Insight on future quantum networks

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In the past few years, significant improvements have been achieved in quantum communication. To extend the communication range, however, a new technology based on quantum memories needs to be developed. In PNAS, Bao et al. (1) give an example of the building blocks of the quantum communication networks we may expect to see in the future. These complex systems will be built on the basic ingredients of quantum state teleportation and quantum memories and will expand over relatively large distances.

Quantum teleportation (2), one of the most spectacular protocols realized so far in the framework of quantum information, is a mysterious way to transport the information associated with the state of a quantum system. Quantum states are very fragile; indeed, they are easily destroyed by a single measurement. Quantum mechanics tells us that we cannot extract the complete information about a quantum state by a single measurement. For this reason, quantum states cannot be copied and transmitted by performing a direct measurement and then using a classic communication channel. Nevertheless, by using the entanglement existing among different quantum systems, quantum teleportation allows one to transfer from one place to another the information encoded in particular degrees of freedom of the particle involved in the process, such as the spin of the particle or the polarization of a photon, without the need for any transport of the particle. Accordingly, it corresponds to the disembodied transport of a quantum state.

After the first experimental realization of the transfer of the quantum state from one photon to another (3–5), quantum teleportation was demonstrated from light to matter (6, 7) and between single ions (8–10). It has definitively emerged as a fundamental tool in a number of quantum communication and quantum computation tasks, such as enabling either the interaction of distant qubits without the requirement of physical proximity or universal quantum computation when combined with single-qubit operations (11).

Another potential application of teleportation deals with distributed computing. Networking allows for tasks that individuals are unable to accomplish on their own. This is known for computing, where grids of processors outperform the computational power of single machines or allow the storage of much larger databases. It is thus expected that similar advantages are transferred to the realm of quantum information by quantum networks, corresponding to lattices of increasing complexity, consisting of local nodes sharing quantum channels. Quantum networking is emerging as a realistic scenario for the implementation of quantum protocols requiring midsized or large registers (12). In this respect, quantum teleportation is an essential part of any robust quantum information system.

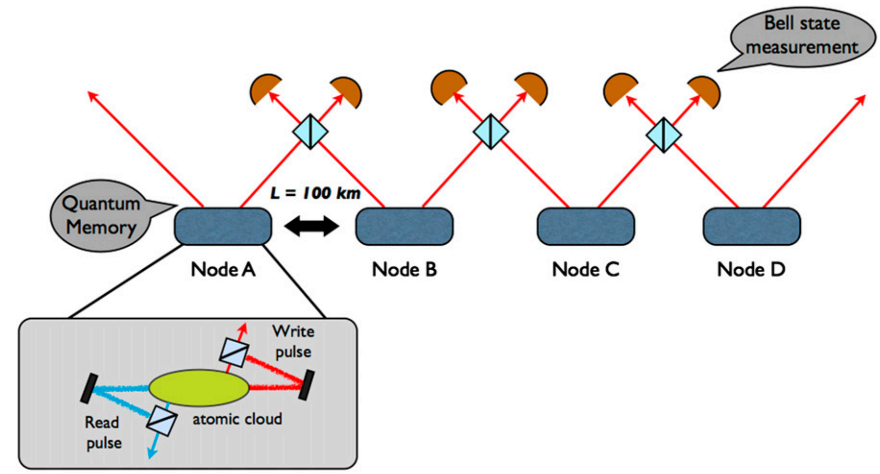

Fig. 1. Sketch of a future quantum communication network expanding over long distances. Each quantum memory consisting of an atomic cloud lies within a node of the network. Quantum states are teleported from one node to another by performing Bell state measurements. (*Inset*) Write and read pulses used to create the entanglement between the atomic ensemble and the write-out photon. L corresponds to the length of the communication channel between two adjacent nodes.

It is likely that the most direct application of teleportation is to perform quantum communication over long distances (13). In this scenario, quantum memories (14), as the basic nodes of future quantum networks, are fundamental. These provide a place for storing quantum information until it is needed later and are able to do it better than any classic state-based memory. Quantum memories are also an essential component in quantum computing. The need for nodes based on quantum memories in long-distance quantum communication is due to photon losses, limiting any kind of communication channel to distances lower than 150 km. The quantum memory approach overcomes this difficulty by combining quantum teleportation and quantum state storage. In this way, a given long distance is divided into shorter elementary links and entanglement is created and stored independently for each link (15). This is possible only if quantum memories with long coherence times and efficient interfacing with photons are available.

In the experiment performed by Bao et al. (1), two quantum memories, composed of two magnetooptical traps located at a relative distance of 0.6 m, play the role of Alice (A) and Bob (B) in the teleportation protocol. Each atomic ensemble corresponds to a node of an elementary quantum network. It consists of a 1-mm atomic cloud of a 10^8 rubidium atoms and is connected to the other by a 150-m optical fiber.

To teleport the quantum state of A into the atomic ensemble B, the entanglement between a collective atomic excitation within system A and the polarization of a single photon was created first; the spin wave induced on the atomic ensemble B was then mapped to a second propagating photon. This operation was accomplished by applying to A and B a sequence of laser pulses, properly chosen to “write” and “read” the variation induced in the quantum states of the two atomic ensembles. To perform the Bell state measurement—a key ingredient of the teleportation protocol—the two photons,

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playing the role of the information carriers, were temporally matched on a polarizing beam splitter, with photon B traveling through the 150-m optical fiber to achieve communication over a long distance. At variance with the teleportation of quantum states of light generated by the spontaneous parametric down-conversion process, the single-photon states used in this experiment are characterized by a long coherence length (7.5 m instead of dozens of microns), making the temporal synchronization of the photons easy. A high quality of the teleportation protocol was measured by analyzing the polarization state of a photon created by a further read laser beam applied to the atomic ensemble B.

In the experiment performed by Bao et al. (1), teleportation is performed with a probability of success that is four orders of magnitude higher than in previous experiments. Another aspect of fundamental relevance is the realization of the protocol in the macroscopic regime. This raises important questions on how large the size of the systems involved in the protocol can be and how far the region where atomic ensembles cease to be quantum and start to behave classically is. Regarding the relative distance between the quantum systems, we also expect that longer values than the one of the present experiment will be tested in the future.

The combination of entangled photons, quantum memories, and high-performance single-photon detectors is the key challenge for the commercial realization of quantum networks.

To achieve teleportation over multinode quantum networks, as sketched in Fig. 1, requires a storage time well beyond the 129 μs of the present experiment. For this purpose, the adoption of optical lattices for confinement of atoms (16) could move the storage lifetime from hundreds of microseconds to fractions of seconds.

Among technological perspectives, the possibility of implementing quantum memories by exploiting rare earth ions frozen in a crystal is attracting growing interest with the first successful implementations (17–20). The combination of entangled photons, quantum memories, and high-performance single-photon detectors is the key challenge for the commercial realization of quantum networks. The achievement reported by Bao et al. (1) represents an important step in this direction.

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