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Simplified Protocol of Quantum Teleportation

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Abstract—A simplified version of quantum teleportation protocol is presented here. Its experimental confirmation will have deep implications for a better understanding of quantum entanglement with a particular projection on quantum communications.

Keywords—Bell’s states; BSM; EPR pairs; LOCC; No-Cloning Theorem; Quantum Communications; Quantum Entanglement; Quantum Teleportation.

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1 Introduction

First, we should mention the key pieces in Quantum Information Processing in general, as well as quantum computing and communications in particular: the Principle of Superposition and quantum entanglement [1], which are both closely related to the work of Erwin Schrödinger [2, 3]. In fact, Schrödinger defined the entanglement of pure states as the pure quantum state $|\Psi_{AB}\rangle$ associated to composite systems like A and B that cannot be represented in the form of simple tensor products of subsystem state-vectors, that is [1],

$$|\Psi_{AB}\rangle \neq |\psi_A\rangle \otimes |\psi_B\rangle \quad (1)$$

where “ \otimes ” indicates the tensor product, also known as Kronecker’s product, while $|\psi_A\rangle$ and $|\psi_B\rangle$ are vectors providing the states of both subsystems, such as elementary particles [2, 3]. Those states of composite systems that can be represented as tensor products of subsystem states constitute the complement in the set of pure states: the product states [1]. In fact, states of the composite system that can be represented in this form are called separable states. Since not all states are separable states, and thus product states, we will carry out the following analysis: we establish a pair of basis: $\{|x_A\rangle\}$ for H_A and $\{|y_B\rangle\}$ for H_B . In $H_A \otimes H_B$, the most general state is of the form

$$|\Psi_{AB}\rangle = \sum_{x,y} n_{xy} |x_A\rangle \otimes |y_B\rangle. \quad (2)$$

Therefore, this state will be separable if vectors $[n_x^A]$ and $[n_y^B]$ exist so that $n_{xy} = n_x^A n_y^B$ yielding $|\psi_A\rangle = \sum_x n_x^A x_A$ and $|\psi_B\rangle = \sum_y n_y^B y_B$. It is inseparable if for any vectors $[n_x^A]$ and $[n_y^B]$ at least for one pair of coordinates n_x^A and n_y^B , we have $n_{xy} \neq n_x^A n_y^B$. If a state is inseparable, it is called an entangled state. On the other hand, in 1935 Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) proposed a thought experiment by which they tried to demonstrate that the wave-function did not provide a complete description of physical reality, and which gave rise to the famous EPR paradox,

and hence that the Copenhagen's interpretation is unsatisfactory. From this point onwards, resolutions of the paradox have had important implications for the interpretation of Quantum Mechanics (QMech) [4]. The essence of this paradox is that particles can interact in such a way that it is possible to measure both their position and their momentum more accurately than what Heisenberg's uncertainty principle allows us to achieve [5] unless we measure one particle which will instantaneously affect the other one preventing this accuracy. Consequently, this individual measurement would involve information transmitted faster than light [6-8], yet forbidden by the theory of relativity (which is known as a "spooky action at a distance") [5, 9-13]. This consequence had not previously been noticed and seemed unreasonable at the time; however, the phenomenon involved is now known as quantum entanglement (QEnta) [1, 5]. Moreover, in 1964 John S. Bell introduced his famous theorem [9] associated with 4 states: 2-qubit vectors into a combined space of Hilbert $H_{AB} = H_A^2 \otimes H_B^2$, and relative to two subsystems A and B,

$$|\Phi_{AB}^{\pm}\rangle = \frac{1}{\sqrt{2}}(|0_A, 0_B\rangle \pm |1_A, 1_B\rangle), \quad |\Psi_{AB}^{\pm}\rangle = \frac{1}{\sqrt{2}}(|0_A, 1_B\rangle \pm |1_A, 0_B\rangle) \quad (3)$$

where they are called Bell's states, and also known as EPR pairs. This theorem raises an inequality, which when violated by QMech establishes the non-locality present in the entanglement of two subsystems like A and B. Besides, a posterior redefinition of this inequality due to Clauser, Horne, Shimony and Holt (CHSH) [14] leads to a more practical way of experimental testing with [13] and without [15] loopholes.

An extremely important concept in Quantum Teleportation (QTele) is the No-Cloning Theorem [5] [16], which states that it is impossible to create an identical copy of an arbitrary unknown quantum state. This No-Go Theorem of QMech was articulated by Wootters and Zurek [16] and Dieks [12] in 1982, and has profound implications in quantum computing as well as related fields. Besides, the No-Cloning Theorem [5] prevents the transfer of information faster than the speed of light [6-8]. We have seen that a measurement on subsystem A instantaneously transforms subsystem B into a well-defined state. The word "instantaneous" has deep implications in Quantum Communication (QComm) [1]. Let us imagine that an entangled pure state has been produced with a subsystem S_A at Alice's location and another subsystem S_B at Bob's location very far away from each other. Alice attempts to transmit one bit of information to Bob by measuring one of the two non-commuting observables on her subsystem S_A . If Bob succeeds in reading out this information on his subsystem S_B , then this implies that it should have been transmitted at a speed greater than that of light contradicting the basic principle of Special Relativity (SRela) [6].

QTele [17-19] is a process by which a quantum state $|\psi\rangle$ can be transferred from one point to another while destroying the original state, which is required by the no-cloning theorem [5, 12, 16]. This process takes place between two different locations. An EPR pair (i.e., two maximally entangled states) is apportioned between Alice and Bob. Alice has the state to be teleported. This state is entangled with her EPR state, and after a process involving quantum gates, Alice performs measurements with a certain probability, so as to identify the original state in the appropriate base. Consequently, she transmits the elements of that base but in its classical version (i.e., two bits) through a classical channel. On the other side, Bob receives both bits, which he uses in tandem with the appropriate quantum gates. As a result, he rebuilds the original state. Clearly, we can see that a QTele depends on a classical communication, which can proceed no faster than the speed of light. In other words, it cannot be used for faster-than-light transport or communication of classical bits. Of course, the classical channel is the weak link in this chain in terms of transmission speed.

On the other hand, since the QEnta has a serious enemy and QTele necessarily depends on the QEnta, then such enemy is inherited by QTele. This enemy is decoherence [20], which usually collapses the entanglement. Decoherence can be viewed as the loss of information from a system into the environment, since every system is loosely coupled with the energetic state of its surroundings. This interaction between the state and its environment is clearly seen during Quantum Measurement (QMeas) [21], which causes the collapse of the wave-function [20, 21]. In order to mitigate this problem, we must apply reconstructive techniques of the state, which results in an increase in the computational cost of the process as a whole [22].

In this paper we present a new protocol of QTele which does not require any disambiguation based on the transmission of classical bits, as in fact it happens in the original version [12, 17-19], which when using two channels (one classical for the bits and another quantum for the distribution of the EPRs) is more vulnerable to attacks. However, the new version is easier to implement in the laboratory than the original. This possibility has its origin in a work of QComm [23] which, through an extensive analysis, reaches the conclusion that such a possibility is viable.

Finally, the main pending aspect within the teleportation is its lack of instantaneity (seen and a whole) and a clear definition of its bandwidth [23]. Both are the responsibility of the classical channel that the protocol mandatory uses. This is the scenario where this work points to based on [23].

2 Setup

For the implementation of QTele, we must use some quantum gates, which we are going to present next. The first one is the Hadamard's gate, which acts on a single qubit. It maps the basis state $|0\rangle$ to $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ and $|1\rangle$ to $\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$, which means that a measurement will have equal probabilities to become 1 or 0 (i.e., it creates a superposition). It is represented by the Hadamard's matrix:

$$H = \frac{1}{\sqrt{2}}(\sigma_x + \sigma_z) = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad (4)$$

where σ_x and σ_z are two of the three Pauli's matrices $(\sigma_x, \sigma_y, \sigma_z)$ [24]

$$\sigma_x = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad \sigma_y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \quad \text{and} \quad \sigma_z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \quad (5)$$

with $i = \sqrt{-1}$. Figure 1 represents the Hadamard's gate [24].

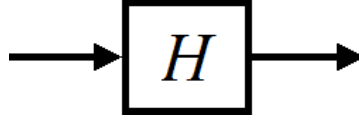


Fig. 1 Hadamard's (H) gate.

The second one is the Controlled NOT gate or simply CNOT, which operates on a quantum register consisting of 2 qubits. The CNOT gate flips the second qubit (the target qubit) if and only if the first qubit (the control qubit) is $|1\rangle$. The inputs are allowed to be a linear superposition of $\{|0\rangle, |1\rangle\}$. As an example of this, we can see that the CNOT gate transforms a superposed quantum state of the kind $a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$ into another like $a|00\rangle + b|01\rangle + c|11\rangle + d|10\rangle$. The CNOT gate can be represented by the matrix:

$$CNOT = |0\rangle\langle 0| \otimes I + |0\rangle\langle 1| \otimes \sigma_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (6)$$

where I is the identity matrix. Figure 2 represents the CNOT gate [24].

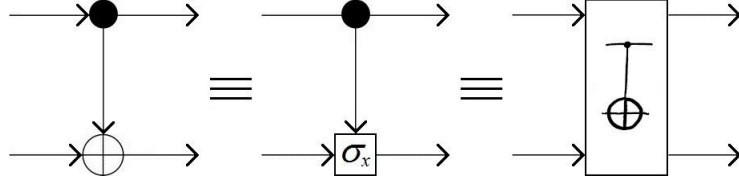


Fig. 2 CNOT gate.

With both gates, we can build the famous Bell's state (or EPR pair, named after Einstein, Podolsky, and Rosen paper [4]) from the computational basis state (CBS) $|0\rangle$ [5], as we can see in Figure 3,

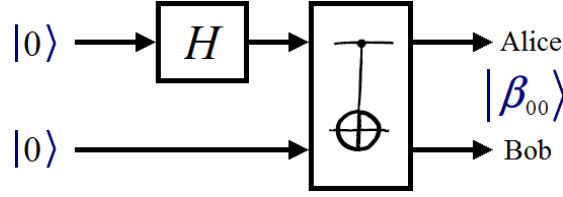


Fig. 3 The output of these gates (Hadamard and CNOT) is an EPR qubit or Bell's state. In fact, it is an EPR pair, one for Alice and another one for Bob.

As an example, we are going to build $|\beta_{00}\rangle$, i.e., the Bell's state of Figure 3 based on two states $|0\rangle$ at its entrance and the application of Hadamard (H) and CNOT gates in that order. Thus, for the upper branch of Figure 3, we have

$$H|0\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{bmatrix} \quad (7)$$

While by the lower branch, simply $|0\rangle = |0\rangle$. Now, and before of CNOT gate, the Kronecker's product " \otimes " intervenes between both branches of Figure 3, the upper and the lower,

$$|0\rangle \otimes H|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \otimes \begin{bmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{bmatrix} = \begin{bmatrix} 1/\sqrt{2} \\ 0 \\ 1/\sqrt{2} \\ 0 \end{bmatrix} \quad (8)$$

Finally, CNOT gate is applied

$$\begin{aligned} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1/\sqrt{2} \\ 0 \\ 1/\sqrt{2} \\ 0 \end{bmatrix} &= \begin{bmatrix} 1/\sqrt{2} \\ 0 \\ 0 \\ 1/\sqrt{2} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \\ &= \frac{1}{\sqrt{2}} |0\rangle \otimes |0\rangle + \frac{1}{\sqrt{2}} |1\rangle \otimes |1\rangle = \frac{1}{\sqrt{2}} |00\rangle + \frac{1}{\sqrt{2}} |11\rangle \\ &= \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle) = |\beta_{00}\rangle \end{aligned} \quad (9)$$

The complete set of Bell's basis are:

$$\begin{aligned}
|\beta_{00}\rangle &= |\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \\
|\beta_{01}\rangle &= |\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle) \\
|\beta_{10}\rangle &= |\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle) \\
|\beta_{11}\rangle &= |\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)
\end{aligned} \tag{10}$$

then,

$$\begin{aligned}
|00\rangle &= \frac{1}{\sqrt{2}}(|\Phi^+\rangle + |\Phi^-\rangle) = \frac{1}{\sqrt{2}}(|\beta_{00}\rangle + |\beta_{01}\rangle) \\
|01\rangle &= \frac{1}{\sqrt{2}}(|\Psi^+\rangle + |\Psi^-\rangle) = \frac{1}{\sqrt{2}}(|\beta_{10}\rangle + |\beta_{11}\rangle) \\
|10\rangle &= \frac{1}{\sqrt{2}}(|\Psi^+\rangle - |\Psi^-\rangle) = \frac{1}{\sqrt{2}}(|\beta_{10}\rangle - |\beta_{11}\rangle) \\
|11\rangle &= \frac{1}{\sqrt{2}}(|\Phi^+\rangle - |\Phi^-\rangle) = \frac{1}{\sqrt{2}}(|\beta_{00}\rangle - |\beta_{01}\rangle)
\end{aligned} \tag{11}$$

On the other hand and as a complement to the tools seen so far in this section, it is necessary to be able to evaluate the quality of the experimental implementation of teleportation protocols in the presence of noise, i.e., how similar the teleported state is in comparison to the original? Therefore, we will need a good metric to be able to evaluate said transfer quality. Then, we recommend here two versions of the most used metric in teleportation: *fidelity* [25]. These versions have to do with the characteristic of the state to teleport, i.e., if it is pure or a mixed state [25]-[27].

Fidelity f is a metric that shows us how similar the initial and final states in a quantum process are [25]. It has widely been used to characterize the performance of various quantum information tasks. Fidelity f is bounded by $0 \leq f \leq 1$, where the unit fidelity ($f = 1$) implies that the initial and final states are equivalent [25]. QTele is designed to transmit all possible (unknown) input states, thus a measure of the average of all inputs is used. That is the average fidelity F which quantifies how well the unknown input states can be transmitted to another location. Thus, F shows the optimality of the QTele where it is shown that the unit average fidelity ($F = 1$) can be obtained when the two remote parties share the maximally entangled states, whereas $F = 2/3$ is the maximum fidelity attainable in any classical schemes which the entanglement cannot use [25].

Therefore, if $|\psi_{in}\rangle$ and $|\psi_{out}\rangle$ are the state to be teleported and the state teleported, respectively,

$$\rho_{in} = |\psi_{in}\rangle\langle\psi_{in}| \text{ and } \rho_{out} = |\psi_{out}\rangle\langle\psi_{out}| \tag{12}$$

will be their respective density matrices. Fidelity quantifies a transformation performance between $|\psi_{in}\rangle$ and $|\psi_{out}\rangle$ states as,

$$f = Tr \left[\left(\sqrt{\rho_{out}} \rho_{in} \sqrt{\rho_{out}} \right)^{1/2} \right]. \tag{13}$$

The quantum teleportation applies to unknown input states so that the average fidelity—an average of the fidelities f over all possible input states—is used:

$$F = \int f d\psi_{in} \tag{14}$$

where $d\psi_{in}$ is Haar's measure with $\int d\psi_{in} = 1$. Here, $F = 1$ implies that the task is perfectly performed for all possible inputs, while $F = 1/2$ implies some kind of uncertainty about the possibility of carrying out the task perfectly [25].

3 Standard Quantum Teleportation

Then, we will develop the standard QTele protocol with and without noise where the noiseless analysis is essential when keeping in mind the implications of the new protocol for the whole Physics. Besides, from the theoretical and the purely experimental point of views, we must consider the reality of the laboratory affected by innumerable noises due to all the gates involved for the purpose of implementing the different protocols. For this last reason, we need a thorough analysis in the presence of noise.

3.1 Noiseless analysis

QTele begins with the distribution of the EPR pair $|\beta_{00}\rangle$ to Alice and Bob. This distribution constitutes the entanglement link between Alice and Bob. After that, we continue with the complete sketch of QTele of Figure 4, where the green line indicates the border between the sides of Alice and Bob, that is, both extremes of the entanglement link. In Figure 4, a single fine line represents a wire carrying one qubit, while a double line represents a wire carrying one classical bit [24], while the classical channel is really a control classical channel for disambiguation purposes (as we will see below through two bits), while the entanglement link is really an entanglement data link. On the other hand, in Figure 4, the following blocks mean: *SPD* (single photon detectors) and *EPR* is the source of $|\beta_{00}\rangle \equiv |\Phi_+^{A \cup B}\rangle$ of Equation (10).

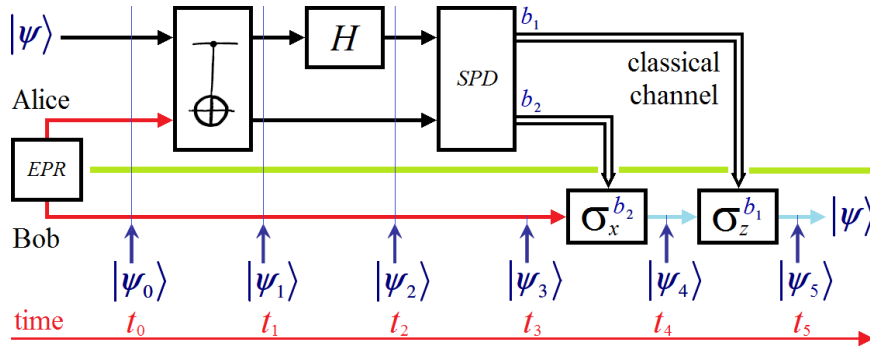


Fig.4 Standard teleportation protocol using an EPR pair and two classical bits for disambiguation.

Now, If $|\psi_0\rangle = |\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ is an arbitrary and unknown state to be teleported with $|\alpha|^2 + |\beta|^2 = 1$ and $\alpha, \beta \in \mathbb{C}$ of a Hilbert's space, then, the initial state (3-partite state) will be,

$$\begin{aligned}
 |\psi_0\rangle &= |\psi\rangle \otimes |\beta_{00}\rangle = |\psi\rangle |\beta_{00}\rangle = (\alpha|0\rangle + \beta|1\rangle) \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \\
 &= \frac{1}{\sqrt{2}}[\alpha|0\rangle(|00\rangle + |11\rangle) + \beta|1\rangle(|00\rangle + |11\rangle)] = \frac{1}{\sqrt{2}}[\alpha|000\rangle + \alpha|011\rangle + \beta|100\rangle + \beta|111\rangle] \\
 &= \left[\frac{\alpha}{\sqrt{2}} \quad \frac{\beta}{\sqrt{2}} \quad 0 \quad 0 \quad 0 \quad 0 \quad \frac{\alpha}{\sqrt{2}} \quad \frac{\beta}{\sqrt{2}} \right]^T
 \end{aligned} \tag{15}$$

where for simplicity (and from here on) we have adopted $|x\rangle \otimes |y\rangle = |x\rangle|y\rangle$ in a generic form, while $(\bullet)^T$ means "transpose of (\bullet) ".

Now, a CNOT gate is applied to Equation (15),

$$\begin{aligned}
|\psi_1\rangle &= \frac{1}{\sqrt{2}}[\alpha|000\rangle + \alpha|011\rangle + \beta|110\rangle + \beta|101\rangle] \\
&= \begin{bmatrix} \alpha/\sqrt{2} & 0 & 0 & \beta/\sqrt{2} & 0 & \beta/\sqrt{2} & \alpha/\sqrt{2} & 0 \end{bmatrix}^T
\end{aligned} \tag{16}$$

In practice, Kronecker's product and CNOT gate are implemented together on the same *beamsplitter* [18, 19]. At this time, we apply a Hadamard's gate to the elements of Equation (16),

$$\begin{aligned}
|\psi_2\rangle &= \frac{1}{2} [|00\rangle \sigma_x^0 \sigma_z^0 |\psi\rangle + |01\rangle \sigma_x^1 \sigma_z^0 |\psi\rangle + |10\rangle \sigma_x^0 \sigma_z^1 |\psi\rangle + |11\rangle \sigma_x^1 \sigma_z^1 |\psi\rangle] \\
&= \frac{1}{2} [| \Phi^+ \rangle \sigma_x^0 \sigma_z^0 |\psi\rangle + | \Phi^- \rangle \sigma_x^1 \sigma_z^0 |\psi\rangle + | \Psi^+ \rangle \sigma_x^0 \sigma_z^1 |\psi\rangle + | \Psi^- \rangle \sigma_x^1 \sigma_z^1 |\psi\rangle] \\
&= \begin{bmatrix} \alpha/2 & \alpha/2 & \beta/2 & -\beta/2 & \beta/2 & -\beta/2 & \alpha/2 & \alpha/2 \end{bmatrix}^T \\
&= \begin{bmatrix} \alpha/2 & 0 & \beta/2 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \rightarrow | \Phi^+ \rangle \rightarrow |00\rangle \rightarrow 00 \rightarrow \sigma_x^0 \sigma_z^0 \\
&+ \begin{bmatrix} 0 & \alpha/2 & 0 & -\beta/2 & 0 & 0 & 0 & 0 \end{bmatrix}^T \rightarrow | \Psi^+ \rangle \rightarrow |10\rangle \rightarrow 10 \rightarrow \sigma_x^0 \sigma_z^1 \\
&+ \begin{bmatrix} 0 & 0 & 0 & 0 & \beta/2 & 0 & \alpha/2 & 0 \end{bmatrix}^T \rightarrow | \Phi^- \rangle \rightarrow |01\rangle \rightarrow 01 \rightarrow \sigma_x^1 \sigma_z^0 \\
&+ \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -\beta/2 & 0 & \alpha/2 \end{bmatrix}^T \rightarrow | \Psi^- \rangle \rightarrow |11\rangle \rightarrow 11 \rightarrow \sigma_x^1 \sigma_z^1
\end{aligned} \tag{17}$$

Besides, Table I synthesizes the complete process of QTele, where Alice measures two of the possible qubits of the basis of Equation (10), and therefore, she transmits the corresponding bits b_1 and b_2 via a classical channel to Bob. The QMeas process is imperative to make the wave-function of the original arbitrary state collapse since this is necessary to do so as not to violate the No-Cloning Theorem. In other words, the QMeas process destroys the original arbitrary state [24].

TABLE I: ALICE'S SIDE: MEASUREMENT OF THE BASE, CLASSICAL TRANSMISSION OF BITS, AND THE COLLAPSE OF STATES, BOB'S SIDE: CLASSICAL RECEPTION OF BITS, GATES APPLICATION FOR THE FINAL RECOVERY OF THE ARBITRARY STATE.

Alice's measurement	Alice transmits	This happens with probability	Collapsed state	Bob applies $\sigma_x^{b_1} \sigma_z^{b_2}$
$ \Phi^+ \rangle \rightarrow 00$	$b_2 b_1 = 00$	$\left\ \frac{1}{2} \sigma_x^0 \sigma_z^0 \psi\rangle \right\ ^2 = \frac{1}{4}$	$ \Phi^+ \rangle \sigma_x^0 \sigma_z^0 \psi\rangle$	$\sigma_x^0 \sigma_z^0 \psi\rangle = \psi\rangle$
$ \Psi^+ \rangle \rightarrow 01$	$b_2 b_1 = 01$	$\left\ \frac{1}{2} \sigma_x^1 \sigma_z^0 \psi\rangle \right\ ^2 = \frac{1}{4}$	$ \Psi^+ \rangle \sigma_x^1 \sigma_z^0 \psi\rangle$	$\sigma_x^1 \sigma_z^0 \psi\rangle = \sigma_x \psi\rangle$
$ \Phi^- \rangle \rightarrow 10$	$b_2 b_1 = 10$	$\left\ \frac{1}{2} \sigma_x^0 \sigma_z^1 \psi\rangle \right\ ^2 = \frac{1}{4}$	$ \Phi^- \rangle \sigma_x^0 \sigma_z^1 \psi\rangle$	$\sigma_x^0 \sigma_z^1 \psi\rangle = \sigma_z \psi\rangle$
$ \Psi^- \rangle \rightarrow 11$	$b_2 b_1 = 11$	$\left\ \frac{1}{2} \sigma_x^1 \sigma_z^1 \psi\rangle \right\ ^2 = \frac{1}{4}$	$ \Psi^- \rangle \sigma_x^1 \sigma_z^1 \psi\rangle$	$\sigma_x^1 \sigma_z^1 \psi\rangle = \sigma_x \sigma_z \psi\rangle$

At this point, it is important to mention that in literature there are several concerns regarding the implementation of teleportation protocols using a bigger or smaller dimensional commitment but always with two classical bits for disambiguation. An interesting example can be found in [28], which shows that the one-qubit teleportation can be considered as a state transfer between subspaces of the whole Hilbert's space of an indivisible eight-dimensional system. However, this as well as the rest of the papers that manipulate high dimensional quantum systems for the implementation of QTele protocols do it with two classical bits for disambiguation.

On Alice's side, the combination of the modules constituted by the following gates: *CNOT*, *H* (Hadamard) and QMeas, constitute what is known as the Bell-State-Measurement (BSM), while on Bob's side, its modules are unitary operations necessary for the reconstruction of the teleported state. Alice's measurement and transmission of the classical bits of disambiguation along with Bob's unitary operations are the clearest examples of Local Operations and Classical Communication (LOCC) [29].

Finally, we must highlight as a fundamental contrast between this version of the QTele protocol with the following one, that here, in Equation (15) we make $|\psi\rangle \otimes |\beta_{00}\rangle$ and that the Kronecker product “ \otimes ” is not commutative.

3.2 Noisy analysis

Starting again from Figure 4, and considering noise in the EPR pair by a disturbance of the shape

$$|\beta_{00}\rangle_n = A|00\rangle + B|11\rangle \quad (18)$$

where subscript n means *noise*, and

$$|A|^2 + |B|^2 = 1, \text{ with } (A \neq B) \wedge (A \neq \frac{1}{\sqrt{2}}) \wedge (B \neq \frac{1}{\sqrt{2}}) \quad (19)$$

Then, repeating Equation (15) but with $|\beta_{00}\rangle_n$ instead of $|\beta_{00}\rangle$, we will have

$$\begin{aligned} |\psi_0\rangle &= |\psi\rangle |\beta_{00}\rangle_n = (\alpha|0\rangle + \beta|1\rangle)(A|00\rangle + B|11\rangle) \\ &= \alpha A|000\rangle + \beta A|100\rangle + \alpha B|011\rangle + \beta B|111\rangle \end{aligned} \quad (20)$$

Now, a CNOT gate is applied to Equation (20),

$$|\psi_1\rangle = \alpha A|000\rangle + \beta A|110\rangle + \alpha B|011\rangle + \beta B|101\rangle. \quad (21)$$

At this time, we apply a Hadamard's gate to the elements of Equation (21),

$$\begin{aligned} |\psi_2\rangle &= \frac{1}{\sqrt{2}} [\alpha A|000\rangle + \alpha A|100\rangle + \beta A|010\rangle - \beta A|110\rangle + \alpha B|011\rangle + \alpha B|111\rangle + \beta B|001\rangle - \beta B|101\rangle] \\ &= \frac{A}{\sqrt{2}} |00\rangle \alpha |0\rangle + \frac{B}{\sqrt{2}} |00\rangle \beta |1\rangle + \frac{A}{\sqrt{2}} |10\rangle \alpha |0\rangle - \frac{B}{\sqrt{2}} |10\rangle \beta |1\rangle + \frac{A}{\sqrt{2}} |01\rangle \beta |0\rangle + \frac{B}{\sqrt{2}} |01\rangle \alpha |1\rangle + \frac{B}{\sqrt{2}} |11\rangle \alpha |1\rangle - \frac{A}{\sqrt{2}} |11\rangle \beta |0\rangle \\ &= \frac{1}{\sqrt{2}} [|00\rangle (A\alpha|0\rangle + B\beta|1\rangle) + |10\rangle (A\alpha|0\rangle - B\beta|1\rangle) + |01\rangle (B\alpha|1\rangle + A\beta|0\rangle) + |11\rangle (B\alpha|1\rangle - A\beta|0\rangle)] \end{aligned} \quad (22)$$

From here on, we will follow a procedure similar to that of Table I but taking into account how sensitively the state is affected by noise.

4 Simplified Quantum Teleportation

First, and unlike the previous one, the new protocol dispenses with a classical channel to transmit the disambiguation bits, as well as it does not require the use of Pauli's matrices in Bob's side in order to reconstruct the teleported state from the mentioned disambiguation bits. These simplifications are the reason for the title of this paper, that is, simplified protocol.

For the new protocol of Figure 5, block “ $|0\rangle$ reset” does a strict reset of the qubit, while, we need to produce $|\beta_{00}\rangle \otimes |\psi\rangle$ instead of $|\psi\rangle \otimes |\beta_{00}\rangle$.

$$\begin{aligned} |\psi_0\rangle &= |\beta_{00}\rangle |\psi\rangle = \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle) (\alpha|0\rangle + \beta|1\rangle) \\ &= \frac{1}{\sqrt{2}} [\alpha|000\rangle + \beta|001\rangle + \alpha|110\rangle + \beta|111\rangle] \\ &= \left[\frac{\alpha}{\sqrt{2}} \quad 0 \quad 0 \quad \frac{\alpha}{\sqrt{2}} \quad \frac{\beta}{\sqrt{2}} \quad \frac{\beta}{\sqrt{2}} \quad 0 \quad 0 \quad \frac{\beta}{\sqrt{2}} \right]^T \end{aligned} \quad (23)$$

Now, a CNOT gate is applied to Equation (23),

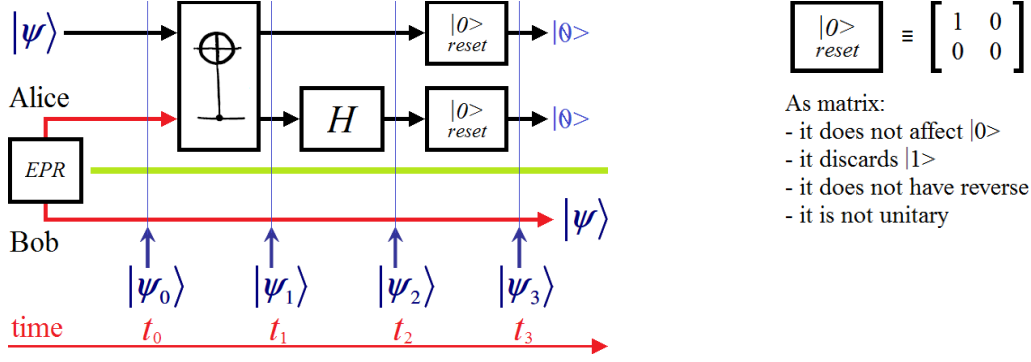


Fig.5 Simplified teleportation protocol using an EPR pair but without classical bits for disambiguation.

4.1 Noiseless analysis

$$\begin{aligned}
 |\psi_1\rangle &= \frac{1}{\sqrt{2}} [\alpha|000\rangle + \beta|001\rangle + \alpha|100\rangle + \beta|101\rangle] \\
 &= \begin{bmatrix} \alpha/\sqrt{2} & \alpha/\sqrt{2} & 0 & 0 & \beta/\sqrt{2} & \beta/\sqrt{2} & 0 & 0 \end{bmatrix}^T
 \end{aligned} \tag{24}$$

Applying a Hadamard's gate to the elements of Equation (24),

$$\begin{aligned}
 |\psi_2\rangle &= \frac{1}{2} [\alpha|000\rangle + \alpha|100\rangle + \beta|001\rangle + \beta|101\rangle + \alpha|000\rangle - \alpha|100\rangle + \beta|001\rangle - \beta|101\rangle] \\
 &= \alpha|000\rangle + \beta|001\rangle = |00\rangle(\alpha|0\rangle + \beta|1\rangle) = |00\rangle|\psi\rangle \equiv |\Phi^+\rangle|\psi\rangle \\
 &= [\alpha \ \beta \ 0 \ 0 \ 0 \ 0 \ 0 \ 0]^T \rightarrow |\Phi^+\rangle \rightarrow |00\rangle \rightarrow 00
 \end{aligned} \tag{25}$$

It is clear from Equation (25) that no disambiguation is necessary. Alice measures (where, both bits are always equal to zero independently of $|\psi\rangle$) in order to annul the entanglement and thus avoid violating the No-Cloning Theorem [5, 16]. We can also see in Figure 5 that it is not necessary for Bob to apply any unitary transformation. This eliminates the classical channel that is responsible for making teleportation as a whole to be carried out in a time greater than zero, i.e., not being instantaneous.

Although this result seems to contradict the relativistic principle of causality [4], the reality is that this never happens. As we can see in [23], the instantaneity of entanglement is possible without the need to resort to superluminal signaling and without contradictions between QMech and SRela. This last fact then covers the new protocol in a direct and complete way.

4.2 Noisy analysis

For noisy EPR pairs we also resorted to Figure 5 using the same version of Equations (18) and (19). Then, repeating Equation (23) but with $|\beta_{00}\rangle_n$ instead of $|\beta_{00}\rangle$, we will have

$$\begin{aligned}
 |\psi_0\rangle &= |\beta_{00}\rangle_n |\psi\rangle = (A|00\rangle + B|11\rangle)(\alpha|0\rangle + \beta|1\rangle) \\
 &= A\alpha|000\rangle + B\alpha|110\rangle + A\beta|001\rangle + B\beta|111\rangle
 \end{aligned} \tag{26}$$

Now, we apply a CNOT gate to Equation (26),

$$|\psi_1\rangle = A\alpha|000\rangle + B\alpha|100\rangle + A\beta|001\rangle + B\beta|101\rangle \tag{27}$$

Applying a Hadamard's gate to the elements of Equation (27), we will have,

$$\begin{aligned}
|\psi_2\rangle &= \frac{1}{\sqrt{2}} [A\alpha|000\rangle + A\alpha|100\rangle + B\alpha|000\rangle - B\alpha|100\rangle + A\beta|001\rangle + A\beta|101\rangle + B\beta|001\rangle - B\beta|101\rangle] \\
&= \frac{A}{\sqrt{2}}|00\rangle(\alpha|0\rangle + \beta|1\rangle) + \frac{B}{\sqrt{2}}|00\rangle(\alpha|0\rangle + \beta|1\rangle) + \frac{A}{\sqrt{2}}|10\rangle(\alpha|0\rangle + \beta|1\rangle) - \frac{B}{\sqrt{2}}|10\rangle(\alpha|0\rangle + \beta|1\rangle) \quad (28) \\
&= \left[\left(\frac{A+B}{\sqrt{2}} \right) |00\rangle + \left(\frac{A-B}{\sqrt{2}} \right) |10\rangle \right] (\alpha|0\rangle + \beta|1\rangle) \\
&= C(\alpha|0\rangle + \beta|1\rangle)
\end{aligned}$$

where

$$C = \left(\frac{A+B}{\sqrt{2}} \right) |00\rangle + \left(\frac{A-B}{\sqrt{2}} \right) |10\rangle \quad (29)$$

The worst consequence of noise in the new protocol is that the teleported state loses its purity, which means, it would not be on Bloch's sphere, in the more general case, given that $C \neq 1$, but even so, the teleported state is recovered without problems and without disambiguation. This clearly indicates that the new protocol is much more robust (immune to noise) than the standard.

5 Conclusions and Future Works

In this work, we have presented a new quantum teleportation protocol in which we have eliminated the classical channel used currently for disambiguation, and since the classical channel is the weak link of standard teleportation in all matters relating to safety and speed, the new protocol seems to be an interesting alternative. We speak of security since quantum cryptography [30] [31] is much more robust than its classical counterpart, being the quantum key distribution (QKD) its main tool [5] [24] [30] [31]. On the other hand, in the standard protocol of QTele, the classical channel forces the communication systems (as a complete unit) to have a speed of transmission equal to the speed of light, that is, the system is not instantaneous. In other words, in the case of an interplanetary communication, the traditional teleportation behaves (from the point of view of speed) as a current classical communication system. Instead, the new protocol is instantaneous since it does not require disambiguation through the use of a classical channel, gaining robustness (i.e., noise immunity), security, and requiring fewer components for its implementation in a laboratory.

The experimental implementation of the new protocol will allow us to verify what is established in [23], which is an attempt to unify the two main pillars of Physics: the Theory of Relativity and QMec, as well as to get a better understanding of the entanglement. This happens because the new protocol takes full advantage of the main attribute of entanglement: the instantaneity.

Furthermore, in the QComm work mentioned above [23] is demonstrated that a superluminal signaling [7, 8] is not necessary for entanglement to be instantaneous.

Future challenges in this area involve: a thorough study of what this work means in black hole theory, and, a formal and detailed analysis of the complete attributes of the entanglement, and therefore, of a quantum channel in terms of its bandwidth, channel capacity and information transit time for QComm [32-34]. Besides, the impact of the aforementioned verification on Quantum Internet [35, 36] and Super Dense Coding [5, 17] is evident.

Finally, considering that there are already precedents of teleportation of energy [37, 38], and keeping in mind the research done in paper [23], an interesting question arises: can we teleport matter through exclusively quantum channels in a not so distant future?

Competing Interests

The author declares that there are no competing interests.

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