Solid-State Quantum Information

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The transfer of a quantum state between distant locations can be realized using condensed matter systems such as spin chains and Josephson junction arrays. The feasibility of such proposals may open the way to use solid state devices also for quantum communication protocols.

The ability to transfer a quantum state between distant parties is one of the basic requirements in many quantum information protocols, we mention for example quantum key distribution or teleportation. A successful arena where the implementation of quantum state transmission has been realized is quantum optics. The carriers of information (photons) can be addressed and transmitted with accurate control and with a low level of decoherence. Very recently, in view of the great potential of solid-state quantum information, attention is also focusing on the problem of the transfer of quantum information in a solid state environment. A possible way to follow would be to properly design couplings between optical and solid state systems. Alternatively one could also think to realize quantum channels using condensed-matter systems. In Ref. [1] Bose showed that a Heisenberg spin chain is able to act as a quantum channel over reasonable distances (~ 100 lattice sites). A great advantage of this approach is that state transfer occurs solely because of the type of interaction between the spin of the chain and no dynamical control is required except for the preparation and the detection of the state. More interestingly, perfect transmission over arbitrary distance is possible [2,3] if the coupling is chosen appropriately. We addressed the effect of the static imperfections [4] on the protocol of Christandl et al. [2]. The quantum communication between two parties can be significantly improved if the receiver is allowed to store the received signals in a quantum memory before decoding them [5]. In the limit of an infinite memory, the transfer is perfect. We proved that this scheme allows the transfer of arbitrary multipartite states along Heisenberg chains of spin-1/2 particles with random coupling strengths. We showed that perfect

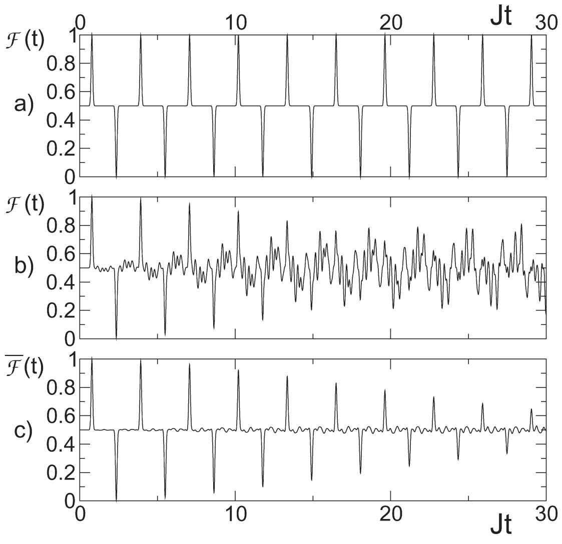

Fig. 1

Fig. 1
Fidelity of the state transmission as a function of time.
a)Without imperfections,
b) With imperfections
c) With imperfections averaged over 100 realizations of the disorder.

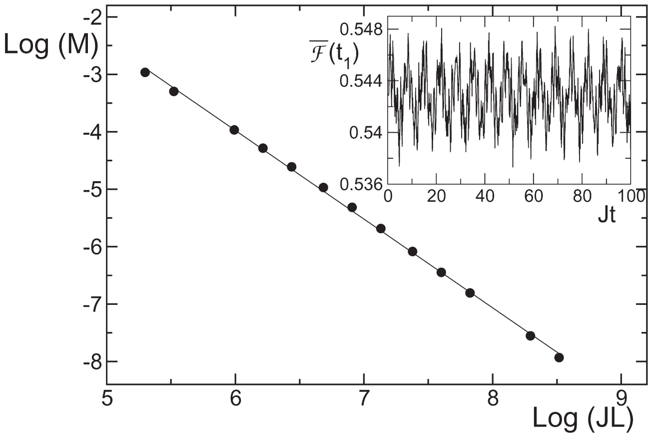

Fig. 2

Fig. 2
In the inset we show the temporal evolution of the fidelity in the presence of disorder. The slope of the main curve gives the fractal dimension of the curve, here D=1.52.

quantum state transfer can also be achieved in systems consisting of uncoupled identical quantum chains of permanently coupled qubits by repetitively monitoring the state of the receiver [6]. We analyzed in details the case of two parallel Heisenberg chains.

The presence of static imperfections, among others, leads to clear signatures of the modified properties of the spectrum in the fidelity. The degradation of the state transfer corresponds to the emergence of a fractal signal, i.e. the fidelity changes from a periodic function of time to a fractal time series. The time dependence of the fidelity F(t) is shown in Fig. 1 and in the inset of Fig. 2. In Fig. 1 the case of ordered a), disordered b), and disorder averaged c) signals are presented. In the standard box counting algorithm the fractal dimension D of the signal is obtained by covering the data with a grid of square boxes of size L. The number M(L) of boxes needed to cover the curve is recorded as a function of the box size L should scale as a $M \sim L^D$. In Fig. 2 the data yield a fractal dimension D=1.52. Treated as a quantum channel, spin chains were therefore analyzed within the theory of quantum communication and therefore information capacities have been analyzed [7]. As a possible solid-state implementation we considered Josephson junction arrays to transfer quantum information between distant sites [8]. A prototype scheme is shown in Fig. 3. The crossed boxes are the Josephson junctions and the preparation and detection regions can be implemented by means of a Cooper pair box and a SET transistor, respectively. The possibility of solid-state quantum channels is not only limited to state transfer. Indeed it has been shown that other information protocols such as quantum cloning [9] or entanglement swapping has been already proposed.

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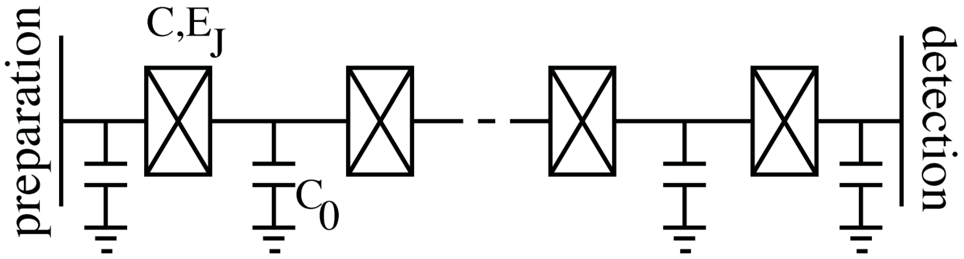

Fig. 3
A prototype scheme: Josephson junction arrays to transfer quantum information between distant sites

References
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