Continuous variable quantum teleportation and Einstein-Podolsky-Rosen steering

M. D. Reid and Q. Y. He

1Centre for Quantum and Optical Science, Swinburne University of Technology, Melbourne 3122 Australia
2State Key Laboratory of Mesoscopic Physics, School of Physics, Peking University, Beijing 100871 China

We revisit continuous variable (CV) quantum teleportation to establish the link with Einstein-Podolsky-Rosen paradox (“steering”) correlations. We generalise traditional protocols by allowing non-unity classical gains, thus considering quantum tele-amplification of a coherent state. By matching the choice of classical gain to the asymmetry in the entanglement of the resource, and employing a local pre-amplification or attenuation, we find that one can enhance the fidelity of teleportation and greatly broaden the class of entangled Gaussian states that are useful for CV quantum teleportation. High fidelity (no-cloning) teleportation is possible using a large subset of Gaussian two-way steerable states. Surprisingly, we find that fidelity can be optimized without maximal entanglement.

Quantum teleportation is a process whereby Alice sends an unknown quantum state to Bob at a different location by communicating only classical information [1]. Quantum teleportation has inspired much interest, both as a fundamental challenge and as a tool for quantum information processing. To achieve quantum teleportation, Alice and Bob share an Einstein-Podolsky-Rosen (EPR) entangled state. Teleportation was first developed for the transfer of qubit (spin-1/2) states, and was extended to continuous variable (CV) spectra by Vaidman [2] and Braunstein and Kimble (BK) [3]. In the CV case, the EPR entanglement shared between Alice and Bob is modeled after the original EPR paradox where Alice and Bob share systems with perfectly correlated positions and anti-correlated momenta [4, 9].

This paper addresses what type of EPR entanglement is useful for CV quantum teleportation. The issue was raised as early as 2001 [10]. There had emerged three types of EPR correlation [11–16]. Yet only one, where the observers Alice and Bob are treated symmetrically, was apparently relevant [8, 17]. CV protocols for the teleportation of a coherent state have to date utilized only a subset of entangled states, where the entanglement can be certified by the Tan-Duan criterion ([h = 2] [14] [15].

\[ \Delta_{\text{ent}} = \frac{1}{4} \left( \frac{1}{4} \left[ \Delta(X_A - X_B)^2 + \Delta(P_A + P_B)^2 \right] \right) < 1 \quad (1) \]

\( (\Delta X)^2 \) is the variance of \( X \), and \( X_A, X_B \) and \( P_A, P_B \) are the positions and momenta of Alice and Bob’s systems. It seems counter-intuitive that no other form of EPR entanglement can be useful, given that teleportation itself is asymmetric with respect to the roles of Alice and Bob: Alice transmits one unique state from her location to Bob. This is related to the fundamental question: “Can any entangled state provide better than classical fidelity of teleportation?” which has been posed [18] and addressed in the affirmative [19] for qubit teleportation. There appears as of yet no clear resolution for the CV scenario.

Here, motivated by these questions, and the recent interest in the asymmetric form of entanglement called EPR steering [20], we revisit CV quantum teleportation. EPR steering refers to the correlations of the original 1935 EPR paradox, which compares quantum mechanics with local realism [4, 11]. Bob at his location can make seemingly paradoxical inferences about Alice’s state, apparently adjusting (“steering”) it remotely. Clearly, in this context Alice and Bob are not equivalent [21]. The role of steering in quantum teleportation was first explored by Grosshans and Grangier, who pointed out that EPR-paradox correlations are required of the resource in order to achieve no-cloning teleportation [22]. It is natural to expect that steering will play an important role in teleportation [23]. We resolve this question, by considering a whole class of protocols, that allow for arbitrary classical communication gain factors \( \bar{g} \) combined with local amplification or attenuation at Alice or Bob’s station.

In this way, our work addresses not only the fundamental question, but also the practical question of whether the fidelity of CV teleportation can be optimised without increasing the squeezing of the EPR resource. CV protocols give the advantage of teleportation without post-selection, because homodyne detection can be performed at Bob’s location with exceptional efficiency [6, 9]. The difficulty has been to achieve high fidelity, since with the BK protocol, the fidelity can only be enhanced by increasing the entanglement of the resource: this for the two-mode squeezed state ultimately requires infinite energy [24]. Our work suggests alternative routes could be possible, based on a heralded noiseless preamplification of the coherent state [25].

Our main result is that for the teleportation of a coherent state \( |\alpha\rangle \), the whole class of relevant CV entangled states certified by the well-known positive partial transpose (PPT) criterion of Peres and Simon [16, 26] becomes useful for quantum teleportation. We show that the fidelity \( F_{\text{amp}}^g \) of the teleportation \( |\alpha\rangle \rightarrow |\bar{g}\alpha\rangle \) is a function of the steering parameter of the EPR resource:

\[ F_{\text{amp}}^g = \frac{2}{1 + g^2 + EPR_{B|A}(\bar{g})}, \quad (2) \]

Here \( EPR_{B|A}(\bar{g}) = \Delta(\bar{X}_B - \bar{g}X_A)\Delta(P_B + \bar{g}P_A) < 1 \) verifies an EPR paradox, and an “EPR-steering” of Bob’s system by measurements made by Alice.

Quantum tele-amplification: We begin by generalising the Braunstein-Kimble (BK) protocol for CV
Figure 1. Quantum teleportation followed by a local operation. The coherent state $|\psi_{in}\rangle = |\alpha\rangle$ is sent from Alice (at A) to Bob (at B) by way of classical communication and the shared entanglement of the continuous-variable EPR beams. We simplify by taking $g_A = g_B = g$, but consider general amplification $g \geq 1$. We allow for non-ideal efficiencies ($\eta_A, \eta_B \leq 1$) and for asymmetric efficiencies where $\eta_A < \eta_B$, which creates a resource with an asymmetric EPR entanglement characterised by a parameter $g_{asym}$. Quantum teleportation is achieved when we select $g = g_{asym}$. We also consider deamplification $g < 1$, in which case the coherent state is pre-amplified at Alice’s station.

teleportation [3], as depicted in Fig. 1] Alice and Bob share an EPR entangled state, often modeled by the two-mode squeezed state (TMSS) $\psi = (1 - x^2)^{1/2} \sum_{n=0}^{\infty} x^n |n\rangle_A |n\rangle_B$ [5, 11]. The systems at Alice and Bob’s locations are assumed to be single modes, with boson creation and destruction operators $a$, $b$ and number eigenstates $|n\rangle_A$, $|n\rangle_B$, respectively. Here $x = \tanh r$, where $r$ is the squeezing parameter that determines the amount of entanglement shared between the two locations. The addition of losses to each of the modes means that the EPR entanglement is better described by a mixed Gaussian state [13, 16, 17]. Defining the position and momentum quadratures as $X_A = a + a^\dagger$, $P_A = (a - a^\dagger)/i$, $X_B = b + b^\dagger$, and $P_B = (b - b^\dagger)/i$, the limit of perfect EPR entanglement $X_B = X_A$, $P_B = -P_A$ is reached for the ideal TMSS system as $r \to \infty$.

A field $V$ is prepared by Victor in the state $|\psi_{in}\rangle$ that is to be teleported to Bob. We restrict attention to the case of a coherent state: $|\psi_{in}\rangle = |\alpha\rangle$. The field V (amplitudes $X_V$ and $P_V$) interferes with Alice’s EPR field (labelled A) on a beam splitter, to produce two fields at the output ports. This allows a simultaneous Bell measurement of the two combined quadratures $X_V - X_A$ and $P_V + P_A$ by homodyne detection, to give outcomes $m_x$ and $m_p$, respectively. The final stage of the teleportation is the displacement by Bob of the amplitudes of his EPR field (labelled B) by an amount given by Alice’s read-out values $m_x$, $m_p$, that are transmitted to him by Alice using classical communication.

Our generalisation of the BK protocol is to allow non-uniform classical gain factors $g_x$, $g_p$ in the two classical channels. For simplicity, we consider equal gains, $g_x = g_p = g$. This means that Bob’s displacement is amplified/deamplified to be $g_m x$ and $g_m p$. In the BK protocol, $g = 1$. After feedback, Bob’s field amplitudes are given by $X_B^f = g X_V + (X_B - g X_A)$, $P_B^f = g P_V + (p_B + g P_A)$. We can see there are two physical effects that will limit the fidelity of teleportation. First, the mean amplitude at Bob’s station is scaled relative to Victor’s, by the classical gain $g$. If $g > 1$, then teleportation amplifies the coherent state, and we know that the maximum fidelity is reduced to $1/g^2$ [27, 29]. Second, the noise in the final reconstruction by Bob of Victor’s amplitudes will be limited by the variances of the linear combinations $X_B - g X_A$, $P_B + g P_A$ which are determined by the asymmetric EPR entanglement present in the EPR resource, as defined by the steering parameter $\eta$.

The measure of success of the teleportation is given by the fidelity, defined as $F = |\beta_{tele}|/|\beta_{out}|$, where $\rho_{out}$ is the density operator of the output state at Bob’s location, and $|\beta_{tele}\rangle$ is the state desired at Bob’s output. The fidelity can be conveniently calculated using Wigner function techniques [3, 8, 30]. We have evaluated the Wigner expression for the output at Bob’s location, including the gain factors $g$ and for a general input state with a Gaussian Wigner function. The result for the fidelity is $F^\text{amp} = \frac{2}{\sigma_Q} \exp\left[-\frac{2}{\sigma_Q} |\beta_{out} - \beta_{tele}|^2 \right]$ [8]. Here, $\sigma_Q = \sqrt{(1 + \sigma_X^2)(1 + \sigma_P)}$ and $\beta_{out} = m_x + i m_p$, where $m_x$, $m_p$ and $\sigma_X$, $\sigma_P$ are respectively the means and variances of the quadratures $X_B$, $P_B$ of Bob’s output field. Calculation shows that $\beta_{out} = (X_B^f + i P_B^f)/g = g \langle X_V \rangle + i \langle P_V \rangle = g \alpha$, as expected. We evaluate the fidelity relative to the desired teleported state $|\beta_{tele}\rangle = |\bar{\alpha}\rangle$. Then we see that the exponential expression vanishes. The final fidelity for the protocol, called “quantum teleport-amplification” (QAT) [29], is

$$F^\text{amp} = \langle g \alpha | \rho_{out} | g \alpha \rangle = \frac{2}{\sigma_Q}.$$ (3)

As we will see later, even though we may desire to teleport the state $|\alpha\rangle$ rather than the amplified one $|g \alpha\rangle$, we can achieve this by a local attenuation at Bob’s station, or else by a local pre-amplification at Alice’s station.

We now express the fidelity [3] in terms of the variances of the EPR resource. We find $\sigma_X = g^2 \sigma_{in} + |\Delta(X_B - g X_A)|^2$, $\sigma_P = g^2 \sigma_{in} + |\Delta(P_B + g P_A)|^2$, where $\sigma_{in}$ is the variance of $X$ and $P$ for the input state $|\alpha\rangle$: i.e. $\sigma_{in} = (\Delta X)^2 = (\Delta P)^2 = 1$. We now restrict to the subclass of two-mode EPR resources symmetric in their position and momentum correlations [3], so that $|\langle X_A, X_B \rangle| = |\langle P_A, P_B \rangle|$, $\sigma_X = \sigma_P$ and $\Delta(X_B - g X_A) = \Delta(P_B + g P_A)$. We call this subclass $X - P$-symmetric. This subclass includes EPR resources such as the two-mode squeezed state including all phase-insensitive losses and noise. This assumption is convenient but not necessary: the full generalisation to include non-$X - P$ symmetric resources will require asymmetric gains $g_x \neq g_p$ to optimise fidelity. On substitution, we see that the fidelity $F^\text{amp}$ of the QAT protocol is given by Eq. (2). The fi-
We give more detail for the Gaussian EPR resources. Such resources are characterised in terms of the symplectic form of the covariance matrix $C$ defined as $C_{ij} = \langle X_i, X_j \rangle = \langle (X_i X_j + X_j X_i)/2 - (X_i)_j \rangle$, where $X \equiv (X_A, P_A, X_B, P_B)$ is the vector of the field quadratures $10$. We use the notation

$$C = \begin{pmatrix} n & 0 & c_1 & 0 \\ 0 & n & 0 & c_2 \\ c_1 & 0 & m & 0 \\ 0 & c_2 & 0 & m \end{pmatrix}$$

and note that in this paper we restrict to the subclass of $X - P$-symmetric Gaussian fields, meaning that $c_1 = -c_2 = c$. To verify the entanglement shared between Alice and Bob, we can observe the EPR correlation by way of noise reduction in the position and momenta, as given by inequality (4). We choose the $\bar{g}$ that minimises $Ent_{B|A}(\bar{g})$: this is $\bar{g} = g_{sym}^{B|A}$ where $33$}

$$g_{sym} = m - n + \sqrt{(m - n)^2 + 4c^2} \over 2c.$$ 

The resulting inequality is equivalent to Simon’s positive partial transpose (PPT) condition for entanglement which is necessary and sufficient for two-mode Gaussian states $33$. Thus, the quantum benchmark for the amplified teleportation $|a\rangle \rightarrow |\bar{g}a\rangle$ from Alice to Bob can be reached for all $X - P$-symmetric Gaussian entangled fields that possess $\bar{g} = g_{sym}^{B|A} > 1$. We simply match the classical gain factor $\bar{g}$ of the protocol to the value $\bar{g} = g_{sym}^{B|A}$ given by the EPR resource. It is easy to verify that $g_{sym}^{B|A} = 1/g_{sym}^{A|B}$. Thus, for Gaussian resources with $g_{sym}^{B|A} < 1$, quantum teleportation can be realised if the EPR channels $A$ and $B$ are exchanged, or else Bob teleports to Alice. Alternatively, we show below that a preamplification protocol is possible in this case. When moments are symmetrical under $A \leftrightarrow B$, $n = m$ and $g_{sym}^{B|A} = 1$. Then, we use the BK protocol. The quantum benchmark is $F_{BK} > 1/2$, and we recover the well-known result that the condition on the resource becomes that of Tan-Duan entanglement: $\Delta_{ent} < 1$.

Clearly, the above strategies optimise the fidelity of the amplified teleportation protocol relative to the quantum benchmark. We see that only for symmetric resources does the BK protocol give the optimal relative fidelity: A second question is what resource will give the maximum fidelity for a fixed amplification $\bar{g}$. Calculation gives the surprising result that symmetric maximal entanglement is not always optimal (see Supplemental Materials $34$).

We can create an asymmetric EPR resource from the two-mode squeezed state by adding loss to each of the EPR channels (Fig. 2). If $\eta_A$ and $\eta_B$ are the resulting efficiencies at $A$ and $B$ respectively, the Gaussian covariances become $n = \eta_A \cosh(2r) + 1 - \eta_A$, $m = \eta_B \cosh(2r) + 1 - \eta_B$, $c = \sqrt{\eta_A \eta_B} \sinh(2r)$. There is entanglement for all $\eta_A$ and $\eta_B$, as confirmed experimentally $17$ $35$. This robustness translates to robustness
delity is determined by the gain $\bar{g}$ on the channel, and the EPR steering parameter $ENT_{B|A}(\bar{g})$. The special case of Braunstein-Kimble reduces to $F_{BK} = 1/(1 + \Delta_{ent})$, where $\Delta_{ent}$ is the Tan-Duan entanglement parameter defined by equation (1).

Quantum benchmarks for quantum teleportation: The threshold where one can rule out all classical “measure and regenerate” strategies and hence claim Quantum Teleportation was determined in Ref. $31$. For amplification $\bar{g} > 1$, the threshold for quantum teleportation is $F_{\bar{g}}^{amp} > 1/1 + g^2$ $22$. On substituting into (2), the condition on the steering parameter of the EPR resource to obtain quantum teleportation is $ENT_{B|A}(\bar{g}) < 1 + g^2$ (provided $\bar{g} > 1$). Importantly, this reduces to a condition on the entanglement of the resource: the quantum benchmark for teleportation using the QAT protocol is reached when

$$ENT_{B|A}(\bar{g}) = \Delta(X_B - \bar{g}X_A)(P_B + \bar{g}P_A) \over (1 + \bar{g}^2) < 1.$$ 

The inequality $ENT_{B|A}(\bar{g}) < 1$ if satisfied will certify entanglement between the two fields at $A$ and $B$ $32$. This is true for any value of $\bar{g}$, which is a real constant. The class of entangled states satisfying this condition is a strict superset of the class defined by the Tan-Duan inequality $1$. In particular, we will show that the inequality $ENT_{B|A}(\bar{g}) < 1$ for an optimally selected $\bar{g}$ is necessary and sufficient for all Gaussian entangled states of the $X - P$-symmetric subclass. This means that the benchmark for quantum teleportation can be reached for all such entangled states, provided the gain factor and direction of teleportation is chosen appropriately.

![Figure 2. (Color online) Creating an asymmetric entangled resource: Here $r = 0.85$. Left: Contour lines show $ENT_{B|A}(g_{sym}^{B|A}) = ENT_{A|B}(g_{sym}^{A|B})$. All regions show entanglement, measured by $ENT_{B|A}(g_{sym}^{B|A}) < 1$. Higher losses on Alice’s EPR channel ($\eta_A < \eta_B)$ implies $g_{sym}^{B|A} > 1$ (and vice versa). The top-left region with $g_{sym}^{B|A} \geq 1$ enables quantum amplified teleportation $|a\rangle \rightarrow |\bar{g}a\rangle$ from Alice to Bob ($\bar{g} = g_{sym}^{B|A}$). The lower region enables QAT from Bob to Alice. Only the diagonal $g_{sym}^{B|A}$ gives $g_{sym}^{B|A} = 1$. Right: Contour lines show the minimum value of $ENT_{B|A}(\bar{g})$, found by selecting $g = c/m$. EPR steering of Alice by Bob ($ENT_{A|B} < 1$) is possible only when $\eta_B > 0.5$.](image-url)
of quantum teleportation to loss, provided the losses are directed away from Bob’s channel.

Late-stage attenuation (lsatt): To properly teleport the original coherent state $|\alpha\rangle \rightarrow |\alpha\rangle$ from Alice to Bob, using a resource with lossy channels. Top left / right ($r = 1.0 / 0.85$): Contours show optimised fidelity values: We maximise fidelity via the late-stage attenuation protocol (region I), or via the early-stage amplification protocol (region II), or via the Braunstein-Kimble protocol (central coned region III). All regions enable QT ($F > 0.5$), but only the upper right where $F > 2/3$ allows secure teleportation (ST). For higher $r$ (left), ST is possible using the asymmetric protocol. Lower left / right: ST ($F > 2/3$) can be achieved via the late-stage attenuation protocol (area I + II), or via the early-stage amplification (area i + ii). The green curve corresponds to $F_{BK} = 2/3$ so that regions II, III and ii give ST ($F > 2/3$) using the BK protocol. Note that for area III, ST can be only achieved by the BK. Regions I and i require asymmetric protocols for ST.

Early-stage amplification (esa): Alternatively, to teleport the original state $|\alpha\rangle \rightarrow |\alpha\rangle$, Alice may choose to amplify the input coherent state at her station by a factor $g > 1$, prior to a teleportation protocol that uses a classical attenuation factor $\tilde{g} = 1/g < 1$. Suppose Alice uses at her station a two-mode squeezed state amplifier [25]. Then the final amplified state at her station is described by a Gaussian Wigner function with mean $g\alpha$ and new variance $\sigma_{in} = 2g^2 - 1$. The final Wigner output after teleportation to Bob has variance $\sigma_X = \tilde{g}^2\sigma_{in} + EPR_{B|A}(\tilde{g})$. Substitution reveals the fidelity $F_{esa}^{\alpha}(\tilde{g})$ for the overall teleportation process to be $F_{esa}^{\alpha}(\tilde{g}) = F_{esa}^{\alpha}(\tilde{g})$. QT requires $F_{esa}^{\alpha}(\tilde{g}) > 0.5$, which requires a resource satisfying the entanglement condition $E_{B|A}(\tilde{g}) < 1$ with $\tilde{g} < 1$. Hence, for an entangled Gaussian resource in the $X - P$-symmetric class with $\langle \tilde{g} \rangle_{sym} < 1$, the choice of protocol with $\tilde{g} = g^{\alpha}_{sym}$ will give QT, by this early-stage amplification protocol. The final fidelity $F_{esa}^{\alpha}(\tilde{g})$ is maximised for $\tilde{g}_{opt} = (X_{A}, X_{A})/(X_{A}, X_{B})$ (provided $\tilde{g}_{opt} < 1$), in which case the fidelity is given by $F_{esa}^{\alpha}(\tilde{g}) = F_{esa}^{\alpha}(\tilde{g})$.

Maximising the teleportation fidelity: Which protocol will teleport the coherent state $|\alpha\rangle \rightarrow |\alpha\rangle$ with maximum fidelity for a given resource? Figure 3 shows the optimal fidelity, for the lossy EPR resource of Figs. 1 and 2. All regions enable QT, via the lsatt-protocol in region I; or by the the esa-protocol in region II; or by the BK protocol as in region III. Teleportation is optimised by the BK protocol where efficiencies for A and B are reasonably symmetric, while optimised at the asymmetric protocols elsewhere.

Secure teleportation (ST): Quantum no-cloning tells us that when the fidelity is high enough ($F > 2/3$), there can be no non-degraded copy of the state that is teleported to Bob [22] [27]. What is the requirement on the resource to achieve such secure teleportation (ST)? For late-stage attenuation protocol, ST leads to the steering condition $EPR_{B|A}(\tilde{g}) < 2g^2 < 1$. On dividing through by $g^2$, we see that this condition also requires steering of $B$ by $A$ i.e. $EPR_{B|A}(\tilde{g}) < 1$, where $\tilde{g} = 1/g$. Thus, “two-way steering” [21] is required of the resource, with a stronger steering needed from Bob to Alice. For the BK protocol $\tilde{g} = 1$, this condition reduces to $\Delta_{ent} < 0.5$.

Results for the lossy EPR resource are shown in Fig. 3. ST requires $\eta_A, \eta_B > 0.5$, consistent with the fact that steering of $A$ by $B$ is destroyed when $\eta_B < 0.5$ (Fig. 2) [17] [55]. ST can be carried out via the BK protocol; or, for larger $r$ (where $r > 0.8814$) via the asymmetric protocol. For some regimes ($I$ and $i$ of lower Fig. 3), an asymmetric protocol is required for ST, i.e., it cannot be achieved with the BK protocol. The white region indicates no ST, despite there being two-way steering.

Discussion: We conclude by suggesting a further application of steering to enhance the fidelity. The early-
stage amplification protocol relies on pre-amplification of a coherent state by a factor \( g > 1 \), which has a limited maximum fidelity of \( 1/g^2 \). Recent methods use heralding to overcome this limitation: heralded noiseless amplification of \( |\alpha\rangle \) to \( |\alpha\rangle \) potentially allows fidelities approaching 1 [25]. The teleportation deamplification \( |\alpha\rangle \rightarrow |\alpha\rangle \) has fidelity \( F = \frac{2}{1+g^2+ \epsilon_P r(\alpha)} \), given by (2) but where \( g = 1/g < 1 \). We show in the Supplemental Material that for the two-mode squeezed state resource, \( g_{\text{opt}} = \tanh(r) \) and \( F = 1 \). This is valid for all \( r \) and hence does not depend on achieving a large entanglement of the resource.

The fidelity for the overall teleportation is then limited by the fidelity of the heralded amplification at Alice’s site, suggesting a promising route for achieving high teleportation fidelities. Finally, we leave as an open question whether all Gaussian entangled states are useful for quantum teleportation, once one allows for adjusting both gains \( g_x \) and \( g_y \) independently.

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