Quantum communication across a 250-kilometre optical-fibre network

Quantum communication over long distances can be achieved by exploiting a property of light called coherence. The coherence-based exchange of a 'quantum encryption key' over an optical telecommunications network demonstrates the feasibility of implementing a large-scale quantum network in existing telecommunications infrastructure.

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The problem

Coherence is the degree to which waves are in phase with each other and thus have the potential to interfere predictably. It underpins coherent quantum communications, in which interference between pulses of dim light reveals correlations between distinct quantum systems. These correlations can be used to extend the range of quantum communications[1] or to implement foundational functions of quantum networks, such as quantum teleportation and entanglement swapping[2,3].

The coherence of light waves deteriorates as they interact with the environment, however, making the practical use of coherent quantum communications over long distances challenging. Laboratory demonstrations that have showcased the benefits of optical coherence[2,3] have relied on complex set-ups, often requiring cryogenic cooling, limiting their practicality and scalability. These demanding requirements have raised doubts about whether coherence-based quantum communication can be implemented in a practical and scalable manner in real-world operational environments over existing networks.

The solution

For any networking solution to be practical, it must comply with the strict safety and infrastructure requirements of telecommunications data centres. To meet these demands, we developed a system architecture for coherence-based quantum communications that relies exclusively on semiconductor components, such as off-the-shelf semiconductor laser sources and avalanche photodetectors (sensitive light-detecting devices) that we then optimized.

Our system uses coherence to implement a secure quantum communications method called twin-field quantum key distribution (TF-QKD)[1]. In TF-QKD, two users each encode secret quantum information into the phase of dim light pulses and transmit them to a central station, which interferes the pulses and publicly announces the result. By combining this outcome with their private encoding choices, the transmitters can independently generate matching secure encryption keys that only they know, ensuring that the communication is provably secure over long distances. Our system's design incorporates practical solutions for distributing optical frequency references to distant locations through optical fibres, and it provides an innovative approach to maintaining optical coherence between pulses at the level of single photons without needing cryogenically cooled equipment. The system is portable, fits into standard 19-inch (0.48 metre) racks and meets the power and weight constraints required for real-world deployment.

We deployed our system across three data centres in Germany, spanning from Frankfurt to Kehl, that were connected by 254 kilometres of optical fibre (Fig. 1). We confirmed the destabilizing effects of such long fibre links on transmitted optical signals. However, through careful optimization, we successfully established and maintained coherence between the interfering signals using a precisely engineered phase-stabilization scheme that compensated for the fluctuations in phase induced by propagation. Once stable phase coherence was established, we successfully implemented the TF-QKD protocol, demonstrating for the first time (to our knowledge) a coherent quantum-communication protocol using existing telecommunications infrastructure, and achieving real-world, practical QKD over a long distance.

The implications

A key conclusion of our work is that coherent quantum-communication technology can be implemented in real-world settings and have useful applications. We used our system to demonstrate a QKD application for securing data communications, but coherence could enable a wide range of applications, including distributed quantum computing[4] and quantum sensor networks[5], which promise to unlock unprecedented computing power and measurement precision.

There is still much to do, however, to enable such applications. In quantum computing, for example, quantum processor units are often based on atoms or ions, the chemistry of which sets stringent demands on the wavelength of light used to interact with them. They typically require near-visible wavelengths, which travel for only a short distance along standard telecommunications fibre, highlighting the need for wavelength conversion or other advances.

We are excited about the opportunities that this result creates, and look forward to exploring innovative quantum applications that use long-range phase stabilization, as well as applying the technology to other telecommunications networks across the world.

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EXPERT OPINION

"The manuscript presents a groundbreaking quantum key distribution (QKD) implementation over Germany's 254-km commercial telecom network. The work represents a substantial advance in QKD technology, doubling the practical communication distance compared with previous implementations. The integration of coherent quantum communications into existing telecommunications infrastructure is novel, and this research makes strides towards the real-world deployment of quantum networks, by aligning quantum-communication requirements with current telecom capabilities."

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FIGURE

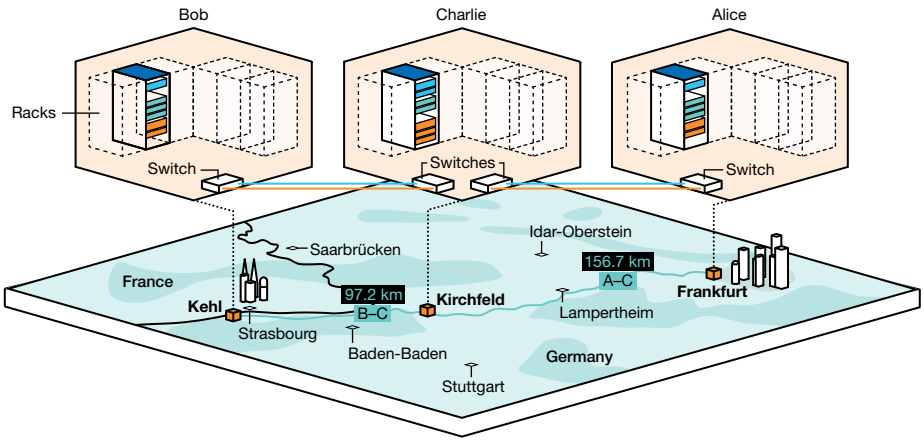

Figure 1 | Schematic of the quantum-communication system deployed across an existing telecommunications network in Germany. The map shows the locations of three data centres (Kehl, Kirchfeld and Frankfurt) connected by standard telecommunications optical fibre. The overlaid schematic shows the deployed quantum-communication system, housed in standard data-centre racks and operating alongside conventional telecommunications equipment. Despite uncontrolled thermal and mechanical disturbances in the fibre links, the system actively stabilized the phase of the light to enable a quantum protocol called twin-field quantum key distribution (TF-QKD). In this protocol, the users, known as Alice and Bob, send phase-encoded pulses of dim light to a central node, Charlie, who measures their interference. This process allows Alice and Bob to generate identical, inherently secure cryptographic keys, enabling long-distance quantum-secure communication beyond the reach of conventional QKD methods.

BEHIND THE PAPER

After years of preparation and meticulous testing in our Cambridge laboratory, deploying the system in Germany was both thrilling and nerve-wracking. No matter how much you prepare, the first real-world deployment of new technology always brings surprises. After installation, the equipment checks and preliminary tests went smoothly. But when we ran the protocol, one of the quantum links simply did not work. We spent hours troubleshooting, testing every possible failure mode, and confirmed that everything should have been working. We tested the last and, in our view, most unlikely hypothesis: that the problem was not with our system, but with the optical-fibre link. It had been checked just weeks before but, sure enough, since then, it had been cut. Relief set in, because it wasn't a fundamental flaw in our approach. Once the fibre was repaired, everything clicked into place, and we were finally able to demonstrate the validity of our method.

M.P.

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FROM THE EDITOR

Developments towards real-world, practical quantum key distribution typically require expensive, highly sophisticated, bespoke laboratory equipment, which is particularly challenging for most modern protocols. We felt that, by presenting an important step towards an affordable solution to this challenge, this paper has the potential to have an impact on the future development of the field.

Federico Levi, Deputy Editor, *Nature*