How to Span the Quantum Gap

Building continental-scale quantum communications links is an arduous task, but scientists believe they have the technology in hand.
A research team at the University of Science and Technology of China, Hefei, was one of two groups last year to demonstrate an “absorptive” memory that could be used in a multiplexed quantum repeater.

G. Wang and Y. Ma/USTC
The fiber optic cables that crisscross the world’s oceans are studded every few tens of kilometers by repeaters—devices that compensate for the fibers’ attenuation by boosting the power of a signal and retransmitting it. The development of all-optical repeaters has made this amplification process extremely efficient, leading to the huge growth in internet traffic seen over the last two decades—and with it, the rise of social media, cryptocurrencies and “smart working.”

But while ever-greater lengths of fiber have been laid out across the seabed, scientists have been busy in the lab trying to build a radically different kind of device: a quantum repeater. This would facilitate the transmission of quantum rather than classical information, and so usher in a range of novel applications not possible with today’s internet. As well as securing classical data via long-distance quantum key distribution (QKD), the research ultimately aims to construct a “quantum internet” that would hook up, among other things, quantum computers, quantum sensors and widely separated optical telescopes.

Quantum repeaters, though, are proving a tough nut to crack. The no-cloning theorem prohibits unknown quantum states from being copied, which makes straightforward amplification of quantum signals a no-no. The idea instead is to establish long-range entanglement between network nodes, allowing information to be teleported between them. This calls for combining a number of very complex components, which has slowed progress, according to Tracy Northup at the University of Innsbruck in Austria. “In the past, people have demonstrated these things individually but haven’t put them together,” she says.

Yet progress is picking up pace. Backed by government programs aimed at realizing quantum networks, a number of groups are making the transition from proof-of-principle physics experiments to working devices. Indeed, Mikhail Lukin of Harvard University, USA, reckons that his group could field-test a prototype repeater within the coming year. “The main challenge now is working on the technology to be able to scale it up,” he says. “But I wouldn’t be surprised if in the next five years or so we are experimenting with systems that can do continent-scale communication.”

No need for trust

One form of quantum communication, QKD, is already used in the real world. The principle here is that Alice (as cryptographers conventionally refer to the sender of an encrypted message) exchanges a quantum-mechanical key, generally in the form of a string of photons, with the receiver Bob. Any eavesdropper hoping to intercept the key will inevitably reveal their presence by affecting Bob’s quantum measurements.

QKD devices are sold commercially; the Swiss company ID Quantique, for example, has marketed them since 2007 for applications such as vote counting and bank transactions. National governments are also taking an active interest. In 2017, China switched on a 2000-km-long fiber optic backbone between Beijing and Shanghai that allows users to send and receive quantum-encrypted messages.

Such technology, however, can only guarantee security against eavesdroppers over a certain distance. Attenuation in fiber means that as the communication distance increases, the probability of any photon reaching the far end drops off exponentially. Thus the rate of secret-key transmission becomes impractically low beyond about 100 km. The Chinese network gets round this limit by using a series of “trusted nodes” positioned along the length of the fiber to boost signals. But to do that, each node must first read the secret key before passing it on—a less-than-ideal solution.

In 1998, Peter Zoller and colleagues at the University of Innsbruck put forward the concept of a quantum repeater as a way of overcoming the distance limit without compromising security. These devices would
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break down a quantum communication channel into a number of equal-length segments, with attenuation confined to within segments rather than acting along the channel as a whole. Limiting the segment length to a few tens of kilometers allows loss to be kept manageable.

This loss-limiting exercise is enabled through so-called entanglement swapping. First, entanglement is established across individual segments; then, quantum repeaters progressively double the entangled distance until the entire channel length is spanned (see “Spooky action at ever-greater distances,” right). In principle, the approach enables greater data rates than in direct (repeaterless) transmission, because while the distance extends geometrically as each round of entangling is completed, the total time needed increases only arithmetically. This implies a polynomial rather than exponential drop in the transmission rate with distance.

However, loss in the fiber and errors caused by the repeaters themselves still exact a price. Because it cannot be known ahead of time whether any attempt at entanglement will be successful, the outcome of all attempts must be communicated along the segments involved. This not only slows down the entanglement process, but means that repeaters require memory to store their delicate entangled states while awaiting “heralding” signals from their neighbors indicating successful entanglement.

It is the interaction between the matter-based quantum bits (qubits) used as memory and the photonic qubits used as information carriers that makes quantum repeaters such a technological challenge, according to Gerhard Rempe at the Max Planck Institute of Quantum Optics, Munich, Germany. In fact, Rempe maintains that repeaters are even harder to build than quantum computers. “There are a smaller number of qubits in the box,” he says.

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**Spooky action at ever-greater distances**

Quantum entanglement involves an intimate correlation between two objects, no matter how far apart they are. Famously described by Einstein as *spukhafte Fernwirkungen* (“spooky action at a distance”), this correlation allows two parties sharing a secret key to check for the presence of an eavesdropper or more generally to establish a link across which they can teleport information.

Two people, Alice and Bob, might set up such a link by using a series of quantum repeaters spaced at regular intervals between them (nodes $C_1$ to $C_3$ in the accompanying diagram). Alice and one half of the repeater $C_i$ each send a photon to a 50-50 beam splitter; the pair only becomes entangled if one of the beam splitter’s outputs registers a photon. The measurement result is communicated to the nodes, and the process is repeated until entanglement is established across that segment—with success marked by a “heralding signal.” Bob does the same thing with one half of the $C_i$ repeater, while the other halves of $C_i$ and $C_j$ do likewise with $C_k$.

Once all the segments have become entangled, the two halves of $C_i$ and $C_j$ are themselves entangled by sending photons to another beam splitter in each repeater, and then awaiting the outcome of that measurement. This is entanglement swapping—a halving in the number of pairs of entangled particles and a doubling in the entangled distance, in this case linking both Alice and Bob to $C_k$. Entanglement is then finally swapped from $C_i$ and $C_j$ to $C_k$, thereby spanning the entire distance between Alice and Bob.

The sequence shown involves only two rounds of entanglement swapping. In principle, though, the process can extend to successive rounds to span ever-greater distances.

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**A simple entanglement-swapping model**

Adapted from figure courtesy of K. Azuma
“But you deliberately open the box, which means all the noise and the funky stuff comes in.”

Efficiency versus staying power

Much research on quantum repeaters has been based on the “DLCZ protocol” proposed by Zoller and colleagues at Innsbruck and Harvard in 2001. This involves repeaters with memories that store entanglement in the collective excitations of ensembles of atoms. These “emissive” memories themselves provide the photons that interfere to establish the entangled states in the first place—each photon being scattered in the forward direction when its ensemble is illuminated by classical pumping pulses.

In 2020, a team led by Jian-Wei Pan at the University of Science and Technology of China, Hefei, showed how this scheme could potentially distribute entanglement over several tens of kilometers. The group did so by linking two atomic ensembles in the same lab via a remote beam splitter connecting the ends of two parallel 11-km-long strands of commercial fiber, converting emitted photons’ wavelength from the near-infrared to a telecommunications band—an essential requirement for future quantum networks.

Numerous other groups, in contrast, have demonstrated entanglement with single quantum particles. Ronald Hanson and colleagues at the Delft University of Technology, Netherlands, exploit the spin of electrons trapped inside crystal defects in diamonds called nitrogen–vacancy centers. In 2015, they showed how to entangle two such centers spaced more than a kilometer apart. Last year, they demonstrated entanglement swapping using a small-scale, three-node network powered by a single laser.

The group has since tested two fully autonomous nodes in the same lab and hopes by the end of this year to have moved one of them to the Hague, thereby distributing entanglement over about 30 km. But major technical challenges remain. Hanson points out that while nitrogen–vacancy centers are fairly long-lived by quantum standards, maintaining their entangled states for about 0.2 s, they are also inefficient, with only 3% of the photons they emit suited to establishing quantum links.

Indeed, all memory qubits have their pros and cons. Northup and colleagues in Innsbruck are investigating trapped ions, which, she says, can be entangled with high fidelity thanks to their much-studied use as qubits in quantum computers. She also explains that the ions’ emission can be fairly readily converted to telecom wavelengths. But the emission needs to be boosted by placing ions in an optical cavity, where the light’s bouncing back and forth slows the process down.

Beating the repeaterless bound

Another option is neutral atoms, which, according to Dieter Meschede of the University of Bonn, Germany, provide a “good compromise” in terms of coherence time and efficiency. Unlike ions, he points out, atoms are not perturbed by any stray charges on a cavity’s mirror surfaces, and thus couple more readily with photons.

Rempe and colleagues in Munich reported last year that they had used a quantum repeater made from two rubidium-87 atoms to successfully carry out QKD
Some researchers argue that any scheme based on memory made from individual qubits is ill-suited to building practical quantum repeaters.

While achieving a key performance metric—beating the rate-versus-distance curve of direct transmission via point-to-point links. Carrying out their experiment over a range of distances up to 2 km, they were able to halve the decay exponent as expected theoretically for a communication channel divided into two equal-length segments.

As Rempe points out, the real aim is to beat the absolute bit rate of repeaterless transmission. He is confident that he and his colleagues can achieve that by making what he describes as technically feasible improvements to their repeater’s decoherence time, efficiency and fidelity. Implementing these changes over 7 km or more, he says, the team’s repeater scheme should finally outdo point-to-point links.

In fact, one group claims to already have done just that. Lukin and colleagues at Harvard have developed a repeater featuring a silicon–vacancy (rather than nitrogen–vacancy) center in diamond, and in 2020 reported having generated key bits for QKD at about four times the rate of direct transmission. Having since shown, in unpublished research, that they can operate their scheme at telecom wavelengths, the team plans to demonstrate its technology using two remote nodes in the Boston area within the next year.

Others, however, are unconvinced that the lab-based demonstration really constitutes defeat of direct transmission. Zong-Quan Zhou of the University of Science and Technology of China, Hefei, argues that the Harvard group must carry out its test with truly independent, distant nodes. Rempe and colleagues, meanwhile, point out that the Lukin team’s reported QKD error rate did not get below 11%, as needed for completely secure communication.

More broadly, some researchers argue that any scheme based on memory made from individual qubits is ill-suited to building practical quantum repeaters. Nicolas Gisin, founder and chairman of ID Quantique, argues that by emitting just one photon at a time, such technology will “remain very slow.” Even if these devices are shown to beat direct transmission up to about 100 km, he argues, they will fail to generate a useful bit rate over the 500 km or so needed to cross continents.

Potent dopants

Previously at the University of Geneva and now at the Schaffhausen Institute of Technology, also in Switzerland, Gisin has spearheaded research on multiplexed repeaters. The idea is to overcome the roadblock imposed by heralding. Rather than waiting for single photons to travel to the central repeater node and information about their interactions to arrive back at the outer nodes, multiplexing instead allows multiple entanglement attempts to be made at the same time. That would speed up transmission roughly in proportion to the number of multiplexed modes.

To make this feasible, a number of groups are working on “absorptive memory.” In contrast to the memory envisioned in the DLCZ protocol, which itself emits the photons for interference measurements, absorptive devices receive photons generated by separate sources. At present, those sources are probabilistic, meaning that they generate photons at a lower rate than the “deterministic” sources based on single emitters. But here, too, researchers are looking to integrate deterministic devices.

One popular type of absorptive memory is made from crystals doped with rare-earth ions. The ions have well-defined transition frequencies, and undergo
collective, coherent excitation after absorbing an incoming photon. Because each ion interacts differently with the crystal, that excitation would normally rapidly dephase. But by preparing the crystal with a second laser, the absorption peaks can be spaced at regular intervals, like the teeth of a frequency comb. This means dephasing is shortly followed by rephasing, so that a train of absorbed photons yields a train of emitted photons—and, thereby, temporal multiplexing.

Two results from last year showed the promise of this technology. Hugues de Riedmatten and colleagues at the Institute of Photonic Sciences (ICFO) in Barcelona, Spain, reported entangling two memories made from crystals doped with ions of praseodymium and placed in separate laboratories spaced a few meters apart. They showed how to carry out multiplexed, single-photon entanglement, which they heralded at telecom wavelengths. They now aim to demonstrate their technology over a 35-km-long link.

The rival group, based at the University of Science and Technology of China, Hefei, instead carried out two-photon entanglement using neodymium-doped crystals. Joint group leader Zong-Quan Zhou explains that this arrangement relaxes the necessary phase stability compared with the Spanish setup and is potentially well-suited to deterministic sources, such as quantum dots. It nevertheless lowers entanglement rates by needing to detect two photons at the central node instead of just one. Zhou adds that he and his colleagues are also planning to carry out a field test, in their case across about 20 km.

**Going the distance**

Exactly how long it will take to develop a practical quantum repeater remains to be seen. Gisin admits to having been too optimistic in the past—in 2007, he predicted that a real-world demonstration would likely take place in the following five to ten years. He says he wouldn’t be surprised if a field test this year were to beat the direct transmission rate over a few tens of kilometers, but estimates that around a decade will be needed to cross continents.

Spanning the entire globe will take longer still. As Gisin points out, repeater nodes themselves can impair the fidelity of entangled states. He argues that the errors per node ought to be low enough that robust links can still be established over distances of up to about 1000 km. But beyond that, he says, successful entanglement distribution will require purification. This involves generating several low-grade entangled pairs of photons for each set of nodes, and then using quantum information processing to yield a single high-grade pair.

One possible solution could come with the advent of more advanced “third-generation” technology that, through quantum error correction, dispenses with the back-and-forth communication involved in heralding, drastically cutting the time needed to establish an entangled link. This potentially both multiplies transmission rates and reduces, if not eliminates, the need for quantum memory—assuming that very efficient quantum gates and optical interfaces can be built (see “The appeal of one-way traffic,” p. 41).
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As to who will prevail in the nearer term, all appear confident. De Riedmatten says that he and his colleagues face some stiff challenges in extending their technology over greater distances. As he explains, they need to increase the number of modes from a few dozen at present to hundreds if not thousands, while also achieving high efficiencies and long coherence times. But he reckons they can span 500 km before the decade is out, which is one objective of the European Union’s €1 billion Quantum Flagship initiative. “There are clear paths to get there,” he says.

Hanson is also bullish, confident that solid-state repeaters can be realized on a similar timescale. He argues that the ability to scale up fabrication could allow many memories to be placed on a single chip—and thereby enable multiplexing from these single emitters. “Many researchers see such integrated quantum photonic chips as highly promising,” he says.

For Meschede—who has served as the spokesperson of a German quantum-repeater consortium for ten years, with plenty of opportunity to discuss different approaches—it is still too early to pick a winner. He thinks more research is needed to identify the technology most suited to real-world conditions. “It is not yet clear which is the best option,” he says.

One quite widely held view, in fact, is that different technologies could end up operating side-by-side. For example, says de Riedmatten, ensemble-based devices could serve as intermediate nodes while single emitters sit at the end nodes to provide processing power. In that case, he says, “we would combine the best of both worlds.”

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The appeal of one-way traffic

Standard quantum repeaters developed to date are first-generation devices that rely on heralding to overcome both channel loss and (eventually) errors at nodes. Second- and third-generation repeaters, in contrast, would employ quantum error correction, with second-generation devices using it to deal only with node errors and third-generation devices tackling both node errors and channel loss.

Analogous to error correction in some quantum computers, third-generation repeaters would encode a message qubit by entangling multiple photons together—preserving the qubit’s state over the long haul, even though many of the individual photons will get lost en route. Such devices would thus operate more like classical repeaters in optical communications networks, refreshing the data they receive and then passing them on, without wasting time waiting for messages sent back along the line.

The necessary multiphoton entangled states could be created using matter qubits with very short memories—far shorter than is needed for heralding. Those qubits could potentially come in the form of either vacancy centers in diamond or highly efficient quantum dots. However, the gates needed for error correction would require fidelities well beyond today’s technology.

A novel “all-photonic” alternative was put forward in 2015 by Hoi-Kwong Lo at the University of Toronto, Canada, and colleagues. This would do away with quantum memory altogether by using efficient single-photon sources to enact “time reversal,” which involves performing entanglement swapping before individual entanglement. Groups in Japan and China have since confirmed different aspects of the scheme experimentally—but, Lo says, those experiments used a tiny fraction of the photons needed for a practical repeater.

For references and resources, go online: optica.org/link/q-repeaters.
Article References and Resources