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Simultaneous Teleportation of Arbitrary Two-qubit and Two Arbitrary Single-qubit States Using A Single Quantum Resource

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Abstract In this paper we present a teleportation protocol by which the multitask of transfer of a two-qubit and two single-qubit quantum states is performed simultaneously with the help of a single entangled channel. The protocol is under the supervision of a controller. There are three pairs of senders and receivers who are connected among themselves along with the controller by a single entangled state. The teleportation protocol is perfect.

Keywords Entanglement · Quantum teleportation · Measurement · Quantum channel

1 Introduction

Teleportation processes are well known protocols in the theory of quantum communications. It was first introduced in the work of Bennet et al. [1] in which a maximally entangled Bell-state was utilized for sending an arbitrary qubit to a distant party. The protocol was extended, modified and applied to teleport quantum states of various nature through different types of quantum channels. There are various kinds of quantum teleportation like controlled teleportation [2–4], probabilistic teleportation [5, 6], bidirectional quantum teleportations [7, 8] etc. There are many research articles on the different aspects of quantum teleportation like [4, 9–39]. Here we qualitatively describe some of them.

In 1994, Vaidman [9] proposed a teleportation protocol of a quantum state of a system with continuous variables. In 2004, Zheng [12] presented a scheme for approximate conditional teleportation of an unknown atomic state without the Bell state measurement. In 2005,

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Rigolin [14] proposed a quantum teleportation of an arbitrary two-qubit state and its relation to multipartite entanglement. In 2005, Cardoso et al. [15] proposed a teleportation protocol of entangled states without Bell state measurement. In 2010, Tsai et al. [20] presented a teleportation of a pure EPR state using GHZ-*like* state. It is known that one of the key step in quantum teleportation is the Bell state analysis. In 2010, Sheng et al. [21] described the first deterministic hyperentanglement Bell state analysis (HBSA). Based on the HBSA, they also described the first quantum teleportation of multiple degrees of freedom of a single photon in the same work. In 2015, they also described the first protocol of teleportation of a logic-qubit based on Bell state analysis [26–28]. Experimental realization of quantum teleportation is reported in works like [40–44] using two or more entangled quantum qubits.

The teleportation of entangled quantum states was attempted at a later point of time. The most general two-qubit quantum state could be perfectly teleported using two GHZ-*like* quantum channels simultaneously [25]. This work is a culmination of several works like those noted in [23, 24, 45], in all of which specific classes of two-qubit entangled state were considered for teleportation through different quantum channels.

In a recent paper [46] Li et al. has shown that three senders Alice, Charlie and Edison can teleport their arbitrary single-qubits to three distant parties Bob, David and Ford respectively by a single protocol which is performed under the supervision of the controller. Following the sprit of this work we show that a controlled protocol is possible by which simultaneous transfer of an arbitrary two-qubit entangled state and two arbitrary single-qubit states in the possession of Alice, Carson and Dick respectively to Bob, Edberg and Federar can be made provided we use a ten-qubit entangled state as a quantum channel shared suitably Alice, Carson, Dick, Bob, Edberg and Federar and the controller. The protocol is a perfect teleportation protocol, in which the transfer of the states are done with certainty and exactness in contrast to the approximate and probabilistic teleportation protocols where the transferred state is either similar to the original state with some fidelity or the process of transfer is probabilistic in nature admitting some cases of failure.

2 The Simultaneous Teleportation Protocol

Alice wants to transmit an unknown two-qubit entangled state to Bob which is given by

$$|\psi\rangle_{ab} = (a_{00}|00\rangle + a_{01}|01\rangle + a_{10}|10\rangle + a_{11}|11\rangle)_{ab}, \tag{1}$$

where the parameters a_{ij} satisfy $\sum_{i=0,j=0}^{1}|a_{ij}|^2 = 1$, Carson wants to transmit an unknown single-qubit state to Edberg which is given by

$$|\psi\rangle_c = (c_0|0\rangle + c_1|1\rangle)_c, \tag{2}$$

where the parameters c_i satisfy $\sum_{i=0}^{1}|c_i|^2 = 1$ and Dick wants to transmit an unknown single-qubit state to Federar which is given by

$$|\psi\rangle_d = (d_0|0\rangle + d_1|1\rangle)_d, \tag{3}$$

where the parameters d_i satisfy $\sum_{i=0}^{1}|d_i|^2 = 1$.

We consider the quantum channel shared between the senders Alice, Carson and Dick and the receivers Bob, Edberg and Federar and the controller Charlie consisting of a ten-qubit entangled state given by,

$$\begin{aligned}|\psi\rangle_{123\ldots 89\,10} = &|0000000000\rangle + |0001000001\rangle + |0010000010\rangle + |0011000011\rangle\\ &+ |0100010100\rangle + |0101010101\rangle + |0110010110\rangle + |0111010111\rangle\\ &+ |1000101000\rangle + |1001101001\rangle + |1010101010\rangle + |1011101011\rangle\\ &+ |1100111100\rangle + |1101111101\rangle + |1110111110\rangle\\ &+|1111111111\rangle)_{123\ldots 89\,10},\end{aligned} \tag{4}$$

where the qubits 1 and 2 are in the possession of the sender Alice, the qubits 3 and 4 are in the possession of the sender Carson and Dick respectively, the qubits 7 and 8 are in the possession of the receiver Bob, the qubits 9 and 10 are in the possession of the receiver Edberg and Federar respectively, and the qubits 5 and 6 are in the possession of a third party Charlie whom we call the controller. The channel need not be normalized.

Thus the state of the whole composite system (1), (2), (3) and (4) is given by,

$$|\Psi\rangle_{abcd123456789\,10} = |\psi\rangle_{ab} \otimes |\psi\rangle_c \otimes |\psi\rangle_d \otimes |\psi\rangle_{123\ldots 89\,10}.$$

To achieve the simultaneous quantum teleportation, Alice performs two Bell state measurements on her own qubit pairs $(a, 1)$ and $(b, 2)$ and informs Carson who then performs Bell state measurement on his own qubit pair $(c, 3)$. He then informs Dick who then performs Bell state measurement on his own qubit pair $(d, 4)$ where for a two-qubit system the Bell states are given by $|\phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$ and $|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$. There are 256 different types of results after the measurement of Alice, Carson and Dick.

First Alice performs the Bell-state measurement on her own qubit pairs $(a, 1)$ and $(b, 2)$, where she obtains $|\phi^+\rangle_{a1}|\phi^+\rangle_{b2}$ and then sends her measurement result to Bob. The combined state collapses to

$$\begin{aligned}&|\Psi^1\rangle_{cd3456789\,10} = {}_{b2}\langle\phi^+|_{a1}\langle\phi^+|\Psi\rangle_{abcd123456789\,10}\\ &= \frac{1}{2}\{a_{00}|\psi\rangle_c|\psi\rangle_d(|00000000\rangle + |01000001\rangle + |10000010\rangle + |11000011\rangle)_{3456789\,10}\\ &+a_{10}|\psi\rangle_c|\psi\rangle_d(|00101000\rangle + |01101001\rangle + |10101010\rangle + |11101011\rangle)_{3456789\,10}\\ &+a_{01}|\psi\rangle_c|\psi\rangle_d(|00010100\rangle + |01010101\rangle + |10010110\rangle + |11010111\rangle)_{3456789\,10}\\ &+a_{11}|\psi\rangle_c|\psi\rangle_d(|00111100\rangle + |01111101\rangle + |10111110\rangle + |11111111\rangle)_{3456789\,10}\}.\end{aligned}$$

Then Carson performs the Bell state measurement on her own qubit pair $(c, 3)$, where he obtains $|\phi^+\rangle_{c3}$ and then sends his measurement result to Edberg. The state then collapses to

$$\begin{aligned}|\Psi^2\rangle_{d456789\,10} &= {}_{c3}\langle\phi^+|\Psi^1\rangle_{cd3456789\,10}\\ &= \frac{1}{2\sqrt{2}}\{a_{00}c_0|\psi\rangle_d(|0000000\rangle + |1000001\rangle)_{456789\,10}\\ &+a_{00}c_1|\psi\rangle_d(|0000010\rangle + |1000011\rangle)_{456789\,10}\\ &+a_{10}c_0|\psi\rangle_d(|0101000\rangle + |1101001\rangle)_{456789\,10}\\ &+a_{10}c_1|\psi\rangle_d(|0101010\rangle + |1101011\rangle)_{456789\,10}\\ &+a_{01}c_0|\psi\rangle_d(|0010100\rangle + |1010101\rangle)_{456789\,10}\\ &+a_{01}c_1|\psi\rangle_d(|0010110\rangle + |1010111\rangle)_{456789\,10}\\ &+a_{11}c_0|\psi\rangle_d(|0111100\rangle + |1111101\rangle)_{456789\,10}\\ &+a_{11}c_1|\psi\rangle_d(|0111110\rangle + |1111111\rangle)_{456789\,10}\}.\end{aligned}$$

Then Dick performs the Bell state measurement on her own qubit pair $(d, 4)$, where he obtains $|\phi^+\rangle_{d4}$ and then sends it to Federar. The state then collapses to

$$\begin{aligned}|\Psi^3\rangle_{56789\,10} &= {}_{d4}\langle\phi^+|\Psi^2\rangle_{d456789\,10}\\ &= \frac{1}{4}\{a_{00}(c_0d_0|000000\rangle + c_0d_1|000001\rangle + c_1d_0|000010\rangle + c_1d_1|000011\rangle)\\ &\quad +a_{01}(c_0d_0|010100\rangle + c_0d_1|010101\rangle + c_1d_0|010110\rangle + c_1d_1|010111\rangle)\\ &\quad +a_{10}(c_0d_0|101000\rangle + c_0d_1|101001\rangle + c_1d_0|101010\rangle + c_1d_1|101011\rangle)\\ &\quad +a_{11}(c_0d_0|111100\rangle + c_0d_1|111101\rangle + c_1d_0|111110\rangle\\ &\quad +c_1d_1|111111\rangle)\}_{56789\,10}.\end{aligned}$$

At the end the controller Charlie performs the single qubit measurement in the basis $|\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$, on his two qubits 5 and 6 where he obtains $|+\rangle_5|+\rangle_6$ then sends the measurement result to Bob, Edberg and Federar. The state then reduces to

$$\begin{aligned}|\Psi^4\rangle_{789\,10} &= {}_6\langle+|_5\langle+|\Psi^3\rangle_{56789\,10}\\ &= \frac{1}{8}(a_{00}|00\rangle + a_{01}|01\rangle + a_{10}|10\rangle + a_{11}|11\rangle)_{78} \otimes (c_0|0\rangle + c_1|1\rangle)_9\\ &\quad \otimes(d_0|0\rangle + d_1|1\rangle)_{10}.\end{aligned}$$

With this information from Charlie and the information from Alice (Carson, Dick) Bob (Edberg, Federar) perform appropriate unitary operation I_{78} (I_9, I_{10}) on the pair (single) qubits $\{7, 8\}$ $(9, 10)$ to reconstruct the original unknown states which were originally in the possessions of Alice (Carson, Dick). The rest are similar and the details of the protocol are presented in Tables 1 and 2 respectively. The diagram is also schematically reported through the Fig. 1.

In the concise expression in the Tables we have used the symbolism of [47] where the signs $\pm_1$, $\pm_2$ $\pm_3$, $\pm_4$ correspond to the Bell state measurements of qubit pairs $(a, 1)$, $(b, 2)$, $(c, 3)$ and $(d, 4)$ in the basis of $\{|\phi^\pm\rangle, |\psi^\pm\rangle\}$ respectively, and they mean multiplication of $\pm$ signs. As illustrations we mention $+_1+_2 = +$, $+_1-_2 = -$, $-_1-_2 = +$, etc, with which $\frac{1}{8}(a_{00}|00\rangle +_2 -_6 a_{01}|01\rangle +_1 +_5 a_{10}|10\rangle +_1 +_2 +_5 -_6 a_{11}|11\rangle)_{78} \otimes (c_0|0\rangle +_3 c_1|1\rangle)_9 \otimes (d_0|0\rangle -_4$

Table 1 Joint measurement outcomes of Bob, Edberg and Federar after the measurements done by Alice, Carson, Dick and Charlie. Here 64 out of 256 results are shown

Measurement by Alice, Carson and Dick	Charlie's Measurement	State shared by Bob, Edberg and Federar
$\|\phi^\pm\rangle_{a1}\|\phi^\pm\rangle_{b2}\|\phi^\pm\rangle_{c3}\|\phi^\pm\rangle_{d4}$	$\|\pm\rangle_5\|\pm\rangle_6$	$\frac{1}{8}(a_{00}\|00\rangle \pm_2 \pm_6 a_{01}\|01\rangle \pm_1 \pm_5 a_{10}\|10\rangle \pm_1 \pm_2 \pm_5 \pm_6 a_{11}\|11\rangle)_{78} \otimes (c_0\|0\rangle \pm_3 c_1\|1\rangle)_9 \otimes (d_0\|0\rangle \pm_4 d_1\|1\rangle)_{10}$
$\|\psi^\pm\rangle_{a1}\|\psi^\pm\rangle_{b2}\|\psi^\pm\rangle_{c3}\|\psi^\pm\rangle_{d4}$	$\|\pm\rangle_5\|\pm\rangle_6$	$\frac{1}{8}(\pm_5 \pm_6 a_{00}\|11\rangle \pm_2 \pm_5 a_{01}\|10\rangle \pm_1 \pm_6 a_{10}\|01\rangle \pm_1 \pm_2 a_{11}\|00\rangle)_{78} \otimes (c_0\|1\rangle \pm_3 c_1\|0\rangle)_9 \otimes (d_0\|1\rangle \pm_4 d_1\|0\rangle)_{10}$
$\|\phi^\pm\rangle_{a1}\|\phi^\pm\rangle_{b2}\|\phi^\pm\rangle_{c3}\|\psi^\pm\rangle_{d4}$	$\|\pm\rangle_5\|\pm\rangle_6$	$\frac{1}{8}(a_{00}\|00\rangle \pm_2 \pm_6 a_{01}\|01\rangle \pm_1 \pm_5 a_{10}\|10\rangle \pm_1 \pm_2 \pm_5 \pm_6 a_{11}\|11\rangle)_{78} \otimes (c_0\|0\rangle \pm_3 c_1\|1\rangle)_9 \otimes (d_0\|0\rangle \pm_4 d_1\|1\rangle)_{10}$
$\|\psi^\pm\rangle_{a1}\|\psi^\pm\rangle_{b2}\|\psi^\pm\rangle_{c3}\|\phi^\pm\rangle_{d4}$	$\|\pm\rangle_5\|\pm\rangle_6$	$\frac{1}{8}(\pm_5 \pm_6 a_{00}\|11\rangle \pm_2 \pm_5 a_{01}\|10\rangle \pm_1 \pm_6 a_{10}\|01\rangle \pm_1 \pm_2 a_{11}\|00\rangle)_{78} \otimes (c_0\|1\rangle \pm_3 c_1\|0\rangle)_9 \otimes (d_0\|1\rangle \pm_4 d_1\|0\rangle)_{10}$

Table 2 Appropriate Unitary transformations performed by Bob, Edberg and Federar

Measurement by Alice, Carson and Dick	Charlie's Measurement	State shared by Bob, Edberg and Federar	Appropriate Unitary operator
$\|\phi^+\rangle_{a1}\|\phi^+\rangle_{b2}\|\phi^+\rangle_{c3}\|\phi^+\rangle_{d4}$	$\|+\rangle_5\|+\rangle_6$	$\frac{1}{8}(a_{00}\|00\rangle+a_{01}\|01\rangle+a_{10}\|10\rangle+a_{11}\|11\rangle)_{78}\otimes (c_0\|0\rangle + c_1\|1\rangle)_9 \otimes (d_0\|0\rangle + d_1\|1\rangle)_{10}$	$I_{78} \otimes I_9 \otimes I_{10}$
	$\|+\rangle_5\|-\rangle_6$	$\frac{1}{8}(a_{00}\|00\rangle-a_{01}\|01\rangle+a_{10}\|10\rangle-a_{11}\|11\rangle)_{78}\otimes (c_0\|0\rangle + c_1\|1\rangle)_9 \otimes (d_0\|0\rangle + d_1\|1\rangle)_{10}$	$(I \otimes \sigma_z)_{78} \otimes I_9 \otimes I_{10}$
	$\|-\rangle_5\|+\rangle_6$	$\frac{1}{8}(a_{00}\|00\rangle+a_{01}\|01\rangle-a_{10}\|10\rangle-a_{11}\|11\rangle)_{78}\otimes (c_0\|0\rangle + c_1\|1\rangle)_9 \otimes (d_0\|0\rangle + d_1\|1\rangle)_{10}$	$(\sigma_z \otimes I)_{78} \otimes I_9 \otimes I_{10}$
	$\|-\rangle_5\|-\rangle_6$	$\frac{1}{8}(a_{00}\|00\rangle-a_{01}\|01\rangle-a_{10}\|10\rangle+a_{11}\|11\rangle)_{78}\otimes (c_0\|0\rangle + c_1\|1\rangle)_9 \otimes (d_0\|0\rangle + d_1\|1\rangle)_{10}$	$(\sigma_z \otimes \sigma_z)_{78} \otimes I_9 \otimes I_{10}$
$\|\phi^-\rangle_{a1}\|\phi^+\rangle_{b2}\|\phi^+\rangle_{c3}\|\phi^-\rangle_{d4}$	$\|+\rangle_5\|+\rangle_6$	$\frac{1}{8}(a_{00}\|00\rangle+a_{01}\|01\rangle-a_{10}\|10\rangle-a_{11}\|11\rangle)_{78}\otimes (c_0\|0\rangle + c_1\|1\rangle)_9 \otimes (d_0\|0\rangle - d_1\|1\rangle)_{10}$	$(\sigma_z \otimes I)_{78} \otimes I_9 \otimes (\sigma_z)_{10}$
	$\|+\rangle_5\|-\rangle_6$	$\frac{1}{8}(a_{00}\|00\rangle-a_{01}\|01\rangle-a_{10}\|10\rangle+a_{11}\|11\rangle)_{78}\otimes (c_0\|0\rangle + c_1\|1\rangle)_9 \otimes (d_0\|0\rangle - d_1\|1\rangle)_{10}$	$(\sigma_z \otimes \sigma_z)_{78} \otimes I_9 \otimes (\sigma_z)_{10}$
	$\|-\rangle_5\|+\rangle_6$	$\frac{1}{8}(a_{00}\|00\rangle+a_{01}\|01\rangle+a_{10}\|10\rangle+a_{11}\|11\rangle)_{78}\otimes (c_0\|0\rangle + c_1\|1\rangle)_9 \otimes (d_0\|0\rangle - d_1\|1\rangle)_{10}$	$(I \otimes I)_{78} \otimes I_9 \otimes (\sigma_z)_{10}$
	$\|-\rangle_5\|-\rangle_6$	$\frac{1}{8}(a_{00}\|00\rangle-a_{01}\|01\rangle+a_{10}\|10\rangle-a_{11}\|11\rangle)_{78}\otimes (c_0\|0\rangle + c_1\|1\rangle)_9 \otimes (d_0\|0\rangle - d_1\|1\rangle)_{10}$	$(I \otimes \sigma_z)_{78} \otimes I_9 \otimes (\sigma_z)_{10}$

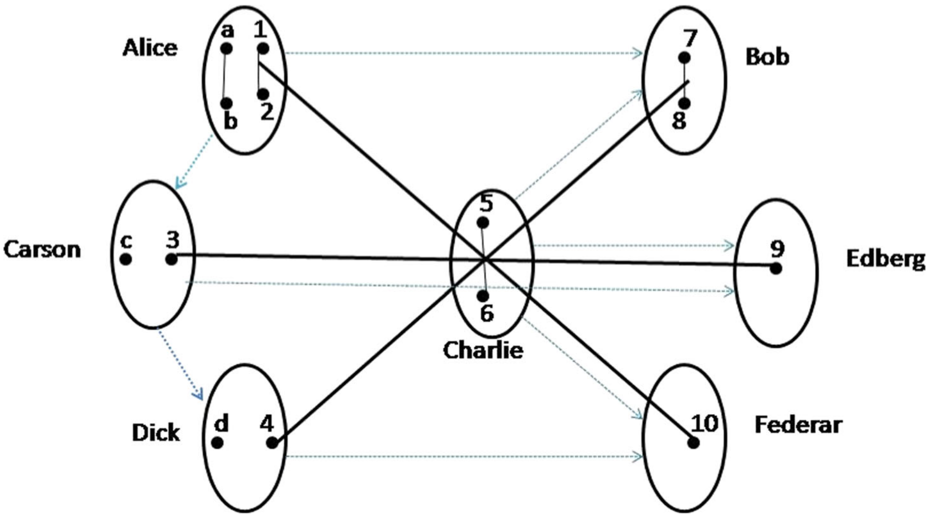

Fig. 1 (Color online)The schematic diagram of the present protocol, where the solids represent the qubits, the connection of quantum channel is represent by the black solid lines and the blue doted lines contend for classical communication

$d_1|1\rangle)_{10}$ means $\frac{1}{8}(a_{00}|00\rangle - a_{01}|01\rangle + a_{10}|10\rangle - a_{11}|11\rangle)_{78} \otimes (c_0|0\rangle + c_1|1\rangle)_9 \otimes (d_0|0\rangle - d_1|1\rangle)_{10}$.

In Table 1 we give some measurements results of Alice, Carson and Dick and the controller Charlie and the corresponding states shared by Bob, Edberg and Federar after the measurements are done. In Table 2 the following eight cases of the appropriate unitary operations performed by Alice and Bob are shown. Other cases of applying unitary operations are similar.

3 Discussion and Conclusion

The quantum mechanical resource used in this protocol is a ten-qubit entangled channel. Quantum entanglement can be created by various methods which are discussed in works like [48, 49]. In particular, a ten-qubit entangled state can be successfully prepared in a linear optical system [50]. It is well known that the entanglement is fragile resource. If it interacts or is made to interact by external agents with another quantum system then the channel becomes noisy and the protocol can not be executed in the manner presented here. In this case the quantum channel becomes an open system which, in its interaction with the external environment may loose some amount of entanglement. These aspects of the protocol are important. We do not consider these matters in the present paper, Nevertheless we stress that these matters are to be considered in future works. We perform the protocol with the help of a single integrated channel. The three simultaneous transfer of states can not be separated nor can we use a part of the channel for performing individually any one of this three transfers. Lastly, we calculate the efficiency of our protocol is in with the formula for efficiency given in [51, 52] as $\eta = \frac{q_s}{q_u + b_t}$, where q_s is the number of qubits that consist of the quantum information to be shared, q_u is the number of the qubits that is used as the quantum channel (except for those chosen for security checking) and b_t is the classical bits transmitted. In our protocol $\eta = 2/13$, in comparison to the protocol in [46] where the value of η is $1/14$.

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