doi: 10.3788/gzxb20124103.0330

Quantum Controlled Teleportation of an Arbitrary *m*-particle State Using a (2*m*+1)-particle Entangled State as Quantum Channel

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Abstract: A general scheme for controlled teleportation of an arbitrary m-qubit (high-dimensional quantum system) state with a d-dimensional $(2m+1)$-particle entangled state is presented. The arbitrary m-qubit state can be teleported if the sender (Alice) performs m generalized Bell state measurements on his particles and the controller (Bob) performs single particle generalized X-basis measurement on his particle. The original m-qubit state can be reconstructed on the receiver's particles if the receiver (Charlie) performs corresponding unitary operations on his particles according to the measurement results of the sender and the controller. The scheme has the advantage of transmitting much less particles for controlled teleportation of an unknown m-qubit state than others. Moreover, the application of the scheme by using a nonmaximally entangled state as its quantum channel is discussed. The original m-qubit state can be probabilistically reconstructed on the receiver's particles if the receiver introduces an auxiliary qubit and performs the general unitary transformation on his entangled particles and the auxiliary qubit. The relationship between the success probability that the receiver obtains the originally m-qubit state and the coefficients of the pure entangled quantum channel is also discussed.

Key words: Quantum information; Controlled teleportation; Generalized Bell state measurement; Pure entanglement

CLCN: O413.2 **Document Code**: A **Article ID**: 1004-4213(2012)03-0330-6

0 Introduction

Quantum teleportation plays an important role in quantum communication[1]. It allows the sender Alice to exploit the nonlocal correlation of quantum entangled state shared between the sender and the receiver in advance to teleport an unknown quantum state from one place to another with an Einstein-Podolsky-Rosen (EPR) state and two bits of classical information. To teleporting the unknown quantum state, the sender Alice performs Bell state measurement on his particles; the receiver can reconstruct the original state by performing corresponding unitary operations on his particle according to the relation between the state of his particle and Alice's measurement result.

Since Bennett *et. al.* first presentd the information of an unknown quantum state could be disassembled into some pieces and reconstruct in another place with nonlocal correlation and some classical information, quantum teleportation has attached much interest since its important application in quantum communication and quantum computation. On the one hand, quantum teleportation has been experimental realized by some group by using entangled photons and ions as quantum channel[2-4]. In 2010, Jin *et. al.* reported a long distant teleportation over 16 km with an optical free-space link[5]; On the other hand, theoretical quantum teleportation schemes for teleporting the unknown quantum states, especially multiparticle quantum state , have been presented by using different quantum channel[6-24]. For example, in 2000 Yang and Guo proposed a scheme for teleporting a N-particle state by N EPR pairs[6]; Yan presented a protocol for teleporting a two-particle state with four-particle pure entangled state in 2006[7]; Dong presented a scheme for probabilistic teleportation of an arbitrary two-particle state via two general W states [9].

Foundation item: The National Natural Science Foundation of China (No. 11047102), the Natural Science Foundation of Guangxi (No. 2011GxNSFB018062), the Educational Commission of Guangxi (No. 201012MS078) and the Key Project of Chinese Ministry of Education (No. 211137)

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Received date: 2011-11-07 **Revised date**: 2012-01-17

In the past few years, controlled teleportation has been studied by some groups[25-42]. In 1999 Karlsson and Bourennane presented the first controlled scheme by using a three-particle Greenberger-Horne-Zeilinger (GHZ) state[25]; Deng proposed a protocol for symmetric multiparty controlled teleportation of an arbitrary two-particle state in 2005[26]; Li introduced an efficient multiparty controlled teleportation scheme for an arbitrary multiparticle qubit (d-level quantum) state by using d-dimensional GHZ state as quantum channel[27]. In 2007, Zhou presented a scheme for controlled teleportation of an arbitrary m-qubit state by using m $(n+2)$-particle pure entangled state as the quantum channel[28]. Recently, Ren *et. al.* presented a scheme for controlled teleportation of an arbitrary three-particle state via a seven-particle entangled state[42].

Although there are some schemes for controlled teleportation of an arbitrary m-qubit state via pure entangled state, the quantum channel is composed of m entangled states[28,40]. Since quantum entanglement is an important resource in real application of quantum communication, controlled teleportation via one pure entangled state is more suitable for application than others. In this work, we will present a general controlled teleportation scheme for an arbitrary m-qubit state by only using one $(2m+1)$-particle pure entangled state as the quantum channel following some ideas in Ref. [42]. The agents need only share one $(2m+1)$-particle entangled state for quantum controlled teleportation of an arbitrary m-qubit state. Moreover, we discuss the application of this scheme with pure entangled state, which makes this scheme more suitable for application than others.

1 Controlled teleportation of an arbitrary m-qubit state with a $(2m+1)$-particle entangled state

The generalized m-particle GHZ state of d-dimensional quantum systems can be written as[1,29,44]

$$|\psi\rangle_{l_1\cdots l_m}=\frac{1}{\sqrt{d}}\sum_{\mu=0}^{d-1}e^{\frac{2\pi i}{d}\mu l_m}|\mu\rangle|\mu\oplus l_1\rangle\cdots|\mu\oplus l_{m-1}\rangle \quad (1)$$

where $l_1,l_2,\cdots,l_m=0,\cdots,d-1$ are used to label d^m orthogonal GHZ state; $|0\rangle,\cdots,|d-1\rangle$ are d eigenvectors of Z_d basis; $|\mu\oplus l_1\rangle$ means $(\mu+l_1)$ mod d. $|t_x\rangle$ $(t=0,\cdots,d-1)$ is the eigenvectors of X_d basis[31].

$$|t\rangle_x=\frac{1}{\sqrt{d}}\sum_{l=0}^{d-1}\oplus\, e^{\frac{2\pi i}{d}lt}|t\rangle \quad (2)$$

Similar to Ref. [42], the entangled $2m$-particle state can be written as

$$|\Psi\rangle=\frac{1}{\sqrt{d}}\sum_{l_1,\cdots,l_m=0}^{d-1}|l_1\cdots l_m\rangle|\psi\rangle_{l_1\cdots l_m} \quad (3)$$

An arbitrary m-qubit state can be written as[28]

$$|\chi\rangle_{\chi_1\cdots\chi_m}=\sum_{k_1\cdots k_m=0}^{d-1}\beta_{k_1\cdots k_m}|k_1\cdots k_m\rangle \quad (4)$$

For controlled teleportation of an arbitrary m-qubit state, the sender Alice first prepared a $(2m+1)$-particle entangled state, shared the entangled state with the controller Charlie and the receiver Bob, and performed m generalized Bell state measurement on his particles. The controller Bob performed generalized X-basis measurement; the receiver can reconstruct the original state by performing corresponding unitary operation on his particle.

That is, Alice first prepared a $2m$-particle entangled state $|\Psi\rangle_{a_1\cdots a_m b_1\cdots b_m}$, then entangled particles $a_1\cdots b_m$ with auxiliary particle c whose original state is $|0\rangle_c$ by performing unitary operation

$$U=\sum_{i=0}^{d-1}|ii\rangle\langle i0| \quad (5)$$

on his particles a_1 and auxiliary particle c[42]. i. e.,

$$|\Psi\rangle'_{a_1\cdots a_m b_1\cdots b_m c}=U|\Psi\rangle_{a_1\cdots a_m b_1\cdots b_m}|0\rangle_c=\frac{1}{\sqrt{d}}\sum_{l_1,\cdots,l_m=0}^{d-1}|l_1\cdots l_m\rangle|\psi\rangle_{l_1\cdots l_m}|l_1\rangle \quad (6)$$

After prepares the $(2m+1)$-particle entangled state, Alice shares the entangled state with controller and receiver. That is, Alice keeps particles $a_1\cdots a_m$ in his hand, sends particle c to the controller, sends particles $b_1\cdots b_m$ to the receiver. Alice can use decoy photons to prevent dishonest agents from stealing the information freely[43-45]. After setting up the quantum channel securely, the sender Alice performs m generalized Bell state measurements on his particle χ_l,a_l $(l=1,\cdots,m)$, the controller Charlie performs generalized X-basis measurement on his particle c, the receiver Bob can reconstruct the original state $|\chi\rangle$ by performing corresponding unitary operation on his particles $b_1\cdots b_m$. In details, the state of the composite system composed of particles $\chi_1,\cdots,\chi_m,a_1,\cdots,a_m,b_1,\cdots,b_m,c$ can be written as

$$|\chi\rangle\otimes|\Psi\rangle'=\frac{1}{d}\sum_{\substack{k_1\cdots k_m,l_1\cdots l_m\\ \mu=0}}^{d-1}\beta_{k_1\cdots k_m}e^{\frac{2\pi i}{d}\mu l_m}|k_1\cdots k_m\rangle\otimes$$

$$|l_1\cdots l_m\rangle|\mu\rangle|\mu\oplus l_1\rangle\cdots|\mu\oplus l_{m-1}\rangle=\frac{1}{d\sqrt{d}^m}\sum_{\substack{r_1,s_1,\cdots r_m,s_m\\k_1\cdots k_m,\mu=0}}^{d-1}|\psi\rangle_{r_1s_1}\cdots|\psi\rangle_{r_ms_m}\cdot e^{\frac{2\pi i}{d}[\mu l(k_m+r_m)-k_1s_1-\cdots k_ms_m-k_1t]}\beta_{k_1\cdots k_m}|\mu\rangle\cdot|\mu\oplus k_1\oplus r_1\rangle\cdots|\mu\oplus k_{m-1}\oplus r_{m-1}\rangle \quad (7)$$

After Alice performs m generalized Bell state measurements on the particles $\chi_l, a_l (l=1,\cdots,m)$, Charlie performs generalized X-basis measurement on particle c, particles $b_1\cdots b_m$ collapse to the state $|\varphi\rangle_{b_1\cdots b_m}$ if Alice gets the outcome $|\psi\rangle_{r_ls_l}$, Charlie gets the outcome $|t\rangle_x$.

$$|\varphi\rangle_{b_1\cdots b_m}=\sum_{k_1\cdots k_m,\mu=0}^{d-1}e^{\frac{2\pi i}{d}[\mu(k_m+r_m)-k_1s_1-\cdots k_ms_m-k_1t]}\cdot\beta_{k_1\cdots k_m}|\mu\rangle|\mu\oplus k_1\oplus r_1\rangle\cdots|\mu\oplus k_{m-1}\oplus r_{m-1}\rangle \quad (8)$$

That is, the state of particle $b_1\cdots b_m$ is determined by the measurement results of the sender and the controller. The receiver can reconstruct the original state $|\chi\rangle$ by performing unitary operation on his particles $b_1\cdots b_m$ according to the measurement result. In details, unitary operation

$$U_{r_1,s_1,\cdots,r_m,s_m,t}=\frac{1}{\sqrt{d}}\sum_{l_1,\cdots,l_{m+1}=0}^{d-1}e^{-\frac{2\pi i}{d}[l_{m+1}(l_m+s_m)-l_1s_1-\cdots-l_ms_m-l_1t]}\cdot|l_1\rangle\cdots|l_m\rangle\langle l_{m+1}|\langle l_{m+1}\oplus l_1\oplus r_1|\cdots\langle l_{m+1}\oplus l_{m-1}\oplus r_{m-1}| \quad (9)$$

can transform state $|\varphi\rangle_{b_1\cdots b_m}$ into state $|\chi\rangle$. i. e.,

$$U_{r_1,s_1,\cdots,r_m,s_m}|\varphi\rangle_{b_1\cdots b_m}=|\chi\rangle_{b_1\cdots b_m} \quad (10)$$

2 Probabilistic controlled teleportation

In practical applications, quantum channel is not maximally entangled states, but mixed states or pure states since the imperfect of the practical signal source[28]. In this section, we discuss the application of our scheme by using a pure $(2m+1)$-particle entangled state as quantum channel.

Supposed the $(2m+1)$-particle entangled state Alice shared with the receiver and the controller is a pure entangled state $|\Psi\rangle''_{a_1\cdots a_mb_1\cdots b_mc}$ since the channel noise[28].

$$|\Psi\rangle''_{a_1\cdots a_mb_1\cdots b_mc}=\sum_{l_1,\cdots,l_m=0}^{d-1}\alpha_{l_1\cdots l_m}|l_1\cdots l_m\rangle\cdot|\Psi\rangle_{l_1\cdots l_m}|l_1\rangle \quad (11)$$

and

$$\sum_{l_1,\cdots,l_m=0}^{d-1}|\alpha_{l_1\cdots l_m}|^2=1 \quad (12)$$

For controlled teleportation of an arbitrary m-qubit state $|\chi\rangle$, the sender Alice first shares the $(2m+1)$-particle pure entangled state with the controller and the receiver, then performs m generalized Bell state measurements on his particles. The controller Charlie performs generalized X-basis measurement on his particle, the receiver can probabilistic reconstruct the original state by introducing an auxiliary qubit and performing unitary operation on his particles and the auxiliary particle. That is, Alice keeps particles $a_1\cdots a_m$ in his hand, sends particle c to controller Charlie, sends particles $b_1\cdots b_m$ to the receiver Bob. Alice can use decoy photons to prevent the dishonest agents from stealing the information freely as we discussed above. After setting up the quantum channel securely, Alice takes generalized Bell state measurements on his particles $\chi_l, a_l(1,\cdots,m)$, the controller performs generalized X-basis measurement on his particle c, and the receiver can probabilistic reconstruct the original state. The state of composite system composed particle $\chi_1,\cdots,\chi_m,a_1,\cdots,a_m,b_1,\cdots,b_m,c$ can be described as

$$|\chi\rangle\otimes|\Psi\rangle''=\frac{1}{d}\sum_{\substack{k_1\cdots k_m,l_1\cdots l_m\\\mu=0}}^{d-1}\beta_{k_1\cdots k_m}\alpha_{l_1\cdots l_m}e^{\frac{2\pi i}{d}\mu l_m}|k_1\cdots k_m\rangle|l_1\cdots l_m\rangle|\mu\rangle|\mu\oplus l_1\rangle\cdots|\mu\oplus l_{m-1}\rangle=\frac{1}{d\sqrt{d}^m}\sum_{\substack{r_1,s_1,\cdots,r_m,s_m\\k_1\cdots k_m,\mu=0}}^{d-1}|\Psi\rangle_{r_1s_1}\cdots|\Psi\rangle_{r_ms_m}\alpha_{k_1\oplus r_1,\cdots,k_m\oplus r_m}\cdot e^{\frac{2\pi i}{d}[\mu l(k_m+r_m)-k_1s_1-\cdots k_ms_m-k_1t]}\beta_{k_1\cdots k_m}|\mu\rangle|\mu\oplus k_1\oplus r_1\rangle\cdots|\mu\oplus k_{m-1}\oplus r_{m-1}\rangle \quad (13)$$

The state of particles $b_1,\cdots,b_m$ collapses to corresponding state $|\varphi\rangle'_{b_1\cdots b_m}$ if the generalized Bell state measurement result of Alice on particles χ_l, $a_l(l=1,\cdots,m)$ is $|\psi\rangle_{r_ls_l}$, the generalized X-basis measurement result of Bob is $|t\rangle_x$ (without normalization).

$$|\varphi\rangle'_{b_1\cdots b_m}=\sum_{k_1\cdots k_m,\mu=0}^{d-1}\alpha_{k_1\oplus r_1,\cdots,k_m\oplus r_m}\beta_{k_1\cdots k_m}\cdot e^{\frac{2\pi i}{d}[\mu l(k_m+r_m)-k_1s_1-\cdots k_ms_m-k_1t]}|\mu\rangle|\mu\oplus k_1\oplus r_1\rangle\cdots|\mu\oplus k_{m-1}\oplus r_{m-1}\rangle \quad (14)$$

For probabilistically getting the state $|\chi\rangle$, Bob first performs the unitary operation $U_{r_1,s_1,\cdots,r_m,s_m}$ on his particles $b_1,\cdots,b_m$, then performs a general evolution $U_{\max}$ on his particles $b_1,\cdots,b_m$ and the auxiliary qubit b_{aux} whose original state is $|0\rangle$ with the way introduced in Ref. [28]. The unitary operation $U_{r_1,s_1,\cdots,r_m,s_m}$ can transfer state $|\varphi\rangle'_{b_1\cdots b_m}$ into state $|\chi\rangle'$.

$$|\chi\rangle'=U_{r_1,s_1,\cdots,r_m,s_m,t}|\varphi\rangle'_{b_1\cdots b_m}=\sum_{k_1\cdots k_m=0}^{d-1}\alpha_{k_1\oplus r_1,\cdots,k_m\oplus r_m}\beta_{k_1\cdots k_m}|k_1\cdots k_m\rangle \quad (15)$$

Suppose

$$|\alpha_{n_1,\cdots,n_m}|^2=\min\{|\alpha_{j_1,\cdots,j_m}|^2, j_1,\cdots,j_m=0,\cdots,d-1\} \quad (16)$$

Under the basis $|0\cdots0\rangle|0\rangle, |0\cdots1\rangle|0\rangle, \cdots, |d-1,\cdots,d-1\rangle|0\rangle, |0\cdots0\rangle|1\rangle, |0\cdots1\rangle|1\rangle, \cdots, |d-1,\cdots,d-1\rangle|1\rangle$, the unitary operation

$$U_{\max}=\begin{Bmatrix} A & \cdots & 0 & \cdots & 0 & B & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & C & \cdots & 0 & 0 & \cdots & D & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & E & 0 & \cdots & 0 & \cdots & F \\ B & \cdots & 0 & \cdots & 0 & -A & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & D & \cdots & 0 & 0 & \cdots & -C & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & F & 0 & \cdots & 0 & \cdots & -E \end{Bmatrix} \tag{17}$$

can transfer state $|\chi\rangle'$ into state $|\chi\rangle$ probabilistically[28]. In Eq. (17), A stands for $\frac{\alpha_{n_1\cdots n_m}}{\alpha_{r_1\cdots r_m}}$, B stands for $\sqrt{1-\left(\frac{\alpha_{n_1\cdots n_m}}{\alpha_{r_1\cdots r_m}}\right)^2}$, C stands for $\frac{\alpha_{n_1\cdots n_m}}{\alpha_{j_1\oplus r_1,\cdots,j_m\oplus r_m}}$, D stands for $\sqrt{1-\left(\frac{\alpha_{n_1\cdots n_m}}{\alpha_{j_1\oplus r_1,\cdots,j_m\oplus r_m}}\right)^2}$, E stands for $-\frac{\alpha_{n_1\cdots n_m}}{\alpha_{(d-1)\oplus r_1,\cdots,(d-1)\oplus r_m}}$ and F stands for $\sqrt{1-\left(\frac{\alpha_{n_1\cdots n_m}}{\alpha_{(d-1)\oplus r_1,\cdots,(d-1)\oplus r_m}}\right)^2}$, That is

$$U_{\max}|\chi\rangle'|0\rangle=\sum_{k_1\cdots k_m=0}^{d-1}\alpha_{k_1\oplus r_1,\cdots,k_m\oplus r_m}\beta_{k_1\cdots k_m}|k_1\cdots k_m\rangle \left(\frac{\alpha_{n_1,\cdots,n_m}}{\alpha_{k_1\oplus r_1,\cdots,k_m\oplus r_m}}|0\rangle+\sqrt{1-\left(\frac{\alpha_{n_1,\cdots,n_m}}{\alpha_{k_1\oplus r_1,\cdots,k_m\oplus r_m}}\right)^2}|1\rangle\right) \tag{18}$$

To probabilistically reconstruct the original state $|\chi\rangle$, Bob measures the auxiliary qubit in Z-basis. The controlled teleportation succeeds if the measurement result is $|0\rangle$, otherwise the teleportation fails. Similar to Ref. [28], The probability that Bob reconstruct the original is $d^m|\alpha_{n_1\cdots n_m}|^2$.

If $\alpha_{n_1\cdots n_m}=\frac{1}{\sqrt{d^m}}$, the success probability of this scheme can attain 100%, the unitary operation $U_{\max}$ is the identify operation, Bob only need to perform unitary operation $U_{r_1,s_1,\cdots,r_m,s_m,t}$ to reconstruct the original state.

3 Conclusion

In summary, we have presented a general scheme for controlled teleportation of an arbitrary m-particle state by using a nonmaximally $(2m+1)$-particle entangled state as quantum channel. The sender shares a $(2m+1)$-particle pure entangled state with the receiver and the controller. The receiver can probabilistically reconstruct the original state by performing corresponding unitary operation on his particles and the auxiliary qubit according to the measurement results of the agents. The scheme has the advantage of transmitting less particles for controlled teleportation of an unknown m-qubit state via a pure entangled state. The relationship between the success probability and the coefficients of the entangled quantum channel is also discussed. The scheme is optimal since the success probability that the receiver obtains the unknown m-qubit state equals the entanglement of the quantum channel.

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基于$(2m+1)$粒子纠缠态的任意m粒子态量子可控离物传态

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摘　要:提出了一个基于高维$2m+1$粒子纠缠态的任意m粒子态量子可控离物传态方案,发送方Alice对需传送的未知态量子系统和手中的纠缠粒子执行m个广义Bell基测量,控制方执行广义X基测量,依据预先共享量子纠缠态非定域相关性,接收方对手中的粒子执行相应的幺正操作就可以重建原来未知量子态.与其他方案相比,方案减少了任意高维多粒子态可控离物传送所需传送粒子数.我们进一步讨论了基于纯纠缠信道的概率量子可控离物传态方案,通过与发送方和控制方合作,接收方只需对手中的纠缠粒子和引入的附加粒子执行联合幺正演化和投影测量,就可以在他的粒子上概率的重建原来的未知量子态,最后,方案计算讨论了基于纯纠缠态量子可控离物传态成功概率与信道纠缠度之间的关系.

关键词:量子信息;量子可控离物传态;广义Bell基;纯纠缠