# Quantum partial teleportation as optimal cloning at a distance

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We propose a feasible scheme of conditional quantum partial teleportation of a qubit as optimal asymmetric cloning at a distance. In this scheme, Alice preserves one imperfect clone whereas other clone is teleported to Bob. Fidelities of the clones can be simply controlled by an asymmetry in Bell-state measurement. The optimality means that tightest inequality for the fidelities in the asymmetric cloning is saturated. Further we design a conditional teleportation as symmetric optimal $N \to N+1$ cloning from $N$ Alice's replicas on single distant clone. We shortly discussed two feasible experimental implementations, first one for teleportation of polarization state of a photon and second one for teleportation of a time-bin qubit.

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## I. INTRODUCTION

One of the main tasks of quantum information processing is how to optimally distribute an unknown quantum state $|\Psi\rangle$ of a qubit to another distant qubit. A perfect quantum teleportation [1] where Alice completely transmits unknown qubit state $|\Psi\rangle$ to distant Bob's qubit is a particular example of this task. As a resource, they share a pair of qubits in a maximally entangled state which can be distributed *a priori* and then, in advantage, they perform only local operations and classical communication (LOCC) in an actual time of the state transmission. After this complete quantum teleportation, Alice has no information about input qubit state. A conditional version of qubit teleportation of a polarization state of photon was experimentally demonstrated using a simple Bell-state analyzer based on balanced beam splitter [2]. Recently, also conditional long-distance quantum teleportation of a time-bin qubit in telecommunication fibers has been realized [3].

In this paper, we extend the conditional teleportation scheme to *partial optimal teleportation* of single replica of unknown qubit state. The partial teleportation means that Alice preserves an imperfect copy $\rho_S$ of input state and Bob obtains the other imperfect copy $\rho_{S'}$. In the partial teleportation the fidelities of copies $F_S=\langle\Psi|\rho_S|\Psi\rangle$, $F_{S'}=\langle\Psi|\rho_{S'}|\Psi\rangle$ can be controlled by an asymmetry in the Bell-state measurement. The optimality in this case says that for a given fidelity of Alice's copy with initial state, Bob cannot in principle obtain a higher fidelity of his copy. This extension of teleportation can be straightforwardly implemented into the recent conditional teleportation experiments [2], using the Bell-state analyzer beam splitter or fiber coupler with a variable reflectivity. Further, we propose a scheme for teleportation from $N$ identical replicas of a qubit state to a single distant copy.

The partial transmission of a quantum state is dissimilar to classical information processing because perfect cloning of an unknown quantum state is impossible [4]. Thus the fidelities of the copies after the partial teleportation are limited by the fidelities in optimal quantum cloning. Previously, universal symmetric optimal quantum cloners were theoretically proposed to *locally* distribute an unknown pure quantum state of a qubit to the copies [5–9] and were also realized experimentally [10,11]. To locally duplicate an unknown quantum state of a qubit with unbalanced fidelities, the asymmetric quantum cloners were theoretically discussed [12]. The asymmetric $1\to 2$ optimal cloning produces two copies from a single replica of an unknown state and obtained state-independent fidelities $F_S$ and $F_{S'}$ of the copies saturate cloning inequality [12]

$$(1-F_S)(1-F_{S'}) \geqslant [1/2-(1-F_S)-(1-F_{S'})]^2. \quad (1)$$

This inequality sets the tightest no-cloning bound on fidelities of $1\to 2$ cloning device that duplicates an unknown qubit state to another qubit with isotropic noise. Thus if the equality occurs in Eq. (1) then for given fidelity $F_S$ one cannot obtained a better fidelity $F_{S'}$. Previously experimentally performed symmetric quantum cloning with identical fidelities $F_{S,S'}=5/6$ arises as a particular case. An enhancement of the fidelities $F_{S'}=5/6$ of a single additional copy can be obtained only if we have $N>1$ identical replicas of the input state and implement symmetric $N\to N+1$ cloning [6,8]. Then a single additional copy of quantum state can be produced with fidelity

$$F_{N\to N+1} = \frac{(N+1)^2+N}{(N+1)(N+2)}, \quad (2)$$

which approaches unity as the number $N$ of replicas increases. From the point of view of quantum cloning, the schemes proposed below can be also reviewed as a conditional implementation of optimal universal asymmetric *quantum cloning at a distance* since one clone is simultaneously teleported to a distant Bob's laboratory. This is a substantial difference to the last experiments on quantum cloning and universal-NOT gate [11] which also use the teleportation scheme. In Ref. [11], only the symmetrical cloning has been demonstrated and in addition, both the clones are obtained locally at Alice's side of the teleportation and the anticlone is teleported on Bob's side. Further, our proposal can be also viewed as a new telecloning procedure in comparison with Ref. [13].

The paper is organized as follows. In Sec. II, we design the partial conditional teleportation scheme and prove that it represents optimal asymmetric $1\to 2$ cloning at a distance. We also discuss local implementation of universal-NOT gate,

 

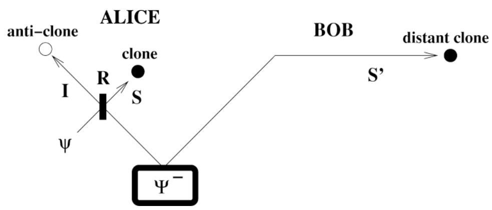


FIG. 1. Scheme of conditional partial teleportation as optimal asymmetric $1 \rightarrow 2$ cloning.

LOCC reversibility of partial teleportation, and the sequential partial teleportation. Further, in Sec. III the partial conditional symmetric $N \rightarrow N+1$ teleportation is described and it is proved that it produces $N+1$ copies with optimal fidelities. Simultaneously, this scheme locally realizes optimal universal-NOT gate for $N$ multiple replicas of input state. In Sec. IV experimental implementations of these schemes for the polarization and time-bin qubits are shortly discussed.

## II. OPTIMAL 1→2 ASYMMETRIC CLONING AT A DISTANCE

A schematic setup for partial conditional teleportation of a qubit is depicted in Fig. 1. In fact, this is a feasible modification of the previous experiment on teleportation of a polarization state of photon [2]. It is based on conditional and partial Bell-state measurement which can be simply implemented by an unbalanced beam splitter with a variable reflectivity $R$, $0 \leqslant R \leqslant 1/2$. We assume such beam splitter mixing two input modes $S,I$ and we denote the output modes after the transmission through the beam splitter by the same symbols. After mixing two photons in the modes $S,I$ on beam splitter we restrict our teleportation only to such cases when both photons leave the beam splitter separately. Then we may effectively describe the unbalanced beam splitter by the following transformation:

$$|\Psi\Psi\rangle_{SI} \rightarrow (T-R)|\Psi\Psi\rangle_{SI},$$
$$|\Psi\Psi_\perp\rangle_{SI} \rightarrow T|\Psi\Psi_\perp\rangle_{SI} - R|\Psi_\perp\Psi\rangle_{SI}, \tag{3}$$

which corresponds to the measurement

$$\Pi^-_{SI}(R) = [(1-2R)1_S \otimes 1_I + 2R|\Psi_-\rangle_{SI}\langle\Psi_-|] \tag{4}$$

on input polarization state of two photons. Assuming that entangled state $|\Psi_-\rangle_{IS'} = (1/\sqrt{2})(|VH\rangle_{IS'} - |HV\rangle_{IS'}) = (1/\sqrt{2}) \times (|\Psi\Psi_\perp\rangle_{IS'} - |\Psi_\perp\Psi\rangle_{IS'})$ is shared by Alice and Bob, we can prove that Alice can conditionally perform partial teleportation of an unknown qubit state $|\Psi\rangle_S$ to Bob. Performing measurement $\Pi^-_{SI}(R) \otimes 1_{S'}$ on a state of total system $|\Psi_S\rangle|\Psi_-\rangle_{IS'}$ we obtain the following local states of clones $S,S'$ and anticlone $I$:

$$\rho_{S,S'}(R) = F_{S,S'}(R)|\Psi\rangle\langle\Psi| + [1 - F_{S,S'}(R)]|\Psi_\perp\rangle\langle\Psi_\perp|,$$
$$\rho_I(R) = [1 - F_I(R)]|\Psi\rangle\langle\Psi| + F_I(R)|\Psi_\perp\rangle\langle\Psi_\perp|, \tag{5}$$

with the following fidelities:

$$F_S(R) = \frac{1}{2P(R)}[(1-2R)^2 + (1-R)^2],$$
$$F_{S'}(R) = \frac{1}{2P(R)}[R^2 + (1-R)^2], \quad F_I(R) = \frac{(1-R)^2}{2P(R)}, \tag{6}$$

where $P(R) = 1 - 3R + 3R^2$. It can be proved that the fidelities $F_S$ and $F_{S'}$ saturate the inequality (1) and therefore the distribution of input state between clone $S$ and distant clone $S'$ is optimal. The symmetric distribution can be obtained for the reflectivity $R = 1/3$. In this case we also obtain optimal universal-NOT gate with fidelity $F_{UNOT} = 2/3$ if we take the anticlone $I$ as output of the universal-NOT. This universal-NOT optimally approximates a transformation $|\Psi\rangle \rightarrow |\Psi_\perp\rangle$ [14], only by mixing the input state with the random mixed state on unbalanced beam splitter with $R = 1/3$.

Now we show that we can probabilistically transform any asymmetric cloner with $R, T \neq 0$ to complete conditional teleportation with unit fidelity only by local measurements on Alice's clone and ancilla, classical communication with Bob and state filtration on Bob's qubit. Assuming input state $|\Psi\rangle_S = \alpha|V\rangle_S + \beta|H\rangle_S$, the state after measurement (4) can be expanded in the following way:

$$\alpha(1-2R)|VVH\rangle_{SIS'} - \beta(1-2R)|HHV\rangle_{SIS'}$$
$$- \alpha(1-R)|VHV\rangle_{SIS'} + \alpha R|HVV\rangle_{SIS'}$$
$$+ \beta(1-R)|HVH\rangle_{SIS'} - \beta R|VHH\rangle_{SIS'}. \tag{7}$$

Generalizing an idea of the state restoration from Ref. [15], we can measure polarization in basis $|V\rangle, |H\rangle$ on Alice's clone and ancilla and the results sent to Bob. The measurement can be experimentally implemented using polarization beam splitter followed on both outputs by single photon detectors which is, in fact, an asymmetric version of Bell-state measurement in teleportation experiment [16]. If we select only such results when the orthogonal polarizations $|V\rangle_S|H\rangle_I$ ($|H\rangle_S|V\rangle_I$) are detected then the Bob's state changes to new one, proportional to $\alpha(1-R)|V\rangle_{S'} - \beta R|H\rangle_{S'}$ ($\alpha R|V\rangle_{S'} + \beta(1-R)|H\rangle_{S'}$). These states can be conditionally transformed to initial state $|\Psi\rangle_S$ by the local filtering $R|V\rangle_{S'}\langle V| - (1-R)|H\rangle_{S'}\langle H|$ ($R|H\rangle_{S'}\langle H| + (1-R)|V\rangle_{S'}\langle V|$). On the other hand, Bob can help Alice to conditionally restore initial state on her clone. Bob has to perform measurement in basis $|V\rangle, |H\rangle$ on qubit $S'$ and Alice the same measurement on qubit $I$. If the detected state is $|H\rangle_I|V\rangle_{S'}$ ($|V\rangle_I|H\rangle_{S'}$) then a state of the Alice clone is converted to state proportional to $\alpha(1-R)|V\rangle_S - \beta(1-2R)|H\rangle_S$ [$\alpha(1-2R)|V\rangle_S + \beta(1-R)|H\rangle_S$] which is equal to initial state after conditional state projection $(1-2R)|V\rangle_S\langle V| - (1-R)|H\rangle_S\langle H|$ [$(1-2R)|H\rangle_S\langle H| + (1-R)|V\rangle_S\langle V|$]. Thus we can at least conditionally prove in feasible experiment that asymmetric cloning procedure is conditionally LOCC reversible.

We shortly discuss a sequence of two partial teleportations in which Alice can conditionally symmetrically distribute an unknown quantum state among three Bobs if they share singlets $|\Psi_-\rangle$, as is depicted in Fig. 2. Since this

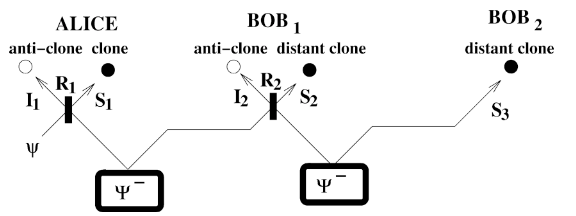


FIG. 2. Scheme of sequential conditional partial teleportation.

scheme is a sequence of partial teleportations we need to generally evaluate the fidelities of clones after every step of the procedure. To find $R_1,\ldots,R_{M-1}$ for a symmetric distribution of $M$ clones we have to solve a set of quadratic equations for fidelities with condition $F_1,\ldots,F_M$, which can be performed numerically. Analytically, we can present the simplest example for $M=3$, in which we set $R_1=3/8$, $R_2=1/3$ to obtain symmetric distribution. As a result, we obtain the same fidelity of all three clones $F=29/38\approx 0.763$. It is slightly worse in comparison with the fidelity $F=7/9\approx 0.777$ of optimal $1\to 3$ cloning [6,8]. Thus we cannot generally use a sequence of asymmetric optimal cloners to distribute information to many users in optimal way. It is apparently dissimilar with classical-like universal cloning when we with a given probability swap an unknown state to one from the $M$ users and to the others we send completely randomized state. In this case, the fidelity of cloning $F_M=\frac{1}{2}[1+(1/M)]$ is always less than optimal universal cloning $F_{1\to M}=2M+1/3M$ but this classical-like $1\to M$ cloning can be implemented by a sequence of $1\to 2$ classical-like cloners.

### III. OPTIMAL $N\to N+1$ CLONING AT A DISTANCE

The setup for symmetric teleportation from $N$ identical replicas of input state $|\Psi\rangle_S$ on single distant copy is depicted in Fig. 3. It is an extension of the previous setup by additional unbalanced beam splitters $BS_2-BS_N$ placed in mode $I$ which have specific reflectivities $R_2,\ldots,R_N$. Thus we implement the following sequence of measurements $\Pi^-_{SN,I}(R_N)\cdots\Pi^-_{S2,I}(R_2)\Pi^-_{S1,I}(R_1)\otimes 1_{S'}$ on a state of total system $|\Psi\rangle_{SN}\cdots|\Psi\rangle_{S2}|\Psi\rangle_{S1}|\Psi_-\rangle_{IS'}$ and optimize the reflectivities $R_n$ in such a way to achieve symmetric distribution of state $|\Psi\rangle$ in $N+1$ copies. To obtain it we must adjust the reflectivities according to

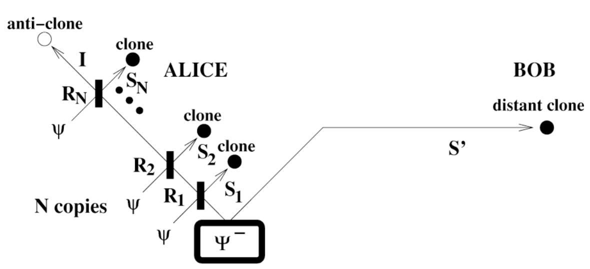


FIG. 3. Scheme of conditional partial teleportation as $N\to N+1$ symmetric optimal cloning.

$$R_n=\frac{1}{n+2}, \tag{8}$$

where $n=1,\ldots,N$ and then Alice obtains $N$ optimal clones of input state in modes $S_1,\ldots,S_N$, single anticlone in mode $I$ and on the other hand, Bob has at a distance a single clone in mode $S'$. To prove this, we calculate the probabilities that state $|\Psi_\perp\rangle$ can be detected in the particular output modes $S'$ and $I$

$$p^\perp_{S'}=\frac{1}{P(N)}\prod_{k=1}^{N}(1-2R_k)^2,\quad p^\perp_{I}=\frac{1}{P(N)}\prod_{k=1}^{N}(1-R_k)^2, \tag{9}$$

and in modes $S_n$

$$p^\perp_{S_n}=\frac{1}{P(N)}R_n^2\prod_{k=1}^{n-1}(1-R_k)^2\prod_{k=n+1}^{N}(1-2R_k)^2. \tag{10}$$

For $R_k$ given by Eq. (8), the total probability $P(N)$ of success can be determined from normalization condition $\Sigma_{n=1}^{N}p^\perp_{S_n}+p^\perp_{S'}+p^\perp_I=1$ and is equal to $P(N)=4/[(N+1)(N+2)]$. Consequently, the fidelity of $n$th clone is $F_n=1-p^\perp_{S_n}$ and inserting reflectivities (8) we can simply prove that all photons in the modes $S_1,\ldots,S_N$ have the same fidelity equal to Eq. (2). The distant Bob's clone in the mode $S'$ has a fidelity $F^{S'}_{n+1}=1-p^\perp_{S'}$ and using Eq. (8) we can subsequently prove that the clone has fidelity equal to Eq. (2). Apart from $N+1$ clones the setup produces also single anticlone in the mode $I$. Using Eq. (9) for fidelity between the anticlone and state $|\Psi_\perp\rangle$, we can simply calculate that the final anticlone has the fidelity

$$F_I=\frac{N+1}{N+2}. \tag{11}$$

As the number of replicas increases we obtain a better and still optimal approximation of the universal-NOT gate for $N$ replicas. For demonstration of local universal-NOT with $N$ replicas we need no source of entanglement and only $N$ unbalanced beam splitters having reflectivity according to Eq. (8) with single port in completely random polarization state is required.

### IV. EXPERIMENTAL IMPLEMENTATIONS

An experimental realization of partial teleportation as optimal asymmetric $1\to 2$ cloning of a polarization state of a photon depicted in Fig. 1 is straightforward modification of a well-known previous experiment demonstrating the total teleportation of polarization state [2]. We only have to be able to control the reflectivity of the beam splitter in the Bell-state measurement. Using single pair of photons in state $|\Psi_-\rangle$ and more input photons prepared as the identical replicas which can be directly extracted from pump beam by strong attenuation $|\Psi\rangle$ we can implement teleportation as $N\to N+1$ optimal cloning. In this way, we also experimentally demonstrate the usefulness of the multiple copies to locally realize universal-NOT gate with a higher fidelity.

These schemes can be also implemented in the experiments on long-distance teleportation of time-bin qubit [3]. A time-bin qubit is a quantum superposition of a photon in different time bins $|\Psi\rangle_S = \alpha|1,0\rangle_S + \beta|0,1\rangle_S$, where basis state $|1,0\rangle_S$ corresponds to first time bin and $|0,1\rangle_S$ to the second one. To teleport time-bin qubit Alice and Bob used shared time-bin entangled state

$$|\Phi_+\rangle = \frac{1}{\sqrt{2}}(|1,0\rangle_I|1,0\rangle_{S'} + |0,1\rangle_I|0,1\rangle_{S'}), \qquad (12)$$

which can be produced from type I nonlinear down-conversion, where the pump pulse is splitted to two separate ones by unbalanced Michelson interferometer. If we restrict only to cases when two photons are emitted either by first pumping pulse or second one we have exactly state (12). The Bell-state measurement was performed by mixing of two time-bin qubits in balanced fiber coupler followed by two single photon detectors and if both the detectors register photons in different time bins the teleportation (up to an unitary operation on Bob side) has been successfully performed [3].

To implement our idea of partial teleportation to time-bin qubit we need only an optical fiber coupler with variable coupling for the Bell-state measurement. If we take into account only detection events when both detectors register only single photon in different time bins we can describe an action of the variable coupler on basis states $|1,0\rangle$ and $|0,1\rangle$ by the same relations as in Eqs. (3). A calculation of partial teleportation of time-bin qubit can be done with the help of previous analysis. Let us consider the unitary operation $U_{S'}$ which converts the state (12) to the state $(1/\sqrt{2})(|1,0\rangle_I|0,1\rangle_{S'} - |0,1\rangle_I|1,0\rangle_{S'})$. This operation consists of mutual flip of basis states $|1,0\rangle_{S'} \leftrightarrow |0,1\rangle_{S'}$ and phase shift $|1,0\rangle_{S'} \to -|1,0\rangle_{S'}$, $|0,1\rangle_{S'} \to |0,1\rangle_{S'}$. Then we obtain analogical teleportation scheme with shared $|\Psi^-\rangle$-like state as has been discussed above. After successful teleportation we implement second thought unitary operation $U_{S'}^\dagger$ on time-bin qubit $S'$ and due to $U_{S'}^\dagger U_{S'} = 1$ we obtain in fact the same result as with the state (12) shared between Alice and Bob. Thus after this teleportation we have the same fidelities $F_S(R)$ and $F_I(R)$ with input state $|\Psi\rangle_S$, however the Bob time-bin qubit is in the state having the $F_{S'}(R)$ with transformed state $|\Psi'\rangle = \alpha|0,1\rangle_{S'} - \beta|1,0\rangle_{S'}$. Therefore Bob has to perform unitary physical operation $U_{S'}$ on time-bin qubit $S'$ to obtain the demanded state having fidelity $F_{S'}(R)$ with state $|\Psi\rangle_S$.

In this paper we propose two extended conditional teleportation schemes as asymmetric $1 \to 2$ and $N \to N+1$ cloning at a distance which can be straightforwardly implemented in the recent quantum teleportation experiments. Further, we discuss an experiment on the conditional LOCC reversibility of the partial teleportation and a conditional realization of optimal universal-NOT operation on the multiple copies.

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