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Improved quantum state transfer via quantum partially collapsing measurements

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HIGHLIGHTS

- A scheme using weak/reversal measurements is devised to improve quantum state transfer.
- It can suppress dissipation allowing optimal quantum state transfer in open system.
- Explicit condition for achieving near-perfect quantum state transfer is established.
- Applications to spin chain and cavity array are considered in detail.

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ABSTRACT

In this work, we present a general scheme to improve quantum state transfer (QST) by taking advantage of quantum partially collapsing measurements. The scheme consists of a weak measurement performed at the initial time on the qubit encoding the state of concern and a subsequent quantum reversal measurement at a desired time on the destined qubit. We determine the strength q_r of the post quantum reversal measurement as a function of the strength p of the prior weak measurement and the evolution time t so that near-perfect QST can be achieved by choosing p close enough to 1, with a finite success probability, regardless of the evolution time and the distance over which the QST takes place. The merit of our scheme is twofold: it not only improves QST, but also suppresses the energy dissipation, if any.

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1. Introduction

Transferring quantum states from one to another location is an important phase in quantum information processing and distributed quantum computing [1]. The transfer can rely either on individual carriers, such as photons, or on collective phenomena, such as the natural dynamical evolution of a permanently coupled chain of quantum systems. In long distance quantum communication, photons are the most suited candidates to carry quantum states as they easily travel far away along optical fibers or through free space and can be readily measured at an arriving location. However, the interconnections of separate quantum processors or registers in a scalable, solid-state quantum computer [2–4] require mapping quantum states between two locations over relatively short distances. In this case, the employment of "quantum wire" made out of many interacting components is more suitable for quantum states' transferring. The first short-distance quantum state transfer (QST) protocol was proposed by Bose in which an unknown state can be efficiently transferred through a spin chain (data bus) via natural evolution [5]. In this protocol, the unknown state is encoded in the sth spin and will be transferred to the rth spin with certain fidelity after waiting for a specific amount of time depending on the length of the chain [5]. Subsequently, perfect QST in spin chains was experimentally realized using liquid nuclear magnetic resonance [6]. For a chain of spins subject to a uniformly coupled Heisenberg Hamiltonian [5], perfect QST is only possible for two or three qubits [7]. In order to achieve a perfect QST, several schemes have been proposed. It was found that, by appropriately engineering the couplings in a spin chain, a perfect or near-perfect QST can be accomplished for arbitrarily long chains [7–14]. However, the engineering of couplings is only be applicable in those physical implementations where interaction strengths can be tuned to appropriate values, as opposed to being "given" [15]. In Refs. [16,17], the QST with Gaussian wave-packet encoding was proposed for a ring of N spins and for open ended spin chains, which have also been suggested for communication through spin-chains under various static external fields [13,18]. The realization of wave-packet encoding should, however, involve several qubits for encoding or continuous time control. Another approach is to couple the sending and receiving qubits weakly to a quantum many-body system [13,19,20], which, however, will result in a slower transfer. By using a spin chain Hamiltonian with a nearest neighbor Ising coupling, in conjunction with "global" pulses (i.e., pulses that act on each spin of the chain in exactly the same manner) at regular intervals, a perfect transport of a state from one end to the other can be obtained [21]. Obviously, the schemes using global pulses are restricted to Ising chains. Burgarth and Bose also suggested a dual-rail channel by adding an auxiliary spin chain to improve transfer capability [15,22]. If enough measurements can be carried out, their protocol will achieve conclusively perfect transfer with certain success probability accessible to 1. Recently, Yao et al. [23,24] have proposed a high-fidelity QST through certain classes of random, unpolarized (infinite temperature) spin chains. Subsequently, the practicality of such spin chain wiring has been analyzed in diamond quantum technologies [25] and a high-dimensional quantum state transfer scheme has also been considered [26]. In addition to spin chains, the schemes to implement QST in other physical contexts have also been proposed [27].

In fact, the spin chain acts as an amplitude damping quantum channel converting the input state $\rho(0)$ to $\rho(t) = M_0\rho(0)M_0^\dagger + M_1\rho(0)M_1^\dagger$, where $M_0 = |0\rangle\langle 0| + |c_r(t)|\,|1\rangle\langle 1|$ and $M_1 = \sqrt{1-|c_r(t)|^2}\,|0\rangle\langle 1|$ are the Kraus operators with $c_r(t)$ the transition amplitude of an excitation (the $|1\rangle$ state) from the sending site to the receiving site of a spin chain [1,5]. Motivated by this fact, we recognize that schemes that can suppress the decoherence effects due to the zero-temperature energy relaxation are beneficial to improve the fidelity of QST through a spin chain. Therefore, in this work, we propose a general scheme by applying two sequential quantum measurements on the sending and the receiving spins, respectively, to boost the QST fidelity without modulating the spins (the data bus) between them. According to the quantum mechanics postulates, quantum (strong) measurement cannot be undone, because it totally collapses the measured system. However, if the measurement is weak (i.e., it only partially collapses the measured system) [1,28], it turns out possible to recover the measured state probabilistically [29,30] through another partially collapsing measurement called quantum reversal measurement. Such schemes based on quantum partially collapsing measurements have been demonstrated experimentally in various contexts, such as the superconducting phase qubit [31], the single-photon qubit [32], and the single trapped and laser-cooled $^{40}\mathrm{Ca}^{+}$ [33]. The idea of