Quantum Teleportation With Nonclassical Correlated States in Noninertial Frames

Hossein Mehri-Dehnavi · Robabeh Rahimi · Hosein Mohammadzadeh · Zahra Ebadi · Behrouz Mirza

Abstract Quantum teleportation is studied in noninertial frame, for fermionic case, when Alice and Bob share a general nonclassical correlated state. In noninertial frames two fidelities of teleportation are given. It is found that the average fidelity of teleportation from a separable and nonclassical correlated state is increasing with the amount of nonclassical correlation of the state. However, for any particular nonclassical correlated state, the fidelity of teleportation decreases by increasing the acceleration.

1 Introduction

Quantum teleportation, initially proposed by Bennett *et. al.* [1], is one of the important quantum protocols because of its several theoretical features and interesting applications. Quantum teleportation is the reliable transfer of quantum state by using a shared source of entanglement, in addition to a classical communication channel.

H. Mehri-Dehnavi
Department of Physics, Babol University of Technology, Babol, 47148-71167, Iran

R. Rahimi
Institute for Quantum Computing, University of Waterloo, Waterloo, ON, N2L 3G1, Canada
Department of Physics, University of Waterloo, Waterloo, ON, N2L 3G1, Canada
Department of Chemistry and Molecular Materials Science, Osaka City University, Osaka, 558-8585, Japan E-mail: rrahimid@uwaterloo.ca

H. Mohammadzadeh
Department of Physics, University of Mohaghegh Ardabili, P.O. Box 179, Ardabil, Iran

Z. Ebadi, B. Mirza
Department of Physics, Isfahan University of Technology, Isfahan, 84156-83111, Iran

The original teleportation assumes Alice and Bob are sharing a perfect
bipartite entangled pair of particles. An unknown quantum state is supposed
to be teleported from Alice to Bob. Alice measures the unknown state and
the part of the shared entanglement in her disposal, in Bell basis, and sends
off the outcome of the measurement, in the form of two bits of classical infor-
mation, to Bob. Consequently, Bob, upon receiving the classical information,
applies appropriate unitary operations and transforms the quantum state to
the original one that Alice had.

Since its original proposal, quantum teleportation has been relying on the
concept of quantum entanglement. Quantum entanglement initially appeared
as a source of paradoxical features of quantum mechanics [2]. There are several
measures for quantum entanglement. Logarithmic Negativity [3] is a measure
of entanglement of bipartite states, and is defined as

$$N(\rho) := \log_2 \sum_i |\lambda_i(\rho^{\mathrm{pt}})|, \tag{1}$$

where, $\lambda_i(\rho^{\mathrm{pt}})$ denotes the eigenvalues of the partial transpose, ρ^{pt}, of the
density matrix ρ of a bipartite quantum system AB.

In the lack of a mathematical proof for the distinct and unique role of
entanglement for quantum information processing and quantum computing,
in general, existence of any nonclassical correlation has been candidated for
the expected super-power source for quantum processors [4]. Deterministic
Quantum Computation with One Quantum Bit (DQC1) [5] that contains very
little or no bipartite entanglement, performs a computation that has no known
efficient classical algorithm.

According to Oppenheim-Horodecki paradigm [6], a nonclassical correlated
state is a state that cannot be represented in the form of a "properly classically
correlated state", ρ_{pcc}, with the following definition

$$\rho_{\mathrm{pcc}} = \sum_{i=1}^{d^A} \sum_{j=1}^{d^B} e_{ij} |v_A^i\rangle\langle v_A^i| \otimes |v_B^j\rangle\langle v_B^j|, \tag{2}$$

where, d^A and d^B are the dimensions of the Hilbert spaces of A and B, re-
spectively, and e_{ij} is the eigenvalue of ρ_{pcc} corresponding to an eigenvector
$|v_A^i\rangle \otimes |v_B^j\rangle$. Quantum Discord, $\mathcal{D}$, is one of the most studied measures for
nonclassical correlation [7]. It is defined [8] as the discrepancy between the
quantum mutual information, $\mathcal{I}$, and the locally accessible mutual informa-
tion, $\mathcal{C}$,

$$\mathcal{D}(A:B) = \mathcal{I}(A:B) - \mathcal{C}(A:B), \tag{3}$$

with the following definitions

$$\mathcal{I}(A:B) = S(\rho_A) + S(\rho_B) - S(\rho), \tag{4}$$

and

$$\mathcal{C}(A:B) = \max_{\{\Pi_k\}} \left[\mathcal{J}_{\{\Pi_k\}}(A:B) \right], \tag{5}$$

where, ρ_A and ρ_B are the reduced density operators of A and B, respectively. $S(\rho) = -\text{Tr}(\rho \log_2 \rho)$ is the von Neumann entropy. $\{\Pi_k\}$'s are von Neumann operators acting on subsystem B and corresponding to the outcome k. $\mathcal{J}$ is locally accessible mutual information defined as

$$\mathcal{J}_{\{\Pi_k\}}(A:B) = S(\rho_A) - S_{\{\Pi_k\}}(A|B), \tag{6}$$

$S_{\{\Pi_k\}}(A|B)$ is the quantum conditional entropy, defined as

$$S_{\{\Pi_k\}}(A|B) = \sum_k p_k S(\rho_{A|k}), \tag{7}$$

where, $\rho_{A|k} = \text{Tr}_B(\Pi_k \rho \Pi_k)/p_k$, with $p_k = \text{Tr}(\Pi_k \rho \Pi_k)$.

Quantum teleportation by using not completely entangled state has been studied [9]. Also, it has been shown that a separable state which involves nonclassical correlation can be used for quantum information transmission [10]. Extension of quantum teleportation to noninertial frames has been perviously studied in an approach different than in our paper [11]. In fact, the previously studied process should be regarded as a "noninertial frame observation" of quantum teleportation since the involved entangled state in the teleportation is not appropriately affected by changing to a noninertial frame. In this work, we keep the original teleportation but apply the appropriate changes on every steps, accordingly.

Suppose that Alice, A, is resting and Rob, R, is the uniformly accelerating Bob, with the acceleration a. The corresponding Minkowski spinor basis states [11,12] are as follows

$$|0\rangle_M = \cos r |0\rangle_\text{I} |0\rangle_\text{II} + \sin r |1\rangle_\text{I} |1\rangle_\text{II}, \tag{8}$$
$$|1\rangle_M = |1\rangle_\text{I} |0\rangle_\text{II}, \tag{9}$$

where, $\cos r = 1/\sqrt{1 + e^{-2\pi\omega c/a}}$ and $\omega = \sqrt{|\mathbf{k}|^2 + m^2}$ denotes the energy of any mode with momentum $\mathbf{k}$ and mass m. Here, the subscripts I and II represent Rindler regions I and II Fock states, respectively.

Quantum teleportation has been demonstrated in different physical systems, including NMR [13]. In NMR and other similar bulk ensemble quantum computation such as electron nuclear double resonance (ENDOR) [14], practically a pseudo-entanglement of the following form is generated

$$\rho_\text{pe} = \frac{1-p}{4} I + p|\Phi^+\rangle\langle\Phi^+|, \tag{10}$$

when intentionally the entangled state $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ is the desired state. Here ρ_pe is entangled if the purity $p > 1/3$. Generally, experimental conditions bring down the state to a region where entanglement is absent and the workable state is just a nonclassical correlated state, Eq. (10). Detecting the status of entanglement or nonclassical correlation of the involved states for these physical systems has been practically of importance [15]. It should be noted also that the quantum teleportation implemented with such physical

systems may not absolutely be relying on a pure entangled state. In this work, we study quantum teleportation with a general nonclassical correlated state, Eq. (10), so the results will be applicable to the above mentioned physical systems.

This paper is organized as follows. In next section, the conventional quantum teleportation with maximal entanglement is described when an observer in noninertial frame is detecting the resultant teleported state. In section 3, quantum teleportation is generalized for the case that a nonclassically correlated state is used, and Rob, the accelerated Bob, is in a noninertial frame, so his preshared nonclassical correlated state is also affected, accordingly. The paper will be concluded by bringing discussions in the last section.

2 A noninertial frame observation of quantum teleportation with maximally entangled state

Consider an arbitrary one-qubit state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, which Alice wishes to teleport to Bob. If Alice and Bob have preliminarily shared the bipartite state $|\Phi^+\rangle$, the total initial state is given by $|\Psi_{\text{in}}\rangle = |\psi\rangle|\Phi^+\rangle$. The first two qubits are in Alice's possession and the third one belongs to Bob. Alice starts quantum teleportation by applying CNot and Hadamard (H) gates, thus changes the total state to $|\Psi'\rangle = (\text{H} \otimes 1 \otimes 1)(\text{CNot} \otimes 1)|\Psi_{\text{in}}\rangle$. Alice measures the state in her possession, in Z-basis, and extracts the state $|ij\rangle$, $i, j = \{0, 1\}$. The total state is then $|ij\rangle|\phi_{ij}\rangle$ with probability of $p_{ij} = \text{Tr}(\langle ij|\Psi'\rangle\langle\Psi'|ij\rangle)$, where $|\phi_{ij}\rangle = X^j Z^i|\psi\rangle$. Alice sends the results of the measurement, i and j, to Bob using classical information channels. Bob retrieves the state, supposed to be teleported, by performing the quantum gate $(X^j Z^i)^{-1} = Z^i X^j$ on the qubit in his possession. The result is given by $|\tilde{\psi}\rangle = Z^i X^j|\phi_{ij}\rangle = |\psi\rangle$, and the corresponding teleportation fidelity is $F = |\langle\tilde{\psi}|\psi\rangle|^2 = 1$.

In [11], Alice finds the values i, j, and sends them to Bob. Bob rewrites the state $|\phi_{ij}\rangle$ in Rindler frame by using Eqs. (8-9) to find the Rob and anti-Rob states, $|\phi_{\text{I,II}}^{ij}\rangle$. By tracing out the anti-Rob, II, modes, he finds the Rob density matrix, ρ_{I}^{ij}. Finally, by applying the operator $Z^i X^j$ on the density matrix, he finds $\tilde{\rho}_{\text{I}}^{ij} = Z^i X^j \rho_{\text{I}}^{ij} (Z^i X^j)^{-1}$.

It is clear from the above notation that, in general, the state $\tilde{\rho}_{\text{I}}^{ij}$ depends on Alice's measurement results, i and j. This fact comes from the non-symmetric property of transformations, Eqs. (8-9), for $|0\rangle$ and $|1\rangle$. In order to make the result $\tilde{\rho}_{\text{I}}^{ij}$ independent of the values i and j, the symmetric dual-rail basis set is used. The indexes are omitted and the teleported state is written as $\tilde{\rho}_{\text{I}} = \tilde{\rho}_{\text{I}}^{ij}$. The fidelity of teleportation is given by $F = \langle\psi|\tilde{\rho}_{\text{I}}|\psi\rangle = \cos^2 r$, for fermionic case [11].

There are objections to this study. Quantum teleportation is studied in noninertial frame with a cost that the original teleportation protocol is modified. Recalling the original teleportation, Bob is not only an observer but he is the party who receives the classical information and applies accordingly

changes to the entangled part in his disposal to extract the desired teleportation state. This implies that if Bob is assumed in the accelerated frame, so is called Rob, then his belonging pre-shared entanglement also should be modified according to the acceleration. Also, the original teleportation protocol is not restricted to any basis set, and is universal. Therefore, even extending quantum teleportation to noninertial frame should be practically possible without any restriction such as dual-rail basis set.

In following, we extend the original quantum teleportation to noninertial frame, in addition, we generalize our study by using a nonclassical channel of the form Eq. (10) instead of a pure entangled state.

3 Teleportation with nonclassical correlated state in noninertial frames

Alice wants to teleport the state $|\psi\rangle$ to Bob, by using the shared state ρ_{pe}. The initial state is given by $\varrho_{\mathrm{in}} = |\psi\rangle\langle\psi| \otimes \rho_{\mathrm{pe}}$, where the first two qubits of ϱ_{in} are the Alice's ones and the third one is the Bob's qubit. Substituting $p = 1$ gives the special case of teleportation with maximally entangled state $|\Phi^+\rangle$. Here, we shall recall Rob, the uniformly accelerated Bob, following the general convention.

If Rob's state starts to degrade with constant acceleration a then the bipartite state, ρ_{pe}, transforms to a tripartite state $\rho_{A,\mathrm{I},\mathrm{II}}$, using Eqs. (8-9). $\rho_{A,\mathrm{I},\mathrm{II}}$ is the quantum state of Alice (A), Rob (I), and anti-Rob (II). Tracing out the anti-Rob modes results the Alice-Rob density matrix, $\rho_{A,\mathrm{I}} = \mathrm{Tr}_{\mathrm{II}}(\rho_{A,\mathrm{I},\mathrm{II}})$ as follows [12]

$$\rho_{A,\mathrm{I}} = \frac{1}{4}\begin{pmatrix} (1+p)\cos^2 r & 0 & 0 & 2p\cos r \\ 0 & 1+\sin^2 r - p\cos^2 r & 0 & 0 \\ 0 & 0 & (1-p)\cos^2 r & 0 \\ 2p\cos r & 0 & 0 & 1+\sin^2 r + p\cos^2 r \end{pmatrix}.$$

We have used the basis $|0\rangle_A|0\rangle_{\mathrm{I}}$, $|0\rangle_A|1\rangle_{\mathrm{I}}$, $|1\rangle_A|0\rangle_{\mathrm{I}}$, and $|1\rangle_A|1\rangle_{\mathrm{I}}$ to write the above matrix. Therefore, we should use $\varrho_{A,\mathrm{I}} = |\psi\rangle\langle\psi| \otimes \rho_{A,\mathrm{I}}$ instead of the initial state ϱ_{in}, for teleportation with uniformly accelerated partner, Rob.

Alice starts the teleportation procedure by performing CNot and Hadamard gates on the particles in her possession. Then, she measures the state in Z-basis. The total state collapses to $|ij\rangle\langle ij| \otimes \rho_{\mathrm{I}}^{ij}$, with probability $p_{ij} = \mathrm{Tr}(\langle ij|\varrho'_{A,\mathrm{I}}|ij\rangle) = 1/4$, where ρ_{I}^{ij} are given by

$$\rho_{\mathrm{I}}^{i0} = \frac{1}{2}\begin{pmatrix} [1+p(|\alpha|^2-|\beta|^2)]\cos^2 r & 2(-1)^i p\alpha\beta^*\cos r \\ 2(-1)^i p\alpha^*\beta\cos r & 1+\sin^2 r - p(|\alpha|^2-|\beta|^2)\cos^2 r \end{pmatrix}, \quad (11)$$

$$\rho_{\mathrm{I}}^{i1} = \frac{1}{2}\begin{pmatrix} [1-p(|\alpha|^2-|\beta|^2)]\cos^2 r & 2(-1)^i p\alpha^*\beta\cos r \\ 2(-1)^i p\alpha\beta^*\cos r & 1+\sin^2 r + p(|\alpha|^2-|\beta|^2)\cos^2 r \end{pmatrix}. \quad (12)$$

Alice sends the results of the measurement, i and j, to Rob by using classical information channels. Consequently, Rob extracts information by performing the quantum gate $(X^j Z^i)^{-1} = Z^i X^j$ on the state in his hand, $\tilde{\rho}_{\mathrm{I}}^{ij} =$

$Z^i X^j \rho_{\mathrm{I}}^{ij} (Z^i X^j)^{-1}$, as follows

$$\tilde{\rho}_{\mathrm{I}}^{i0} = \rho_{\mathrm{I}}^{00}, \tag{13}$$

$$\tilde{\rho}_{\mathrm{I}}^{i1} = \frac{1}{2} \begin{pmatrix} 1 + \sin^2 r + p(|\alpha|^2 - |\beta|^2)\cos^2 r & 2p\alpha\beta^* \cos r \\ 2p\alpha^*\beta \cos r & [1 - p(|\alpha|^2 - |\beta|^2)]\cos^2 r \end{pmatrix}, \tag{14}$$

where ρ_{I}^{00}, is given by Eq. (11).

For $p = 1$, $r \neq 0$, we have quantum teleportation with maximally entangled state in noninertial frame. The result is different than [11] because we use a general non-symmetric basis set instead of the symmetric dual-rail basis. Also, if $r = 0$, for a general p, the quantum teleportation is same as to the one in inertial frame using a general nonclassical correlated state. The resultant state extracted by Rob is independent of the results of the Alice's measurement, i and j, as it is expected.

For a general case the fidelities, $F_{ij} = \langle \psi | \tilde{\rho}_{\mathrm{I}}^{ij} | \psi \rangle$, are given as follows

$$F_{i0} = \frac{1}{2} \left\{ |\beta|^4 [2 - (1 - p)\cos^2 r] + |\alpha|^4 (1 + p)\cos^2 r \right.$$
$$\left. + 2|\alpha|^2 |\beta|^2 [p(2 - \cos r)\cos r + 1] \right\}, \tag{15}$$

$$F_{i1} = F_{i0} + (|\alpha|^4 - |\beta|^4)\sin^2 r. \tag{16}$$

We evaluate the average fidelity by using the Bloch sphere representation of the initial state, namely $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle := \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$. Thus, the average fidelity is given by,

$$< F_{ij} > = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} F_{ij}(\theta, \phi) \sin\theta \, d\theta \, d\phi. \tag{17}$$

Using equations (15-16) the average fidelity is obtained as follows,

$$< F > = < F_{ij} > = \frac{1}{6} \left(3 + p\cos^2 r + 2p\cos r \right). \tag{18}$$

Logarithmic negativity and discord for $\rho_{A,\mathrm{I}}$ should be calculated in order to evaluate the contributions from entanglement and nonclassical correlation to the above fidelity of teleportation. We employ the corresponding calculation results from our previous work [12], where we have studied the logarithmic negativity and discord for ρ_{pe} in noninertial frames. In addition, here, the eigenvalues of the partial transpose of $\rho_{A,\mathrm{I}}$ are given in order to study the contribution into the fidelity of teleportation from a state with a purity of threshold, p_{th}. The quantum state $\rho_{A,\mathrm{I}}$ with p_{th} involves maximum nonclassical correlation for a separable state. Hence, the corresponding fidelity of teleportation can be regarded as the maximum attainable fidelity of teleportation if the pre-shared state in teleportation is not entangled but involves nonclassical correlation.

$$\lambda_{1,2}(\rho_{A,\mathrm{I}}^{\mathrm{pt}}) = \frac{1}{4} \left\{ 1 - p\cos^2 r \pm \sqrt{\sin^4 r + 4p^2 \cos^2 r} \right\},$$

$$\lambda_{3,4}(\rho_{A,\mathrm{I}}^{\mathrm{pt}}) = \frac{1}{4} \left\{ 1 + p\cos^2 r \pm \sin^2 r \right\}. \tag{19}$$

Fig. 1 The fidelity of teleportation for a nonclassical correlated state, with the threshold purity, Eq. (20), in noninertial frame with acceleration corresponding to r.

The entanglement threshold for $\rho_{A,I}$ is corresponding to the purity threshold given as

$$p_{\text{th}} = \frac{3 - \cos 2r}{7 - \cos 2r}. \tag{20}$$

As an example $p_{\text{th}} = 1/3$ for $r = 0$. Then by substituting p_{th} as function of r in Eq. (18), we find the attainable fidelity of teleportation for a state with p_{th}, as plotted in Fig. 1. In this figure, the given fidelity for any r should be also regarded as the maximum attainable fidelity of teleportation from a sperable but nonclassically correlated state. It is clear that the achievable fidelity of teleportation from a separable but nonclassically correlated state is a decreasing function of r. It has the maximum value $2/3$ for $r = 0$, in accordance with Ref. [16]. Also, teleportation with a separable and classical correlated state gives fidelity of $1/2$ that is same as the success probability from a random guess. Then we conclude that fidelity of teleportation for a separable and nonclassical correlated state $< F_{\text{ncc}} >$ satisfies $\frac{1}{2} \leq < F_{\text{ncc}} > \leq \frac{2}{3}$, in any noninertial frame, and the maximum value is achieved for $r = 0$, an inertial frame.

4 Discussions and conclusion

In this work, we studied quantum teleportation with nonclassical correlated state in noninertial frame. Fidelity of teleportation, discord, and logarithmic negativity are evaluated as functions of r, corresponding to the acceleration a, and the purity, p, of the state.

Fig. 2 shows the fidelity of teleportation, discord, and the logarithmic negativity for two extreme accelerations, corresponding to $r = 0$ and $r = \pi/4$, in addition to an intermediate case, $r = \pi/8$. The logarithmic negativity for $r = 0$ is

Fig. 2 For the extreme cases $r = 0$ (the solid lines), and $r = \pi/4$ (the dotted lines), in addition to an intermediate case $r = \pi/8$ (the dashed lines), the average fidelity of teleportation, $< F >$, discord, and logarithmic negativity are plotted as functions of the purity, p.

nonzero for $p > p_{\text{th}} = 1/3$ and increases to reach the maximum 1, that is when the state, Eq. (10), is a Bell state. For $r = \pi/8$, p_{th} is 0.364, and for $r = \pi/4$, p_{th} is $3/7$, and the logarithmic negativity is an increasing function with the maximum values $N(p = 1, r = \pi/8) = 0.890$, $N(p = 1, r = \pi/4) = 0.585$. In Fig. 2, discord is nonzero for any nonzero purity, p, and it has maximum value same as the values for the corresponding logarithmic negativity. In this figure, the fidelity of teleportation is an increasing function with the purity. It is $1/2$ only for a separable and a classical correlated state. Any nonclassical correlation is sufficient for extracting fidelity of teleportation greater than $1/2$. Specifically, for $r = 0$, the fidelity of teleportation from a separable and nonclassical correlated state calculated from this work is in a good agreement with the original work by Horecki et al. [16], in which the optimal fidelity of teleportation in an inertial frame, $r = 0$, is given as a function of the maximally attainable singlet function. To be more precise in this circumstance, the optimal fidelity is calculated to be $2/3$ for a noisy singlet Eq. (13) of [16], as a generalization of the 2×2 Werner state. This fact is generally studied for any r and the results are illustrated in Fig. 3.

The special cases, $p = 1/3$ and $p = 1$ are shown in Fig. 3. Logarithmic negativity is zero for $p = 1/3$, regardless of the acceleration. However, $\mathcal{D}(p = 1/3, r = 0) = 0.126$, $< F(p = 1/3, r = 0) >= 2/3$, and these functions decrease by increasing r, and reach the minimum values $\mathcal{D}(p = 1/3, r = \pi/4) = 0.063$, $< F(p = 1/3, r = \pi/4) >= 0.606$. For $p = 1$, all the three functions start from the maximum value one, and decrease to different minimum values, $N(p =$

Fig. 3 The average fidelity, $< F >$, discord and logarithmic negativity, as functions of r. The upper-full curves are plotted for the maximally entangled states, $p = 1$, and lower-dashed curves are plotted for $p = 1/3$.

$1, r = \pi/4) = 0.585$, $\mathcal{D}(p = 1, r = \pi/4) = 0.601$, and $< F(p = 1, r = \pi/4) >= 0.819$.

Any nonzero nonclassical correlation gives fidelity of teleportation larger than the achievable fidelity from a purely classical state, and the fidelity of teleportation is generally decreasing with increasing acceleration in noninertial frame.

References

1. Bennett, C. H., Brassard, G., Crépeau, C., Jozsa, R., Peres, A., Wootters, W. K.: Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels, Phys. Rev. Lett. **70**, 1895 (1993).
2. Einstein, A., Podolsky, B., Rosen, N.: Can quantum-mechanical description of physical reality be considered complete?, Phys. Rev. **47**, 777 (1935).
3. Peres, A.: Separability criterion for density matrices, Phys. Rev. Lett. **77**, 1413 (1996); Życzkowski, K., Horodecki, P., Horodecki, A., Horodecki, M.: Volume of the set of separable states, Phys. Rev. A **58**, 883 (1998).
4. Datta, A., Shaji, A., Caves, C. M.: Quantum discord and the power of one qubit, Phys. Rev. Lett. **100**, 050502 (2008).

5. Caves, E., Laflamme, R.: Power of one bit of quantum information, Phys. Rev. Lett. **81**, 5672 (1998).
6. Horodecki, M., Horodecki, P., Horodecki, R., Oppenheim, J., Sen(De), A., Sen, U., Synak-Radtke, B.: Local versus nonlocal information in quantum-information theory: Formalism and phenomena, Phys. Rev. A **71**, 062307 (2005).
7. SaiToh, A., Rahimi, R., Nakahara, M.: Nonclassical correlation in a multipartite quantum system: Two measures and evaluation, Phys. Rev. A **77**, 052101 (2008); SaiToh, A., Rahimi, R., Nakahara, M.: Evaluating measures of nonclassical correlation in a multipartite quantum system, Int. J. Quantum Inform. **06**, 787 (2008).
8. Ollivier, H., Zurek, W. H.: Quantum Discord: A measure of the quantumness of correlations, Phys. Rev. Lett. **88**, 017901 (2001).
9. Zhao, M. J., Li, Z. G., Fei, Sh., Wang, Z. X., Li-Jost, X.: Faithful teleportation with arbitrary pure or mixed resource states, J. Phys. A: Math. Theor. **44**, 215302 (2011).
10. Wang, L., Huang, J., Dowling, J. P., Zhu, Sh.: Quantum information transmission, Quantum Inf. Process. **12**, 899 (2013).
11. Alsing, P. M., Milburn, G. J.: Teleportation with a uniformly accelerated partner, Phys. Rev. Lett. **91**, 180404 (2003);
    P. Alsing, P. M., McMahon, D., Milburn, G. J.: Teleportation in a non-inertial frame, J. Opt. B **6**, S834 (2004).
12. Mehri-Dehnavi, H., Mirza, B., Mohammadzadeh, H., Rahimi, R.: Pseudo-entanglement evaluated in noninertial frames, Ann. Phys. **326**, 1320 (2011).
13. Nielsen, M. A., Knill, E., Laflamme, R.: Complete quantum teleportation using nuclear magnetic resonance, Nature **396**, 52 (1998).
14. Rahimi, R., Sato, K., Furukawa, K., Toyota, K., Shiomi, D., Nakamura, T., Kitagawa, M., Takui, T.: Pulsed ENDOR-based quantum information processing, Int. J. Quantum Inf. **3**, 197 (2005).
15. Rahimi, R., Takeda, K., Ozawa, M., Kitagawa, M.: Entanglement witness derived from NMR superdense coding, J. Phys. A: Math. Gen. **39**, 2151 (2006); Rahimi, R., SaiToh, A., Nakahara, M., Kitagawa, M.: Single-experiment-detectable multipartite entanglement witness for ensemble quantum computing, Phys. Rev. A **75**, 032317 (2007); Rahimi, R., SaiToh, A.: Single-experiment-detectable nonclassical correlation witness, Phys. Rev. A **82**, 022314 (2010).
16. Horodecki, M., Horodecki, P., Horodecki, R.: General teleportation channel, singlet fraction, and quasidistillation, Phys. Rev. A **60**, 1888 (1999).