10kHz repetition rate pulsed laser to the satellite for APT and synchronizing time, and the CMOS camera plays the role of imaging the beacon laser sent by the receive (top right the figure's c part). Inside the satellite Figure 4d, which is equipped with an identical APT system with the one from the transmitter. A polarization analyzer that has a HWP, a PBS, and a QWP, also containing: single-photon detectors (SPD1 and 2), CMOS cameras, laser diodes (LD1-3), and interference filter (IF).

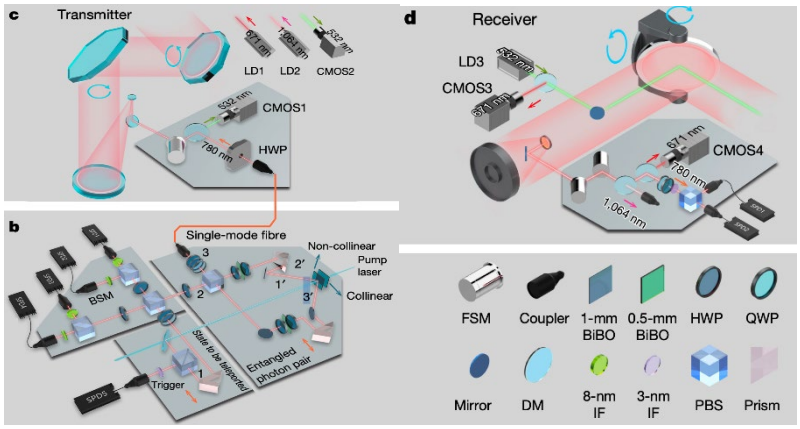


Figure 4. A visualization of the experimental setup of Pan's group [10].

Breakthrough in quantum teleportation of microwaves in the cryogenic environment has achieved by Fedorov's group in 2021. The team utilized two-mode squeezing and analog feedforward to experimentally achieve unconditional quantum teleportation of propagating coherent microwave states over a distance of 0.42m [5].

As illustrated in figure 5, sectors are connected with Nb/Ti superconducting coaxial cable. Path-entangled TMS states are produced in a section that consisting entanglement Josephson parametric amplifiers (JPAs) and a hybrid ring. The entangled states distribution between Alice and Bob can simply be done using Nb/Ti superconducting cables. A new hybrid ring is utilized to entangle the input state and the TSM state on Alice's section, and the outcomes are then undergoing a pair of measurement JPAs. Another hybrid ring on Alice's side takes the outcomes of the measurement JPAs step to perform a superimposition and send a feedforward signal to Bob's side. The goal of this feedforward signal is to compensate the imperfection in the classical channel.

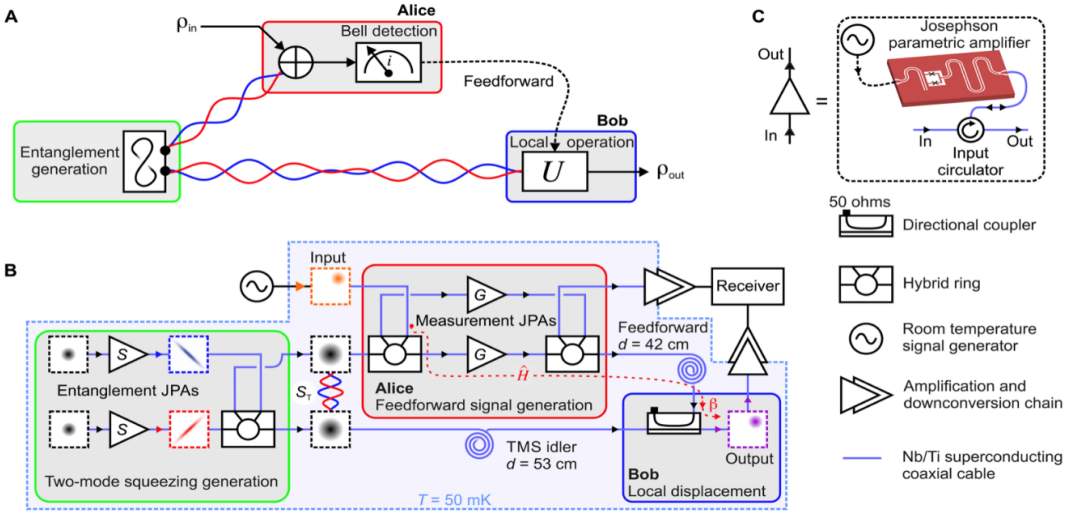


Figure 5. The experiment teleports states of a microwave between two superconducting system (0.42m) by generating two-mode squeezed (TMS) microwaves [5].

5. Applications

Mozi is the world's first satellite designed to conduct quantum science experiments. It has many experimental tasks, but the main two experiments are quantum secret key distribution and quantum teleportation.

Within the city limits, building a metro quantum communication network through optical fibers is the best solution. Nevertheless, to achieve long-distance and even global quantum communication, it's difficult to rely on optical fiber quantum communication technology. In outer space, the vacuum environment has almost no attenuation of light transmission, and there is also no decoherence effect. Therefore, if single photon or entangled photon pairs can be transmitted out of the atmosphere,

combined with spaceborne platform technology and beam precise positioning technology, it is possible to realize long-distance quantum communication in free space. At the same time, satellites are the most promising way to realize ultra-long-distance practical quantum cryptography and quantum teleportation on a global scale due to their unique advantage of conveniently covering the entire Earth.

Quantum teleportation adopts the method of transmitting entangled photons on the ground and receiving them in the sky. When the "Mozi" transits, it establishes an optical link with the Ali ground station in Tibet at an altitude of 5100m. The ground light source generates 8,000 quantum teleportation instances per second, and the ground emits entangled photons to the satellite. The experimental communication distance ranges from 500 kilometers to 1,400 kilometers. All six states to be teleported exceed the classical limit with a confidence level of more than 99.7%. If this work were repeated in the same length of fiber, it would take 380 billion years to observe one event. This important achievement has laid a reliable technical foundation for future research on quantum communication networks at the space scale, as well as research on space quantum physics and quantum gravity experiments [10].

The backbone of the superconducting quantum networks can take a huge advantage on the microwave cryogenic links. It will also benefit the optical links due to its single-photon transmission with high quantum efficiencies, and a simple technical implementation. The microwave QT along with its technological advances, can be applied to the establishment of the quantum networks with quantum processors. In addition, the experiment contributes to the distribution of superconducting quantum computers and at the same time provides a fine base for building secure and save communication system in use of microwaves.

6. Limitation and Future expectations

The chief obstacles that stand in our way of the development of the QT system in the society are the cost of QT infrastructure, and superconducting technology. Quantum teleportation is based on quantum entanglement, and the current research is achieved with photons and photon entanglement as resources, and the theory is not limited to this. In fact, the entanglement of photons and atoms or the entanglement of phonons and ions is also satisfied, and these two kinds of entanglement can also be used as media to transfer quantum state information.

7. Conclusions

In summary, this paper discussed the progress of quantum teleportation from the perspective of quantum communication. To be specific, QT uses quantum entanglement to transmit information and users can know clearly that whether the information has been leaked. Therefore, QT will be a critical ingredient for quantum communication. Many applications have been developed, e.g., the Mozi and the Beijing-Shanghai railway line. There are still many goals in the future, to build a complete wide-area quantum communication network system with integrated space, to form a strategic emerging industry with leading international status and the next generation of national information security ecosystem, to explore the test of general relativity, quantum gravity and other basic principles of physics. Overall, these results offer a guideline for new types of experiments and investigations of the foundations of quantum mechanics.

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