Letter

Davies theory for teleportation of quantum Fisher information under decoherence

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Abstract
We have investigated the teleportation of quantum Fisher information (QFI) for a single-qubit system by using two different maximally entangled pure states as resources influenced by a Davies-type Markovian environment. According to the definition of QFI, we first derive the explicit analytical results of QFI with respect to the weight parameter \(\theta\) and phase parameter \(\phi\) under decoherence. Our analytical results show that the teleportation of QFI is seriously affected by two classes of environment, including dissipative and pure dephasing, depending on the parameter \(\theta\) of the teleported state during the teleportation process. In particular, for \(\theta = \frac{\pi}{2}\) the optimal precision of estimating the weight parameter \(\theta\) is only affected by a dissipative environment with temperature, while the precision of estimating the phase parameter \(\phi\) is merely influenced by the dephasing environment.

Keywords: quantum teleportation, quantum Fisher information (QFI), Davies-type Markovian environment

(Some figures may appear in colour only in the online journal)

1. Introduction
The teleportation protocol originally introduced by Bennett et al. in [1] has become one of the most fascinating protocols in quantum communication and quantum computation networks. A maximally entangled state enables an unknown quantum state to teleport from one partner to another without transferring the physical carrier of the state by performing local quantum operations and classical communication. Owing to the potential applications in the field of quantum information and quantum communication, teleportation has attracted considerable attention in the past few decades [2–8].

As is well known, to perform a teleportation protocol faithfully one must resort to a maximally entangled state as a resource. However, in a realistic regime, quantum systems inevitably suffer from decoherence or dissipation due to interaction with the surrounding environment, which leads to the degradation of quantum entanglement or even the sudden death of entanglement and influences the quality of teleportation. On the other hand, despite related entanglement loss, effective teleportation is not excluded. Using a mixed state as an entanglement resource that is tantamount to a noisy channel has been reported by Bowen and Bose [9]. So far, most research on teleportation in open systems has generally
followed one of two routes. One focusses on how environmental noise affects teleportation [10–16]. The other is devoted to improving the fidelity of teleportation against noisy environments by using local operations, weak measurement technology and so on [17–20].

As a further step along this line, we are going to address how the thermal environment, in terms of the Davies map, affects the teleportation of an arbitrary unknown quantum state. Unlike the above-mentioned research [10–20] in which more attention was paid to teleportation of the whole quantum state, we are interested in teleportation of the information encoded into a particular parameter rather than the whole quantum state itself. What is more, in contrast to conventional teleportation where the quality of teleportation is characterized by fidelity, the credibility of teleportation of specific information is usually determined by quantum Fisher information (QFI), which describes how accurately a parameter encoded into the quantum state of the system is estimated [21]. In fact, the idea of considering the QFI for teleportation first appeared in [22] where the authors used the QFI to characterize the information flow of open quantum systems; it was subsequently generalized to investigate the dynamics of QFI under various noisy environments [23–28] as well as QFI teleportation [29–34].

In this paper, our aim is to examine the transformed information encoded in the quantum state but not the whole quantum state itself. By using the QFI as a measure of estimating the teleported information, we have explored QFI teleportation for two different entangled resources under the same Davies-type Markovian environment. In quantum information processing, a Davies-type Markovian environment has been applied to investigate all kinds of problems since Roga et al [35] first investigated the dynamics of a quantum system weakly coupled to a thermal reservoir, such as the effect of the thermal environment on the Leggett–Garg inequality [36], teleportation [37], quantum entanglement [38], quantum discord [39] and the properties of geometric phases of qubits in open quantum systems [40]. We here focus on the effect of a Davies-type Markovian environment on the precision of estimating parameters for an arbitrary unknown quantum state, and compare two different entangled pure states as resources. The explicit analytical results for QFI with respect to the weight parameter $\theta$ and phase parameter $\phi$ under decoherence are derived. Our results show that QFI teleportation is not only dependent on two different decoherence environmental parameters but also on the parameter $\theta$ of the teleported state during the teleportation process. When $\theta = \frac{\pi}{2}$, the optimal precision of estimating the weight parameter $\theta$ is only affected by the dissipative decoherence (i.e. energy exchange between the system and its environment), while the precision of estimating the phase parameter $\phi$ is affected by the dephasing decoherence (i.e. the exchange of information between the system and its environment without energy exchange).

The layout is as follows: in section 2 we illustrate the noisy model and teleportation protocol. In section 3 we examine the QFI teleportation of a single-qubit state in a Davies-type Markovian environment. Finally, we give our conclusion in section 4.

## 2. Noise model and teleportation

We consider a pair of non-interacting qubits A and B belonging to Alice and Bob interacting with their own environments, respectively $E_A$ and $E_B$. The Hamiltonian of the total system is written as

$$H = H_1 + H_E + H_I$$

where $H_I$ is the Hamiltonian of the qubits, which takes the form $H_I = \frac{1}{2} \sum_i \{ - |0\partial i |0\partial i \rangle\langle 0\partial i - |1\partial i |1\partial i \rangle\langle 1\partial i \}$, where $\omega_i$ is the energy splitting of the $i$th qubit. $H_E$ models the thermal environment and $H_I$ describes the qubit–environment interaction. In order to determine the qubit dynamics, in this work we assume that the interaction between the qubit and its environment is very weak and satisfies the Davies coupling conditions [35]. Based on the Davies weak coupling approach, the qubits’ reduced dynamics can be described by the generator of a completely positive semigroup as follows

$$\chi_{AB}(t) = (\Phi^A_t \otimes \Phi^B_t)\rho_{AB}(0).$$

A super-operator $\Phi^i (i = A, B)$ acting on single-qubit density matrices in bases $\{|0\rangle, |1\rangle\}$ is defined by the following:

$$\Phi^A_t |0\rangle\langle 0| = [1 - \nu(t)]|0\rangle\langle 0| + \nu(t)|1\rangle\langle 1|,$$

$$\Phi^A_t |1\rangle\langle 1| = r(t)|0\rangle\langle 1|,$$

$$\Phi^A_t |1\rangle\langle 0| = r(t)^*|1\rangle\langle 0|,$$

where $\nu(t) = p[1 - \exp(-At)], \mu(t) = (1 - p)[1 - \exp(-At)]$ and $r(t) = \exp(-i\omega t - Gt)$. The parameters $A = 1/\tau_R$ and $G = 1/\tau_D$ are related to the energy relaxation time $\tau_R$ and the dephasing time $\tau_D$, respectively. In the Davies approach, $A$ and $G$ obey the inequalities, $G \geq A/2$ $\geq 0$. The limiting case $A = 0$ and $G \neq 0$ corresponds to pure dephasing without dissipation of energy, while the opposite case, i.e. $G = 0$ and $A \neq 0$, cannot be physically realized because the energy dissipation is necessarily accompanied by finite dephasing. The parameter $p$ can be interpreted as a rescaled temperature as it ranges from $p = 0$ for the zero temperature limit up to $p = 1/2$ for an infinite temperature.

In order to perform teleportation protocol, we state that Alice and Bob share two different maximally entangled states as resources under a Davies-type environment to teleport an arbitrary unknown pure qubit state $|\psi\rangle_A$ from one to the other, where $|\psi\rangle_A$ takes the form

$$|\psi\rangle_A = \cos \frac{\theta}{2} |0\rangle + e^{i\phi} \sin \frac{\theta}{2} |1\rangle$$

with $0 \leq \theta \leq \pi$ and $0 \leq \phi < 2\pi$. It is clear that such an interaction turns the maximally entangled state, originally shared by Alice and Bob, into a mixed entangled state. In fact, the teleportation protocol that uses a mixed state as a quantum channel resource is tantamount to a noisy channel, and has been proved in the standard teleportation protocol by Bowen and Bose [9]. According to their results, an input state is destroyed and its replica (output) state appears at a remote
place after applying a local measurement and unitary transformation in the form of linear operators:

\[
\rho_{\text{out}} = \sum_{i=0}^{3} (\Psi_{\text{Bell}}^i | \chi_{AB}(t) \rangle | \Psi_{\text{Bell}}^i \rangle) \sigma_i (| \psi \rangle \rangle A (| \psi \rangle \rangle) \sigma_i
\]  
(8)

where \( | \Psi_{\text{Bell}}^i \rangle \) are four maximally Bell-entangled states:

\( | \Psi_{\text{Bell}}^0 \rangle = \frac{1}{\sqrt{2}} (| 01 \rangle - | 10 \rangle), \)
\( | \Psi_{\text{Bell}}^1 \rangle = \frac{1}{\sqrt{2}} (| 00 \rangle - | 11 \rangle), \)
\( | \Psi_{\text{Bell}}^2 \rangle = \frac{1}{\sqrt{2}} (| 00 \rangle + | 11 \rangle) \)
and
\( | \Psi_{\text{Bell}}^3 \rangle = \frac{1}{\sqrt{2}} (| 01 \rangle + | 10 \rangle) \), respectively.

In the present paper, we uncover some curious features that arise when two different maximally entangled states are exposed to Davies-type Markovian environments. We consider the following two cases as examples:

Case 1. The partners initially shared a maximally entangled state: \( | \Psi^\pm \rangle = \frac{1}{\sqrt{2}} (| 01 \rangle \pm | 10 \rangle) \). The optimal behavior of single-qubit teleported QFI with respect to \( \theta \) for a resource state \( | \Psi^\pm \rangle = \frac{1}{\sqrt{2}} (| 01 \rangle \pm | 10 \rangle) \) in a Davies-type Markovian environment with \( \rho = 0.15 \), to the standard teleportation protocol given by equation (8), one can obtain the explicit form of the output state as:

\[
\rho_{\text{out}}^{\Psi^\pm} = \frac{1+ (1-2\mu) (1-2\nu) \cos \theta}{\frac{1}{\sqrt{2}} \sin \theta e^{-2Gt+\delta} + \frac{1}{\sqrt{2}} \sin \theta e^{-2Gt-\delta}}\frac{1}{1-\mu(1-2\nu) \cos \theta}. \]
(10)

Substituting equation (10) into equation (9), the teleported QFI with respect to the parameters \( \theta \) and \( \phi \), respectively, is obtained:

\[
F_\theta = \frac{1}{4} e^{-4Gt} [4 \cos^2 \theta + 2 \delta \sin^2 \theta e^{4Gt} (3-2e^{4Gt} + \cos 2\theta - \sin^2 2\theta)] \]
\[
F_\phi = e^{-4Gt} \sin^2 \theta \]
(11)

where \( \delta = (1-2\mu)^2 (1-2\nu)^2 \). From the above equations, one can find that the teleportation of \( F_\theta \) is not only related to the Davies-type Markovian environmental parameters \( G \) and \( A \) but also to the teleported state parameter \( \theta \) during the teleportation process. In order to estimate the parameters as precisely as possible, one should maximize the QFI. For any given input state \( | \psi \rangle \rangle A \) with \( 0 < \theta < \pi \), and \( 0 < \phi < 2\pi \), the optimal QFI with respect to \( \theta \) satisfies the necessary and insufficient conditions \( \frac{\partial F_\theta}{\partial \theta} \rangle \rangle \theta = z \rangle \rangle 0 \) and \( \frac{\partial^2 F_\theta}{\partial \theta^2} \rangle \rangle \theta = z < 0 \). When \( \theta = \frac{\pi}{2} \), equation (11) reduces to

\[
F_\theta = (1-2\mu)^2 (1-2\nu)^2 \]
(13)
which is only affected by dissipative decoherence with temperature. While \( \theta \neq \frac{\pi}{2} \), the QFI with respect to \( \theta \) is heavily affected by two classes of decoherence: pure dephasing coupling without exchange of energy with the environment and dissipative coupling (with exchange of energy).

Similarly, \( \hat{F}_\phi \) has a maximum value at \( \theta = \frac{\pi}{2} \), namely

\[
\hat{F}_\phi = e^{-4Gt} \]
(14)
which is only affected by phase decoherence.

Figure 1 displays the optimal time evolution of teleported QFI with respect to \( \theta \) for a resource state \( | \Psi^\pm \rangle = \frac{1}{\sqrt{2}} (| 01 \rangle \pm | 10 \rangle) \).
in a Davies-type Markovian environment with $p = 0.15$. It is seen that QFI teleportation first decays to zero and then gradually revives to a stable value. With the dissipative parameter $A$ decreasing, the behavior of QFI decays more slowly. In particular, when the dissipative parameter $A \to 0$, $\mathcal{F}_\theta$ is immune to the Davies-type Markovian environment.

Figure 2 shows the optimal time evolution of teleported QFI with respect to $\theta$ for a resource state $|\Psi^\pm\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$ in a Davies-type Markovian environment with $A = 1$. 

3.2. Case two

We now analyze what happens when the source state shared between Alice and Bob is initially a maximally entangled state $|\Phi^\pm\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$ in the same decoherence environment. Similar to Case one, according to equation (8) one can obtain the explicit form of the output state as follows:

$$
\mathcal{F}_{\phi} = \frac{2^{-\Delta} \cos(2\theta) \cos^2 2\omega t + 2\Delta e^{iGt} \sin^2 \theta}{2 - \Delta - \Delta \cos(2\theta)e^{2iGt} - 2 \cos^2 2\omega t \sin^2 \theta} \quad (16)
$$

$$
\mathcal{F}_\phi = e^{-2Gt} \cos^2 2\omega t \sin^2 \theta \quad (17)
$$

where $\Delta = \frac{1}{4}[(1 - 2\mu)^2 + (1 - 2\nu)^2]^2$. Considering the teleported QFI with the best precision, we can manage the teleported state by choosing the weight parameter as $\theta = \frac{\pi}{2}$. Therefore, the above equations (16) and (17) reduce to

$$
\mathcal{F}_\theta = \frac{1}{4}[(1 - 2\mu)^2 + (1 - 2\nu)^2]^2 \quad (18)
$$

$$
\mathcal{F}_\phi = e^{-2Gt} \cos^2 2\omega t. \quad (19)
$$

It can be seen that the optimal estimation of the weight parameter $\theta$ is only affected by the dissipative environment while the optimal estimation of the phase parameter $\phi$ is affected not only by the pure dephasing environment but also by the energy splitting $\omega$ of the qubit system.

The optimal time evolution of single-qubit teleported QFI with respect to $\theta$ for a resource state $|\Phi^\pm\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$ in a Davies-type Markovian environment is shown in figures 4 and 5. It is clearly seen that $\mathcal{F}_\theta$ is similar to that of a resource state $|\Psi^\pm\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$, i.e. $\mathcal{F}_\theta$ first degrades with increasing time $t$ and then recovers to a certain stable value that is dependent on $p$ in the dissipative environment. The phenomenon of the recovery of QFI is a clear manifestation of the exchange of energy between the qubit and the environment. However, the value of $\mathcal{F}_\theta$ decreases with increasing time $t$ from 1 to a certain non-zero value. These results indicate that, on the one hand, $|\Phi^\pm\rangle$ as a resource state is more robust against a dissipative environment than the resource state $|\Psi^\pm\rangle$ and, on the other hand, different Bell states as
teleported resources can have very different properties, even though these source states have local unitary equivalence.

It is worth emphasizing that in the above discussion we have taken the optimal estimation of the weight parameter $\theta$ into consideration. In the following we consider the case where the optimal estimation of the phase parameter $\phi$ is subjected to a Davies-type Markovian environment. Based on equation (19), for resource qubits having the same energy splitting, namely $\omega = 0$, the result obtained for $F_\phi$ is the same as equation (4) (the obtained result is shown in figure 3). However, for two qubits with different energy levels, $\omega \neq 0$ and the oscillatory term occurs. In order to make the results comparable, we have plotted the behavior of QFI with respect to the phase parameter $\phi$ for two qubits with different energy levels $\omega = 1$, as shown in figure 6. As we can see, the behavior of $F_\phi$ displays oscillatory decay. The oscillation of QFI with time implies that the precision of estimation may increase again during some time period. From this result, oscillation of the QFI can occur by adjusting the different energy levels of two qubits. In a sense, this phenomenon can also be understood as a reverse flow of information from the environment back to the system.

4. Conclusion

In summary, we have studied the standard quantum teleportation of an arbitrary one-qubit state for the situation in which the maximally entangled state as a resource shared between partners is subjected to a Davies-type Markovian environment. We are only concerned with the transformation of information about a specific parameter of the quantum state. By using the QFI to quantify the quality of teleportation, the explicit analytical results for the precision of estimation of unknown parameters $\theta$ and $\phi$ in the decoherence environment are obtained. Unlike the previous results obtained in [37, 42], where the fidelity of teleportation was affected by both the dissipative decoherence and dephasing decoherence induced by the Davies type Markovian environment, our results show that dissipative decoherence only affects the optimal precision of estimating the weight parameter $\theta$, while the dephasing decoherence affects the precision of estimating the phase parameter $\phi$. These results indicate that the information encoded in the weight parameter is better protected against dephasing decoherence during teleportation. However, the extraction of information encoded in the phase parameter is more robust against dissipative decoherence.

We also show that under same decoherence interactions, different Bell states give rise to noisy entangled states that can have very different properties even though the source states are local unitary equivalent. Our results mean that a priori knowledge of a Bell state shared between Alice and Bob might be helpful for estimating parameters with high precision.

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