Article:
Pirandola, Stefano and Braunstein, Samuel Leon (2016) Unite to build a quantum internet. Nature. pp. 169-171. ISSN: 0028-0836

https://doi.org/10.1038/532169a

Unite to build a quantum internet

Advances in quantum communication will come from investment in hybrid technologies, explain Stefano Pirandola and Samuel L. Braunstein.

Just over 20 years ago, physicists [1] discovered a way of ‘teleporting’ a quantum system from one place to another without moving it. There are physical limits: nothing can be transmitted faster than the speed of light; and the uncertainty principle restricts what we can know about a quantum system’s state at a given time. Nonetheless the replica can perfectly mimic the original thanks to the weirdest feature of quantum mechanics – entanglement, which Einstein described as “spooky action at a distance”. This is the property of quantum systems to become intimately correlated with each other so that an action on one has an instantaneous `effect' on the other, even for systems too far apart to interact.

Due to the fragility of quantum states, it is often impractical to move them through communications lines. Quantum teleportation offers the best way to transfer quantum information across a network. It provides the working mechanism of a future quantum internet which would make our communications completely secure and would non-trivially increase our distributed computational power, well beyond the capabilities of the current classical infrastructure.

Many technologies for teleporting different types of quantum information – be it the polarization state of a photon, the spin of an electron or the excitation state of an atom – have been developed [2]. But there are practical restrictions on what can be teleported and how. Depending on the task, one technology is better than another and each has limitations. For example, polarized photons have transferred quantum information over a hundred kilometres but only probabilistically. Superconducting devices send full information over a chip but only for a split second, after which the information scrambles owing to interactions with the environment.

Hybrid approaches are needed. A global distributed quantum computer or Quantum Internet will need to integrate different sorts of quantum technologies. Light-based teleportation, for long-distance quantum communication, will need to be linked to matter-based quantum memories and quantum computers for data storage and processing. Here we outline the main challenges and call for researchers to focus on the interfaces between quantum technologies as well as pushing individual methods forward.

Two approaches

The best technique for long distance communication is teleporting quantum information embedded in optical light. Once implemented in an ideal way, this method would allow us to perfectly transfer quantum states between remote quantum computers. Quantum information (qubits or `quantum bits') may be encoded using either discrete properties of a light pulse such as its polarization state or continuous aspects of an electromagnetic wave such as the intensity and phase of its electric field [3]. Sending this information requires the sender and receiver each own one of a pair of entangled quantum systems; when the sender alters the state of one, the receiver’s system is also affected.

In terms of distance, polarized qubits perform best– 143km is the record [4]. But with current experimental setups, only 50% of these qubits can be teleported; the rest are uncertain. Teleporting requires that the sender is able to carry out a process known as ‘Bell detection’, in which the optical polarizations of two qubits are perfectly correlated in four possible configurations (see BOX). But there is no practical way to measure all 4 outcomes. Simple optics and photodetectors distinguish at most 2. Using extra qubits to go further only adds to the technical complications [5].

Inconclusive outcomes are acceptable for quantum cryptography, where secret keys are generated randomly and part of the information can be discarded**.** But for quantum communication information must be sent in full.

Teleporting over long distances [2] adds technical difficulties such as compensating for atmospheric turbulence and ground settlement and using atomic clocks for synchronisation. Transferring information from a low-Earth-orbit satellite (at 500km altitude) to the ground is within the reach of current technology, as telescopes with meter-size apertures can collect most of the light from the beam that has spread out during its passage**.** Ground-to-satellite or inter-satellite experiments are much more challenging because satellites cannot carry large optics.

By contrast, it is easy to measure all the Bell detection outcomes for continuous-variable systems, with simple linear optics and standard photodetectors**.** By their nature continuous variable systems may convey the equivalent of many qubits simultaneously**,** making them appealing for high-rate quantum communications [6]. But, because their distance tends to be more limited in practical implementations, continuous-variable systems are not currently used as often as qubits.

What's needed are approaches which combine the best features of discrete variables (long distances and high fidelities) and continuous variables (deterministic teleportation at high rates). Such combinations have been demonstrated over table-top distances. For example, one experiment [7] combined a discrete qubit with a continuous variable entangled source to teleport information deterministically. Further studies are needed to extend the range of this kind of set up, and to integrate qubits with other types of quantum technologies, for instance with quantum memories for the storage of the teleported information.

Studies of hybrid technologies will require collaborations by researchers with broad backgrounds and more interaction between teams with different specializations.

Quantum Internet

How might we construct a worldwide distributed quantum computer or quantum Internet [8]? Once entanglement is distributed to the nodes, qubits can be teleported between any pair and then processed by local quantum computers.

Ideally nodes should be entangled beforehand, either pair by pair or by creating a large multi-entangled 'cluster state', which is broadcast to all nodes. Large cluster states able to entangle thousands of nodes have been created in the lab [9]. The challenge is to demonstrate how these might work over large distances, how to store states at the nodes and how to update them continuously using quantum codes.

A quantum network requires the development of memories which shield quantum information from unwanted environmental interactions and store it, ideally for hours. This is needed for quantum computing at the nodes and for the faithful long-distance distribution of entanglement via quantum repeaters, whose mechanism requires the storage of qubits.

Quantum memories need to convert radiation into physical changes in matter, ideally with near-perfect fidelity and high capacity. Options include 'spin ensembles' such as cold atomic gases containing around a million Rubidium atoms. Such gases convert a photon into a collective atomic excitation, a spin wave, with storage times approaching the threshold of 100 milliseconds required to transmit a light signal world-wide.

Solid-state quantum memories are even more appealing. Crystalline solid spin ensembles offer hours-long coherence times at cryogenic temperatures. Such memories are being created by inserting nitrogen-vacancies in diamonds or by doping rare-earth crystals with ions. The most promising architecture to be scaled up into large quantum computers are solid state quantum memories integrated with superconducting quantum processors [10].

Superconducting qubits, defined from the quantization of physical quantities such as the charge of a capacitor or the flux of an inductor, interact by releasing and absorbing microwave photons, which propagate over a quantum processor. The most important issue that needs to be solved is making the storage and retrieval of quantum information fully reversible. This will require an efficient interface between these microwave photons and the atomic spins of a solid state quantum memory attached to the processor.

For the construction of a quantum internet one would also need to interface microwave photons, processed and stored locally, with optical signals, which are the most robust carriers of quantum information for long distance communications, for instance in fibres. A hybrid solution is emerging from the field of optomechanical quantum transducers [11].These devices exploit nano-mechanical oscillators (such as microscopic vibrating mirrors) to transform optical photons into microwave ones, and vice versa. The challenge is to improve their efficiency so that qubits are not lost during the conversion process and all the quantum features are preserved. Today their conversion efficiency is below 1%.

Over the next 15 years we may see the construction of a hybrid-technology quantum internet. Here superconducting quantum processors may be integrated with solid state memories for local quantum storage, and augmented with optomechanical (or other) microwave-optical transducers for long-distance optical communication. Once two remote nodes are connected in this way, one could distribute entanglement and perform teleportation between distant quantum processors.

Next steps

In our view the following areas are priorities for quantum teleportation science.

First, more research – theoretical and experimental – is needed at the interface between discrete and continuous variables to combine and exploit the best of both approaches. Satellite experiments with polarization qubits should be pursued; continuous-variable teleportation should be extended outside the lab over metropolitan distances through free space or through fibres. Continuous and discrete variable approaches should be blended. Dedicated conferences would help here.

Second, computation and storage are inseparable. We need a more efficient interface between superconducting circuits and solid-state quantum memories, increasing the performance of storage and retrieval of microwave photons. A tangible next step could be the on-chip teleportation between a superconducting qubit and a nitrogen-vacancy centre of a local quantum memory.

Third, we should design and integrate microwave-optical converters which efficiently connect on a chip microwave with optical photons for long distance quantum communication. Two remote chips could be connected by a pair of microwave-optical converters, paving the way for long distance quantum teleportation between superconducting qubits.

These steps necessitate a closer interaction between research teams working in superconducting quantum computing and those developing long-distance quantum optical communications. Today the use of solid-state quantum memories is the only point of contact between these two communities. Industry too needs to be involved, especially those multi-national corporations which are leaders in computer hardware and telecommunications. The great potential of quantum technology is attracting private stakeholders, but the development of a Quantum Internet needs investment on a much larger scale.

Stefano Pirandola is reader and Sam Braunstein is professor in the Computer Science department at the University of York, UK.

References

[1] Bennett, C. H., et al. Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels. Phys. Rev. Lett. 70, 1895 (1993).

[2] Pirandola, S., Eisert, J., Weedbrook, C., Akira, F., & Braunstein, S. L. Advances in Quantum Teleportation. Nature Photon. 9, 641-652 (2015).

[3] Weedbrook, C., et al. Gaussian Quantum Information. Rev. Mod. Phys. 84, 621 (2012).

[4] Ma, X.-S., et al. Quantum teleportation over 143 kilometres using active feed-forward. Nature 489, 269-273 (2012).

[5] Knill, E., Laflamme, R. & Milburn, G. A scheme for efficient quantum computation with linear optics. Nature 409, 46-52 (2001).

[6] Pirandola, S., et al. High-rate measurement-device-independent quantum cryptography. Nature Photon. 9, 397-402 (2015)

[7] Takeda, S., Mizuta, T., Fuwa, M., van Loock, P. & Furusawa, A. Deterministic quantum teleportation of photonic quantum bits by a hybrid technique. Nature 500, 315 (2013).

[8] Kimble, H. J. The Quantum Internet. Nature 453, 1023 (2008).

[9] Yokoyama, S., et al. Ultra-large-scale continuous-variable cluster states multiplexed in the time domain. Nature Photon. 7, 982-986 (2013).

[10] Schoelkopf, R. J. & Girvin, S. M. Wiring up quantum systems. Nature 451, 664–669 (2008).

[11] Andrews, R. W., et al. Bidirectional and efficient conversion between microwave and optical light. Nature Phys. 10, 321 (2014).