Increasing Communication Rates Using Photonic Hyperentangled States

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Abstract: We propose a mechanism for increasing transmission rate of quantum communication channels, by multiplexing spin and multiple orbital angular momentum states on a single photon, transmitting the photon, and demultiplexing them to different photons.

Entanglement is a fundamental resource in quantum communication protocols, where photons are an optimal carrier of information, given their resilience to decoherence and ease of creation and transportation. Photon-based quantum information uses the DoFs of light, where qubits are implemented on any physical states that can be regarded as two-level states. Since any binary quantum alternative can serve as a qubit [1], a single quantum particle can naturally possess multiple degrees of freedom (DoFs) and thus it can represent several qubits. A state of two particles entangled by two or more DoFs is called a hyperentangled state [2].

In recent years, multipartite entanglement for increasing the channel capacity has been proposed and demonstrated [3–5]. However, at present, the main obstacle in establishing large-scale quantum networks are inherent losses of the transmission channels. Due to the ever-increasing demand for high-capacity communication, hyperentangled photonic states are an excellent platform for various quantum communication protocols, as it allows to encode a greater amount of information in a single physical photon [6]. However, when information is stored on a single photon there are some limitations, since the non-classical correlations manifesting the entanglement are always local. In this work we show how to overcome the limitations of encoding on a single photon using quantum teleportation [7].

Here, we present a scheme for transmitting qubits at a higher rate by multiplexing N qubits on a single photon via a quantum teleportation protocol, transmitting the single photon, and eventually demultiplexing the quantum information to N photons each carrying a single qubit, where the information can be processed in parallel exploiting the nonlocality of quantum information processing.

For our protocol, we use quantum teleportation [7], which provides a 'disembodied' way to transfer quantum states from one object to another at a distant location, assisted by previously shared entangled states and a classical communication channel. Recently, the teleportation of multiple DoFs in a single photon was demonstrated [9]. In this work we propose the teleportation of several DoFs from a single photon to multiple photons.

As an example, we propose to use DoFs of spin angular momentum (SAM) and orbital angular momentum (OAM). Our scheme has two parts: a multiplexing part, where we teleport the SAM and the OAM of Photons P_1 and P_2, respectively, to Photon C, and a demultiplexing part- where we teleport again the DoFs from photon C (in this example, SAM and OAM) to separate photons E and F (Fig. 1(a)). Our encoding protocol comprises of Photon C (the "information carrier") and Photons A and B, which are entangled (separately) in their SAM and OAM with Photon C, respectively. The decoding protocol comprises of Photons D, E and F.

We generate these entangled states using a metasurface (Fig. 1(b)). These are masks imprint a different wavefunction to each polarization of the electromagnetic field. These devices enable local control of optical polarization and were recently used to imprint entanglement between the SAM and the OAM of a photon [8]. The transmitter prepares ahead a hyperentangled photon pair with Photons A and C entangled in their SAM, and Photons B and C entangled in their OAM, simultaneously, as follows:

$$\begin{aligned}&(|\sigma_+,+1\rangle_C \otimes |S_B,-1\rangle_B - |\sigma_+,-1\rangle_C \otimes |S_B,+1\rangle_B) \otimes |\sigma_-,L_A\rangle_A \\ &- (|\sigma_-,+1\rangle_C \otimes |S_B,-1\rangle_B - |\sigma_-,-1\rangle_C \otimes |S_B,+1\rangle_B) \otimes |\sigma_+,L_A\rangle_A\end{aligned} \tag{1}$$

where $\sigma_\pm$ represents the SAM states of the photon (right and left-handed circular polarizations), ± 1 represents one quanta of OAM, S_B is the SAM DoF of Photon B and L_A is the OAM of Photon A. This state yields a set of 16 hyperentangled Bell states. Next, a necessary step in the transmitter's local teleportation protocol is to perform a two-particle joint measurement of Photons A and P_1, projecting them onto the 16-basis of orthogonal and complete hyperentangled Bell states, and discriminating one of them.

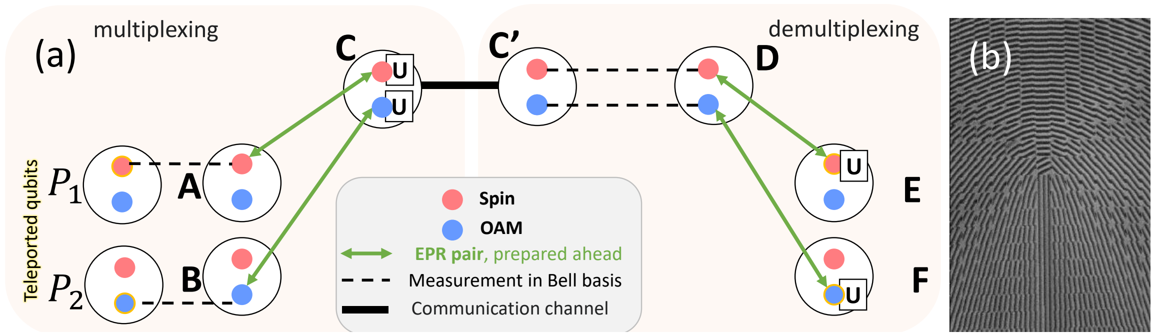

*Fig. 1. **(a)** Scheme for multiplexing, transmitting and demultiplexing hyperentanglement using quantum teleportation. The unitary transformation on a single DoF is labeled by the letter 'U'. **(b)** A geometrical phase mask [8] that generates our initial state for the setting in (a), the SAM DoF in photon A entangled with a SAM DoF in photon C, and the OAM of photon B entangled with the OAM of photon C.*

After the measurement in the Bell basis of Photons A and P_1, Photon C is projected in its SAM onto the initial state of Photon A. The measurement results in the Bell basis of photons A and P_1 is encoded as four-bit classical information, which allows us to apply appropriate Pauli operations on the SAM of Photon C to perfectly reconstruct the initial SAM of Photon P_1. This process is also performed with Photons B and P_2, which are encoded with an OAM DoF.

This mechanism is an effective way to multiplex quantum information on a single photon. The single photon can now be transmitted to a desired destination (which could be far away), where the information can be demultiplexed into multiple photons, facilitating *nonlocal* quantum operations. The transmission is over a single communication channel – a transmission of a single photon carrying two qubits, which doubles the quantum transmission rate.

To demultiplex the quantum information at the receiver, the local process of teleportation is repeated, separating the DoFs to Photons E and F, demultiplexing the hyperentangled state. Finally, the decoder can perfectly reconstruct the teleported qubits. Thus, the encoder has locally teleported a hyperentangled state from a single photon to two distinct photons. Similarly to the multiplexing process, our decoder uses the teleportation of separate DoF to demultiplex the qubits to various photons (each DoF on a different photon). With this scheme, the information can be processed in parallel, exploiting the nonlocality of quantum information processing.

This protocol of multiplexing quantum information on a single photon, transmitting it, and eventually demultiplexing into multiple photons while recovering the quantum information in full, can be scaled up with more DoFs. In addition, it is possible to teleport the qubits from one kind of DoF to another DoF [10].

This basic scheme presented in Fig.1(a) can serve another important goal: **generating non-local entanglement between a transmitter and a receiver who are distant from each other, at twice the rate**. By sending only a single photon we generate two non-local pairs of entangled photons. In this setting we include the additional two physical photons, Photons P_3 and P_4 (see Fig. 2). Our transmitter prepares ahead two entangled pairs: The SAM of Photons P_3 and P_1, and the OAM of Photons P_2 and P_4. Then our transmitter repeats the multiplexing part, but now he generates entanglement between the SAM of Photon C and P_3, and the OAM of Photons C and P_4. After the demultiplexing part, we end up with two ***separate*** pairs of entangled photons – Photon E is entangled with Photon P_3 (in SAM DoF), and Photon F is entangled with Photon P_4 (in OAM DoF).

This generation of entangled pairs of photons at twice the rate can be beneficial and important in entanglement-assisted communication, increasing the channel capacity. *Our protocol enables not only increasing the transmission rate of a quantum communication channel, but also increasing the rate of generating entangled pairs of qubits in remote locations*.

To conclude, we presented a simple protocol for teleporting multiple DoFs, multiplexing them on a single photon, transmitting the single photon at higher channel capacity, and eventually demultiplexing the information onto different photons. Our setting paves the way towards quantum communication with a higher transmission rate, more efficient entanglement generation, and refined control over scalable quantum technologies.

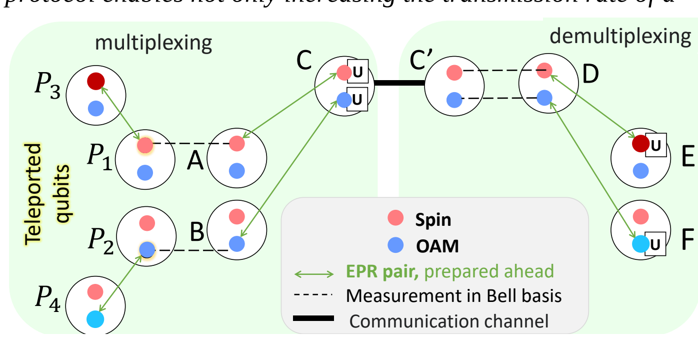

Fig. 2. Scheme for generating entangled photon pairs at a double rate.

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