Increasing Communication Rates Using Photonic Hyperentangled States

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Quantum communication is based on the generation and use of quantum states and resources for communication protocols. Photons are an optimal carrier of information, given their resilience to decoherence and ease of creation and transportation. Hyperentanglement [1], a state with two parties entangled with several degrees of freedom (DoFs), provides an excellent platform for these tasks, due to its high data capacity and error resilience.

Here, we propose a mechanism for increasing the transmission rate of quantum communication channels by using an hyperentangled state, based on multiplexing different DoFs on a single photon, transmitting the photon, and demultiplexing the DoFs to different photons, using quantum teleportation protocol. Following our scheme, one can generate two entangled photon pairs by sending a single photon. Our work lays the groundwork for novel quantum communication protocols with higher transmission rate and refined control over scalable quantum technologies.

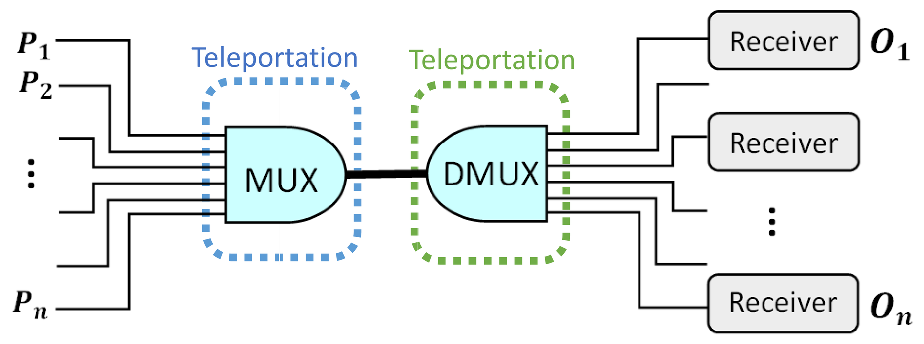
Hyperentanglement

A single quantum particle can naturally possess multiple degrees of freedom (DoFs) and thus it may represent several qubits. **A state of two particles entangled by two or more DoFs is called a hyperentangled state [1].** That is, we cannot we cannot separate the j^{th} DOF state $|\psi_{AB}\rangle_j$ as:

$$|\psi_{AB}\rangle_j \neq |\phi_A\rangle_j \otimes |\chi_B\rangle_j \quad , for\ j = 1,2,\ldots,n \ , \qquad where\ n \geq 2$$

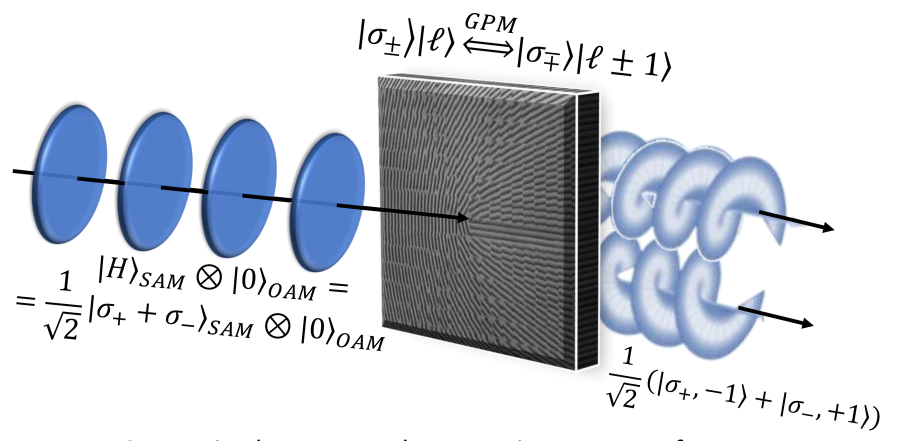
The Scheme

- Our scheme can be implemented using different DoFs. For example, we propose using the DoFs of spin angular momentum (SAM) and orbital angular momentum (OAM). It 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.

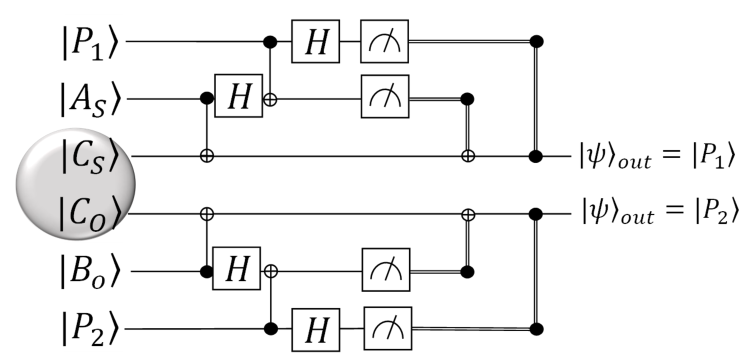


- We prepare **a pre-shared hyperentangled pair of photons**, using a metasurface. These masks imprint a different wavefunction to each polarization of the electromagnetic field, and were recently used to imprint entanglement between the SAM and the OAM of a photon [3].
- The transmitter prepares ahead a hyperentangled photon pair with Photons A and C entangled in their SAM, and Photons B and C entangled in their OAM, simultaneously:

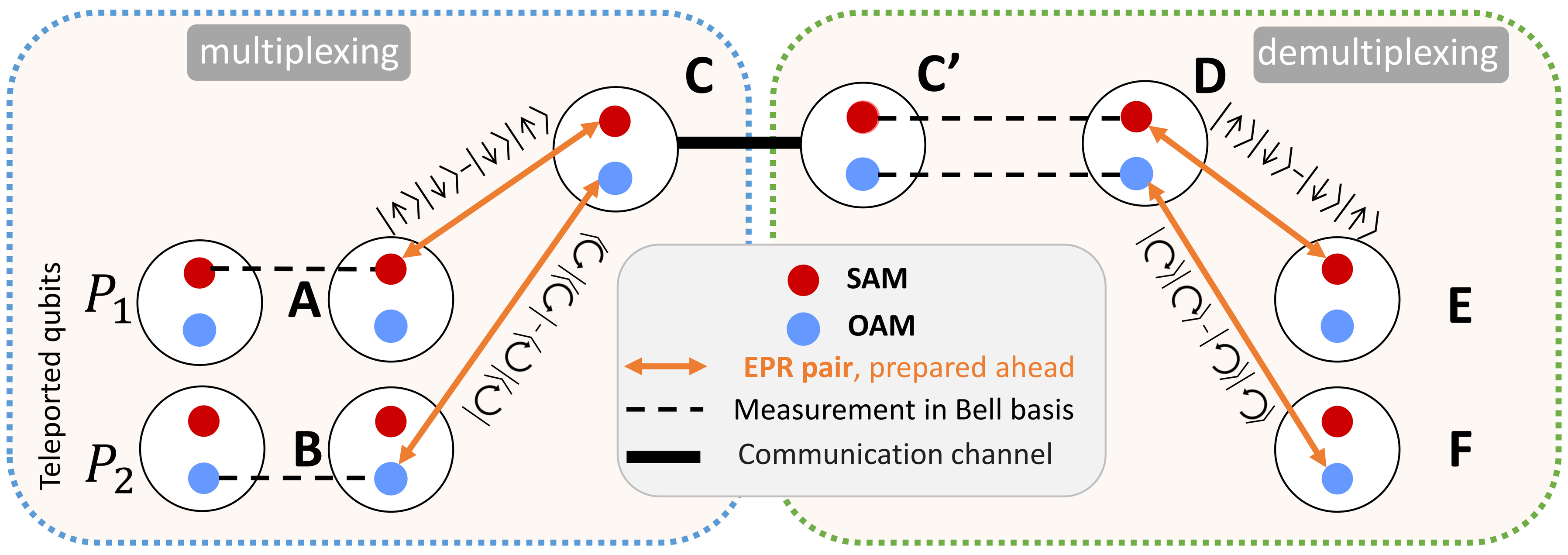
$$(|\sigma_+, +1\rangle_C \otimes |S_B, -1\rangle_B - |\sigma_+, -1\rangle_C \otimes |S_B, +1\rangle_B) \otimes |\sigma_-, L_A\rangle_A$$
$$- (|\sigma_-, +1\rangle_C \otimes |S_B, -1\rangle_B - |\sigma_-, -1\rangle_C \otimes |S_B, +1\rangle_B) \otimes |\sigma_+, L_A\rangle_A$$



Generating hyperentanglement using a metasurface



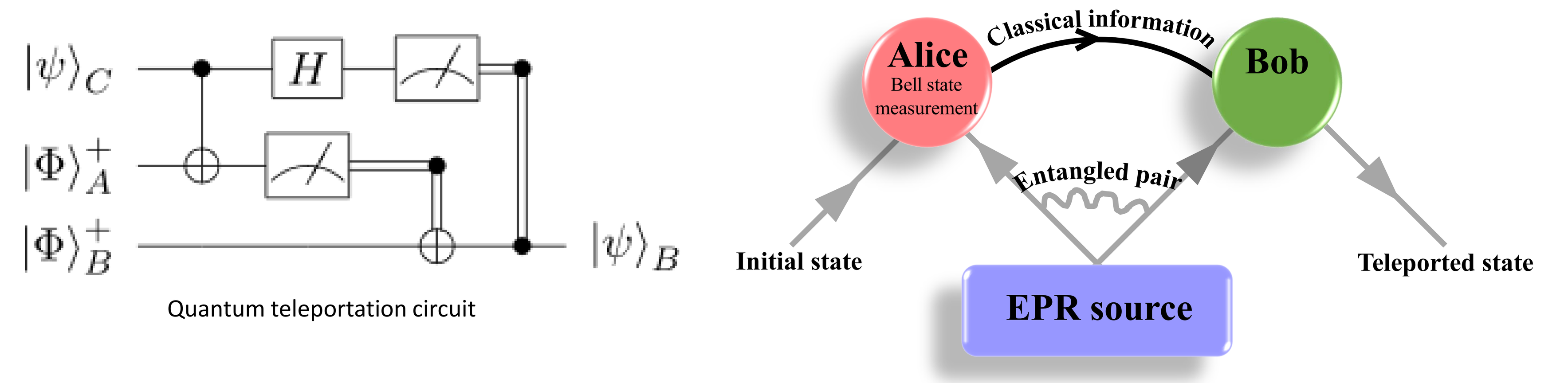
Quantum teleportation circuit for the multiplexing part



Scheme for multiplexing, transmitting and demultiplexing hyperentanglement using quantum teleportation. The multiplexing part (demultiplexing) is performed by teleporting SAM and OAM DoFs from separate photons (single photon) to a single photon (distinct photons) and is labeled in dashed blue (dashed green) line.

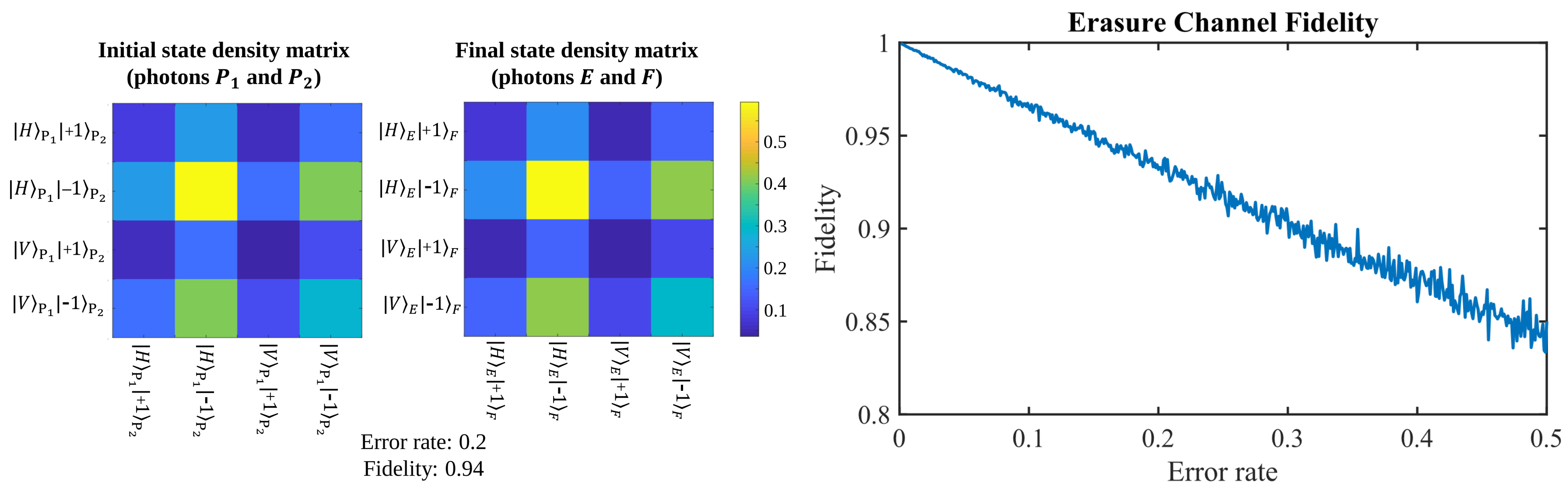
Quantum Teleportation

Quantum teleportation [2] provides a 'disembodied' way to transfer quantum states from one object to another at a distant location, assisted by pre-shared entangled states and a classical communication channel.



Transmitting two bits by broadcasting a single photon

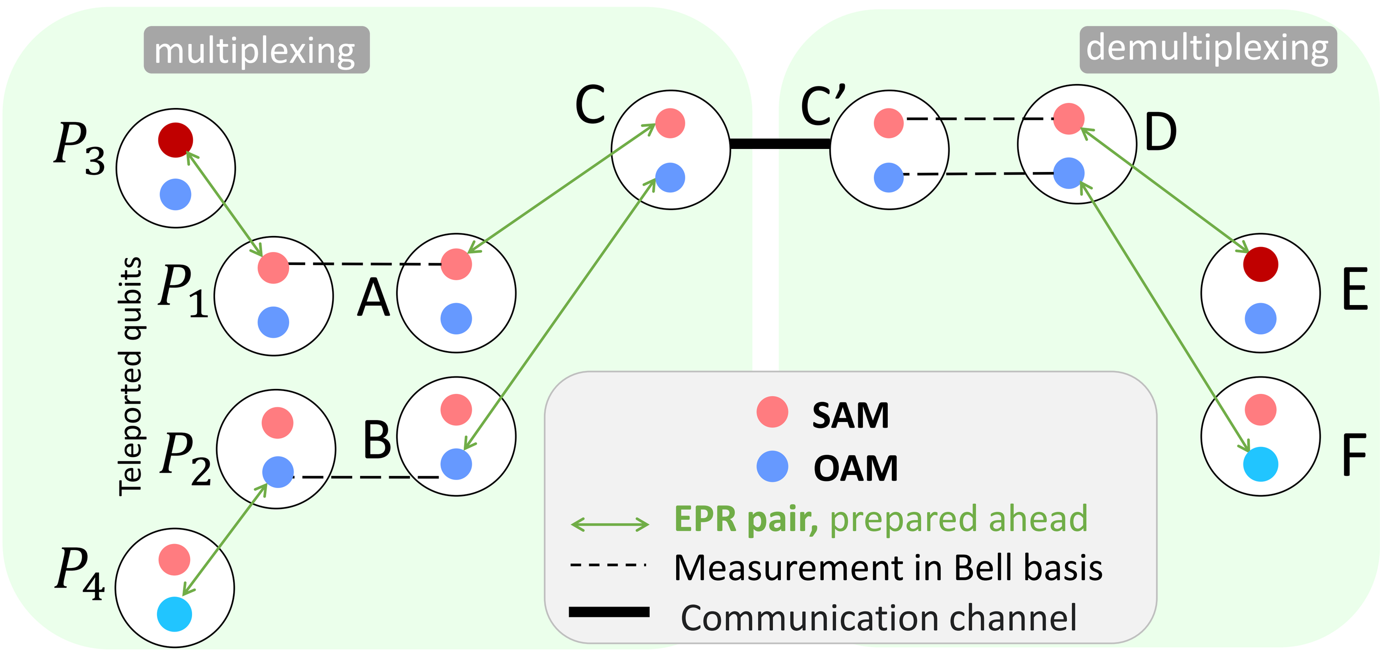
- In recent years, multipartite entanglement as a means to increase the channel capacity has been proposed and demonstrated [4-6]. Hyperentanglement is an excellent platform for various quantum communication protocols, as **it allows encoding a greater amount of information in a single physical photon** [7].
- We simulate our protocol, **sending two bits of information using the transmission of a single photon**. We assume an erasure channel – where a transmitter sends a qbit, and the receiver either receives the qbit correctly, or loses the qubit with some probability.



Left: density matrices of the initial (before the multiplexing) and final (after the demultiplexing) states. The initial state is randomized (similarly to the process in teleportation, where the transmitted state is unknown). **Right:** calculated Fidelity, depending on an error parameter (each point represents the average of 70 randomized states with the same error rate).

Entanglement generation at twice the rate

This basic scheme generates 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**.



Doubling the rate of entanglement generation may revolutionize the field and set a practiced route to entanglement-assisted communication, with a higher channel capacity. Specifically, the entanglement-assisted classical capacity- the highest rate at which classical information can be transmitted from a sender to a receiver when they share an unlimited amount of noiseless entanglement.

[1] P. G. Kwiat, J. Mod. Opt. 44, pp. 2173-2184 (1997)
[2] C. H. Bennett et al, Phys. Rev. Lett. 70, 1895–1899 (1993)
[3] T. Stav et al, Science 361.6407, 1101-1104, (2018)
[4] J. T. Barreiro et al, Nat. Phys. 44 4, 282–286 (2008)
[5] P. B. Dixon, et al, Phys. Rev. Lett. 108, 143603 (2012)
[6] X. M. Hu et al, Sci. Adv. 4, 1–6 (2018)
[7] B. G. Englert et al, Phys. Rev. A, 63,032303 (2001).