From Einstein's Gedankenexperiment to research on quantum networks

White paper

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Entanglement and teleportation explained — how quantum physics provides new opportunities for realizing quantum networks and enhancing network security, and the research challenges Nokia Bell Labs is overcoming to realize this goal.

Acknowledgement: A special thank you to my colleagues Rene Essiambre, Ayed Sayem, Tzu-Yung Huang, Jeremie Renaudier, Amir Ghazisaeidi, and Ludovic Noirie for insightful discussions, input about their research and review of the paper.

Contents

Introduction

The present paper explains how the concept of quantum entanglement can be used to transfer a quantum state across a future quantum network to realize end-to-end quantum security, distributed quantum computing and distributed sensing. Previous articles by Nokia Bell Labs have discussed how quantum physics is reshaping the fundamentals of communication [1] and established more realistic expectations for quantum internet [2].

In order to grasp the spooky capabilities of quantum technology, we will start with a short history of experimental quantum mechanics, beginning with the Gedankenexperiment of Albert Einstein in 1935 and concluding with the first experimental realization of quantum entanglement by Alain Aspect in 1982.

This paper will then elaborate on how entanglement can be used to transfer a quantum state across a link and even a network. This transfer is sometimes called quantum teleportation, though it has nothing to do with the means of transportation known from the popular science fiction series Star Trek. The fundamental principle of quantum entanglement provides a means to detect eavesdropping over a communications channel. Hence quantum key distribution (QKD) is one of the first expected applications of a future quantum network. Other applications are the interconnection of quantum computers to scale up quantum compute capacity and distributed quantum sensing. We will discuss these potential applications in the latter sections of the paper.

The research on quantum networks is still in its infancy. The paper thus concludes with the research challenges we are overcoming and the building blocks we are exploring at Nokia Bell Labs.

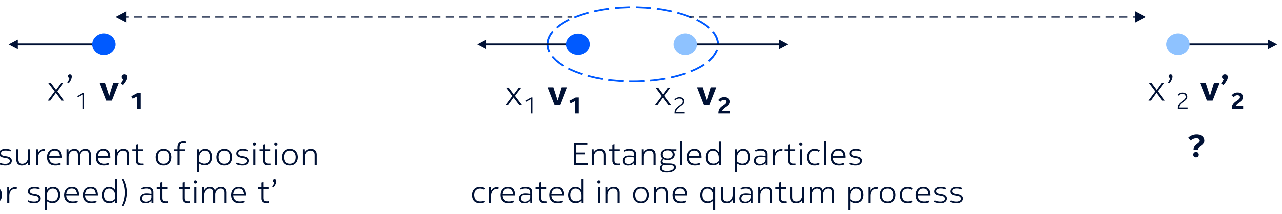
From Einstein’s thought experiment to Alain Aspect’s experimental proof

It is well known that Albert Einstein struggled to accept the weird uncertainty of quantum mechanics and the idea that quantum theory could not predict the outcome of an experiment in a deterministic manner. He famously said, “God didn’t play with dice.” He and Niels Bohr would have endless debates on whether the quantum state is unknown until an experiment is performed (Bohr’s view) or the state is already determined and there is a yet-to-be-discovered theory that could explain the statistical observations (Einstein’s view). To support their views, they would argue by proposing Gedankenexperimente, or thought experiments.

One of the later thought experiments developed by Einstein with Boris Podolsky and Nathan Rosen in 1935 was pivotal for the concept of quantum entanglement and the notion of spooky action at a distance that we are trying to exploit for future quantum networks. It is often referred to as EPR for the initials of the authors of the related paper [3].

Figure 1 briefly explains the idea. Assume two particles are created in the same quantum process and therefore their quantum states are entangled. After a certain time, the particles respectively move to position x'_1 with speed v'_1 and position x'_2 with speed v'_2. According to Heisenberg’s uncertainty principle, there is a fundamental limit to the accuracy of the position and speed, and an experiment trades off high precision of position measurement for lower precision of speed or vice versa.

Figure 1. EPR Thought experiment showing how a measurement on particle 1 at the left side influences the state of particle 2 on the right side (“spooky action at a distance”).

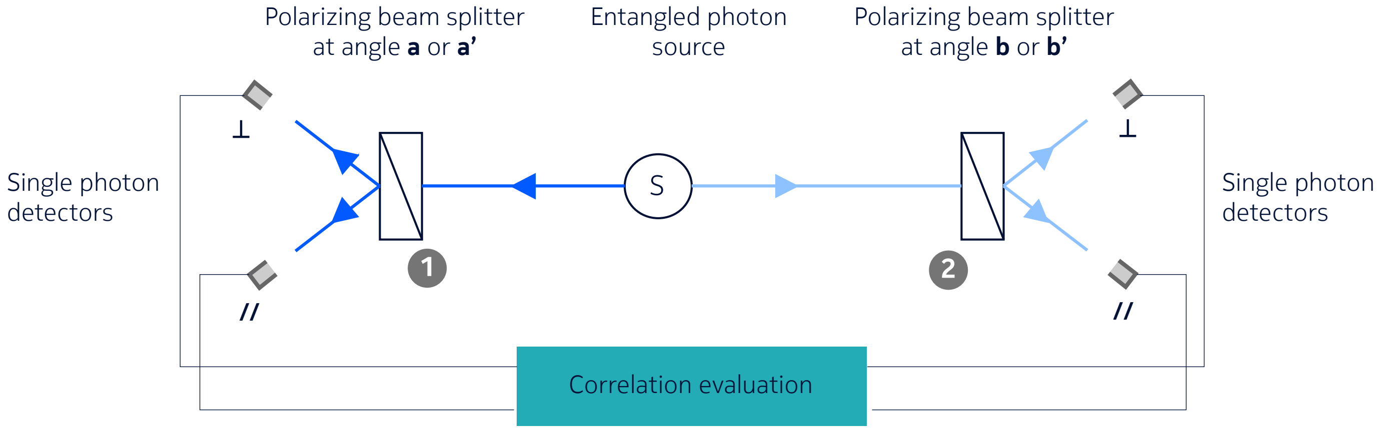


An experiment on particle 1 will yield a particular measured value for position x'_1 (and because of the quantum uncertainty, this value may be different for each subsequent measurement with a statistical distribution). With the outcome of one experiment for particle 1, it is possible to exactly calculate the respective position of particle 2, because they were created in the same quantum process and there is conservation of momentum. The experiment in one location hence instantaneously determines the outcome in the other location, faster than the speed of light, which can appear as a violation of the causality principle in Einstein’s relativity theory.

Einstein believed that the outcome of a physical experiment must be entirely determined by local conditions and with 100% predictability. Einstein argued that quantum mechanics is incomplete because the position of particle 2 cannot be predicted by the theory in a deterministic way (there is the uncertainty of particle 1) and is non-local (the outcome of 2 is determined by the measurement of 1). According to Einstein, there must be another theory, yet to be discovered, that explains this “spooky action at a distance”. The particles would carry so-called hidden variables determined at the time of creation, which would explain the behavior in a predictable manner. The scientific community paid little attention to the EPR paradox, because there was so much experimental evidence that validated quantum theory. Bohr’s reaction to EPR was that quantum physics is uncertain, probabilistic in nature and non-local — just accept it.

A few scientists remained intrigued by the EPR paradox and came up with simplified variants of the thought experiment that ultimately resulted in realizable experiments. In 1951, David Bohm reduced the problem to a thought experiment of entangled particles that have two discrete states (spin up and spin down), and he even formulated a hidden-variable theory for it. This inspired John Bell to come up with a mathematical proof called Bell’s Theorem. According to Bell, if hidden variables exist for a process of entangled particles with two possible states, the statistical distribution of independent measurements must show an inequality, which came to be known as the Bell Inequality [4]. If on the other hand, an experiment shows a violation of the Bell Inequality, it would mean that there are no hidden variables and quantum processes can be non-local. In 1969, John Clauser (together with Michael Horne, Abner Shimony and Richard Holt) reformulated the Bell Inequality for entangled photons with two possible polarization states [5]. It became possible to actually test the EPR thought experiment and put an end to the Einstein-Bohr debate!

Figure 2. Setup to evaluate Bell Inequality by monitoring the polarization at two entangled photons.



Alain Aspect took up the challenge and built on Clauser's work using the setup in Figure 2. It involves an entangled photon source S and two polarizing beam splitters that separate light into two orthogonal polarizations [6].

It is worthwhile explaining this in a bit more detail because it helps to develop an intuitive understanding of how future quantum networks could work. Figure 3 shows a few simple possible configurations:

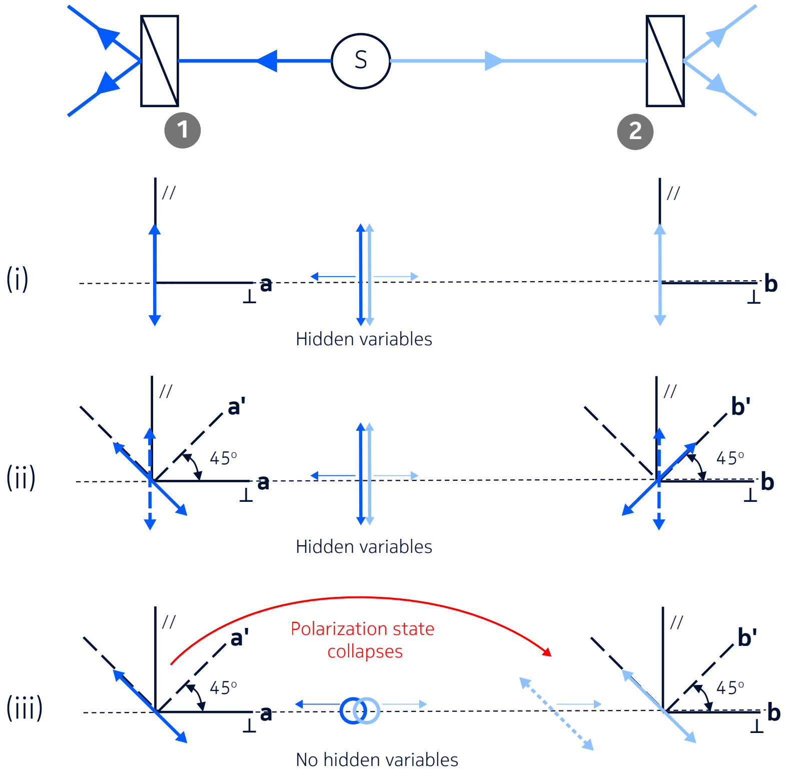
(i) Assume that the hidden variable theory is true (Einstein's view) and the two photons have a polarization at the time of creation that is parallel to one direction of the polarizing beam splitters in location 1 and 2. The detectors on either side will measure a perfect correlation of 100%.

(ii) The second configuration still assumes hidden variables that describe both photons with a parallel polarization, but the polarizing beam splitters are each at an angle of 45° with the polarization of the photons. The photons now have an equal 50% probability of exiting either polarization behind the beam splitter (in a classical approach, 50% of a light beam intensity passes a polarizer at 45°). The two photons in location 1 and 2 may not exit the same polarization and the statistical correlation of a measurement series will be less than 100%. This suggests the existence of an inequality for hidden variables that Bell formulated in a more generic way.

(iii) The third drawing shows what happens if the state is undetermined at the time of creation (Bohr's view) and there are no hidden variables. The polarization state is then determined when one of the two photons encounters a polarizing beam splitter. Due to the entanglement, the other photon collapses to exactly the same polarization state (spooky action at a distance). The outcome of repeated experiments will always show perfect correlation and there is no inequality.

A way to understand this spooky action at a distance is to see both entangled photons as part of the same quantum wave function. The wave collapses the very moment an experiment is conducted at the first photon, which immediately renders the wave function to a particular state that influences the second photon.

Figure 3. Example states of entangled photons assuming the polarization state is determined by hidden variables at the time of creation (i) and (ii), or there are no hidden variables (iii).



The actual experiment to establish or rule out the existence of hidden variables is more general than the configurations of Figure 3. If there are hidden variables, the polarization state at time of creation is not necessarily at equal angles with the polarizing beam splitters and can randomly vary over a range of 180°. Furthermore, the angle of the polarizing beam splitters must be switched randomly between a and a’ in location 1 and between b and b’ in location 2 (Figure 3). The switching of these two beam angles must be done independently from one other and — most importantly — at a time after the entangled photons are created to avoid any possibility that the orientation of the polarizing beam splitters could influence the outcome of the experiment. The mathematical formulation of the general case of Bell Inequality for photons was developed by Clauser et al. but is beyond the scope of this paper [5].

Aspect was the first to successfully conduct the full experiment and show that Bell Inequality is violated in 1982. It proved that there are no hidden variables and that quantum mechanics is probabilistic and non-local. His experiment settled the debate between Einstein and Bohr in favor of the latter, though neither of them lived long enough to know the outcome. Aspect demonstrated entanglement for photons propagating in free space over short distances. Anton Zeilinger demonstrated photon entanglement over much longer distances on fiber in 1997. Clauser, Aspect and Zeilinger were rewarded with a shared Nobel Prize in 2022. But I would argue, much of the credit should go to Einstein who fully understood the consequences of quantum mechanics better and earlier than anybody else — he just had difficulty accepting them. His continuous questioning helped to advance the understanding and are at the root of quantum entanglement that are now opening new opportunities for quantum computing and quantum networks.

A new way to communicate information

The experiment of photon entanglement suggests a new way to communicate information. It raises two intriguing questions:

(1) Is it possible to use spooky action at a distance to convey information faster than the speed of light?

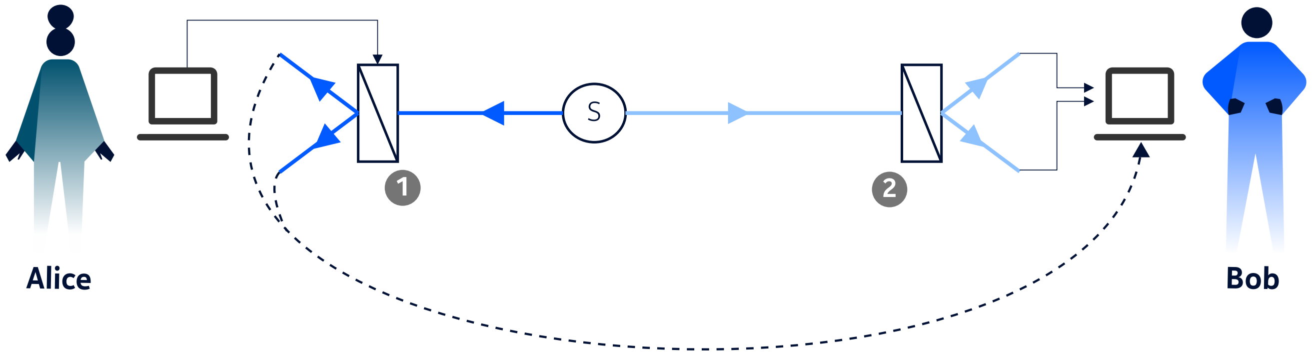
(2) Does this approach allow for increasing transmission capacity beyond the Shannon Limit?

The current view is that the answer to both questions is no, as explained in Figure 4. Using a pair of entangled photons sent to Alice and Bob, Alice can switch the angle of the polarizing beam splitter (PBS) by 45° at her end to influence the polarization state of the second photon traveling to Bob. As already explained in Figure 3 (iii), this happens instantaneously, faster than the speed of light. There is, however, no utility at this stage for Bob, because the changes still appear random to him. Only when Alice sends her measurement of the polarization stage through a classical channel at the speed of light or slower will Bob know how to observe the polarization state at his end and determine what information Alice has coded by switching the PBS at her end. The output of the two detectors at Alice and the two detectors at Bob jointly define the so-called Bell State, i.e., one of four possibilities that the photon pair is entangled (not to be confused with Bell Inequality explained earlier).

Figure 4. Concept of how quantum entanglement can be used to transmit information, but not faster than the speed of light.

Alice can instantaneously change polarization of entangle photon at Bob’s site by switching angle PBS **a** to **a’**.

Bob cannot detect these instantaneous changes solely by himself. They will appear as random changes.



Bob can find out after comparing with Alice’s results communicated via a classical channel at speed of light.
Causality is not violated.

As there is a superposition of two possible quantum states, people have speculated that it may be possible to double the channel capacity and break the Shannon Limit. However, one needs an additional bit to convey the measurement at Alice’s side to Bob, which offsets the gain.

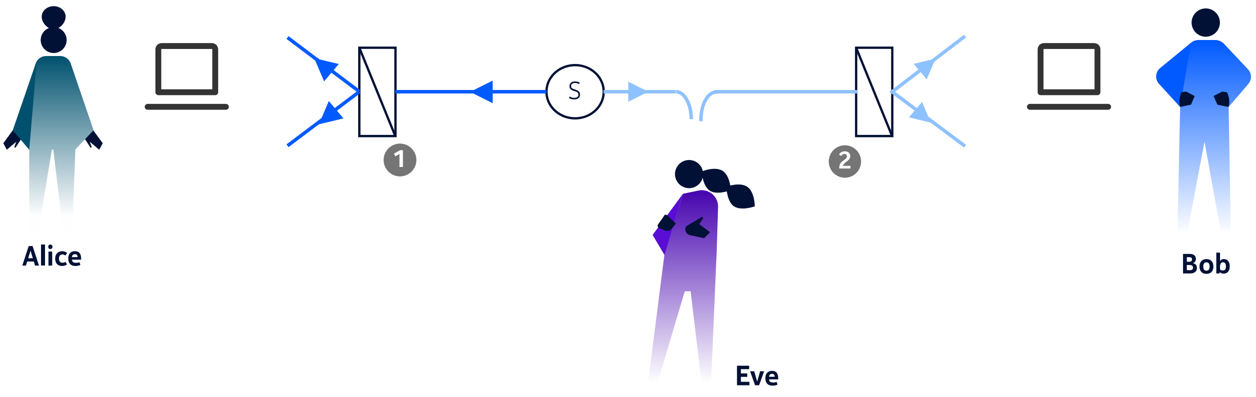
If all benefits are canceled out, why is quantum networking still of interest? We will try to answer this in the next sections.

Quantum key distribution

An important application for transmitting information using quantum entanglement is secure quantum key distribution (QKD) as shown in Figure 5. Here we see, eavesdropper Eve intercepting the message that Alice is sending to Bob. Eve then reproduces the information and passes it on to Bob so that the interception goes unnoticed. This trick is possible in a classical, but not over a quantum channel. The quantum entangled state of the photons collapses because Eve intervenes. It is fundamentally impossible for Eve to copy or clone a quantum state. Furthermore, Alice and Bob are able to observe that Eve has broken the quantum entanglement during the transmission of information (e.g., by evaluating the Bell Inequality described in previous section). The process is not useful for the secure transfer of data itself because secret information would already have reached Eve and the process would be too slow. But it can be used to exchange encryption keys.

Using polarization encoding, Alice can send an encryption key to Bob. If they observe that entanglement is maintained, they can trust the exchanged key and then use this key to encrypt data on a classical high-speed channel. If they notice that entanglement is lost because Eve tried to eavesdrop, they will discard the key information and attempt to send another key. By updating quantum keys at regular intervals, hackers are unable to collect enough data to discover the active encryption key before it is replaced. There are various protocols for quantum key exchange. The first was invented by Charles Bennett and Giles Brassard in 1984 (hence known as BB84) [7]. They also developed an improved protocol together with David Mermin in 1992 (BBM92) [8]. Bennett and Brassard received the Turing Award in 2026.

Figure 5. How quantum entanglement can be used to detect an eavesdropper.



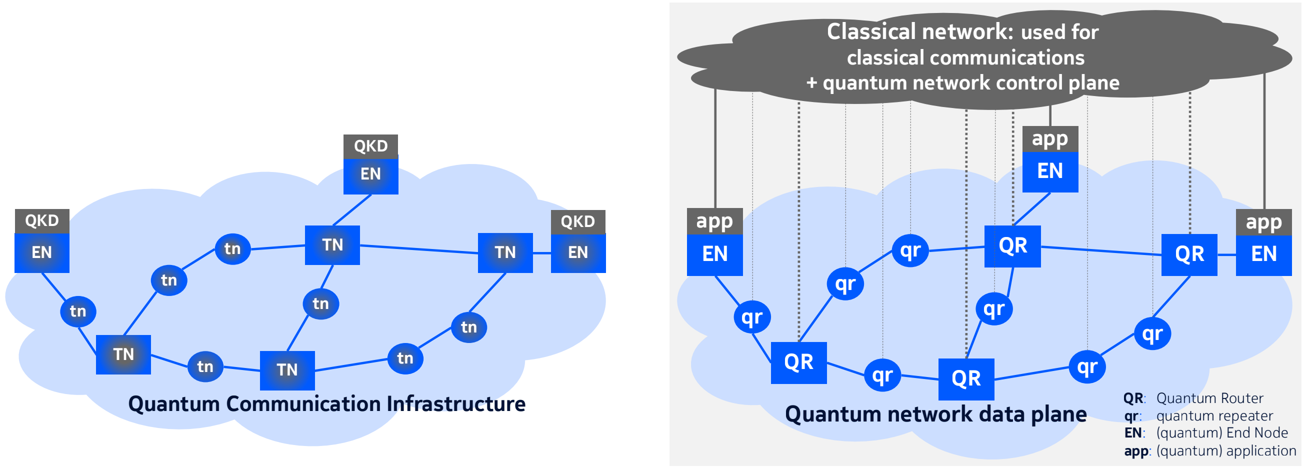
A challenge with the use of the polarization of a photon to transfer a quantum state in fiber is the need to maintain polarization in the fiber. As an alternative, so-called time-bin qubits, which use two coherent quantum states separated in time, are more robust against perturbations in the fiber than polarizations [9].

Another important family of protocols is continuous-variable quantum key distribution (CV-QKD), introduced by Frederic Grosshans and Philippe Grangier (GG02), who showed that quantum key distribution can be realized with coherent states and continuous measurements [10]. Instead of encoding the key in discrete properties such as the polarization of single photons, Alice encodes random values in the continuous amplitude and phase quadratures of weak coherent light pulses, and Bob recovers this information using homodyne or heterodyne detection. CV-QKD is attractive because it can be implemented with standard telecom components, such as commercial lasers and coherent receivers.

QKD is commercially available, and Nokia already provides quantum safe solutions in its portfolio [11]. Many of these solutions are used for secure fiber-optic transmission of information by banks and governments. Note that these terrestrial solutions only work on a single fiber link typically up to 100 km. Any repeater on the link will disturb the entanglement in the same way as Eve. Furthermore, the probability of losing entangled photons increases with distance due to photon scattering or absorption caused by imperfections or impurities in the fiber (they are the same attenuation mechanisms seen in classical optical communications).

One approach to achieve secure communication over wider areas is to perform quantum key exchange on an optical link via satellite. The satellite is used as a trusted repeater node for the quantum key exchange, while the terrestrial network is then used for the transmission of the encrypted data [13]. Another approach is a quantum communication infrastructure as shown in Figure 6 (a) (e.g., EuroQCI [12]). It relies on QKD between end nodes (EN) and trusted nodes (TN). The reliance on trusted nodes, however, is a security weakness.

Figure 6. (a) Quantum communication infrastructure with trusted nodes (TN) and
(b) quantum network with quantum repeaters (qr) and quantum routers (QR).



(a)

(b)

Quantum networks

The architecture shown in Figure 6 (b) is what we envision for quantum networks in the future. Quantum repeaters (and even quantum routers) would relay quantum states, allowing for quantum key exchange between end nodes without the security weaknesses of trusted nodes. In addition to the quantum repeaters at the physical layer there is a classical network in the control plane to convey the bits that define the Bell State of the pairs of entangled photons in each link. There are still many open research challenges before practical quantum networks will become a reality. Some people call this the quantum internet [14], but it is important to note that it will not replace the classical Internet [2]. Once QKD is achieved via a quantum network, encrypted data is transferred via a classical network in a much more efficient way than a quantum network ever could.

QKD is the most immediate use case for quantum networks, but there are potentially others. Further out in the future, quantum networks could be used to interconnect quantum computers and quantum sensing.

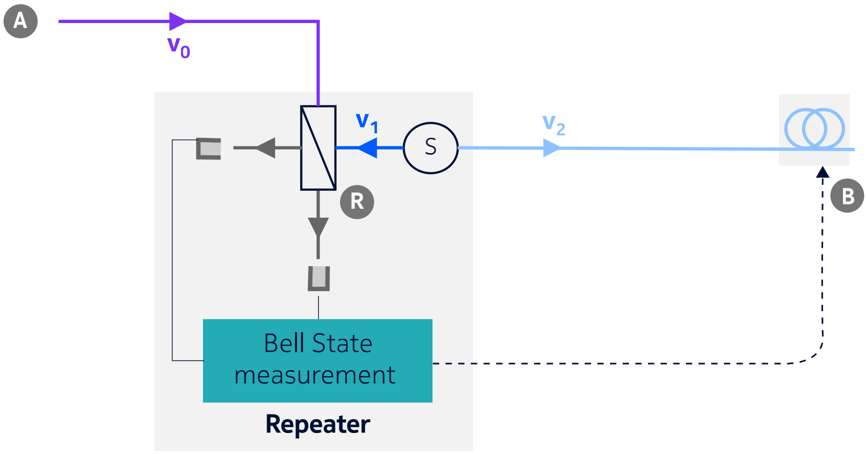
Quantum networks can be used to increase the capacity of a quantum computer to overcome the scaling limitations of some qubit concepts because of the ability to maintain quantum coherence between distributed quantum-computer elements. This will be more likely for a local cluster of quantum computers inside a data center, but possibly — in a very advanced stage — for distributed quantum computing across centers. A quantum network can also interconnect and maintain entanglement between distributed quantum sensors, enhancing their sensitivity beyond what is possible for sensors connected in a classical way (e.g., [17]).

Quantum teleportation: transferring a quantum state through a network repeater

Quantum repeaters are an essential building block of quantum networks. They rely on the concept of entanglement swapping, also known by the more intriguing name “quantum teleportation”. It is fundamentally impossible to clone or copy a quantum state [16]. Hence it isn’t possible to capture a quantum state on one side of a repeater and regenerate it at the other side like we would in a classical repeater implementation. Figure 7 explains how a quantum state can be transferred (swapped, teleported) from photon v_0 on the link from node A of the repeater R to photon v_2 on the link to node B. It is demonstrated here with polarization states, but similar reasoning can be applied for other photon states like the more practical time-bin qubits.

At the repeater R, source S generates two entangled photons, v_1 and v_2. Photons v_0 and v_1 then interact while simultaneously passing through the polarizing beam splitter before hitting one of the two detectors. Because of the measurement, the original states of photons v_0 and v_1 are lost (or altered). In the process the state of v_0 is transferred to v_2. There are four possible outcomes: two photons in the first detector, two photons in the second detector and two outcomes with one photon in each detector. These detector outcomes determine the Bell State that is transmitted via a 2-bit signal to node B. The Bell State determines the basis of how the quantum state of photon v_2 must be observed at B so that it is the same state as the original state of v_0. Quantum memory at B is needed to hold photon v_2 until the 2-bit signal with the Bell State arrives via a classical channel (the memory is shown as a fiber spool, but it can be any quantum memory concept).

Figure 7. Quantum repeater that teleports the quantum state from photon v_0 to photon v_2.



It is important to note that the repeater is not determining the actual state of photon v_0 itself. Therefore, the repeater is not a mechanism that an eavesdropper could use to intercept quantum information. The quantum state is merely transferred/teleported to another photon. The concept was first proposed by Bennet, Brassard et al. in 1993 [18], and it was first realized by Zeilinger [19] and independently verified by Sandu Popescu in 1997 [20].

The term teleportation should not be confused with the popular concept from science fiction. There is no transfer of matter, nor a reconstruction of a complex body of many molecules. Quantum teleportation is merely the transfer of a quantum state from one particle to another identical particle.

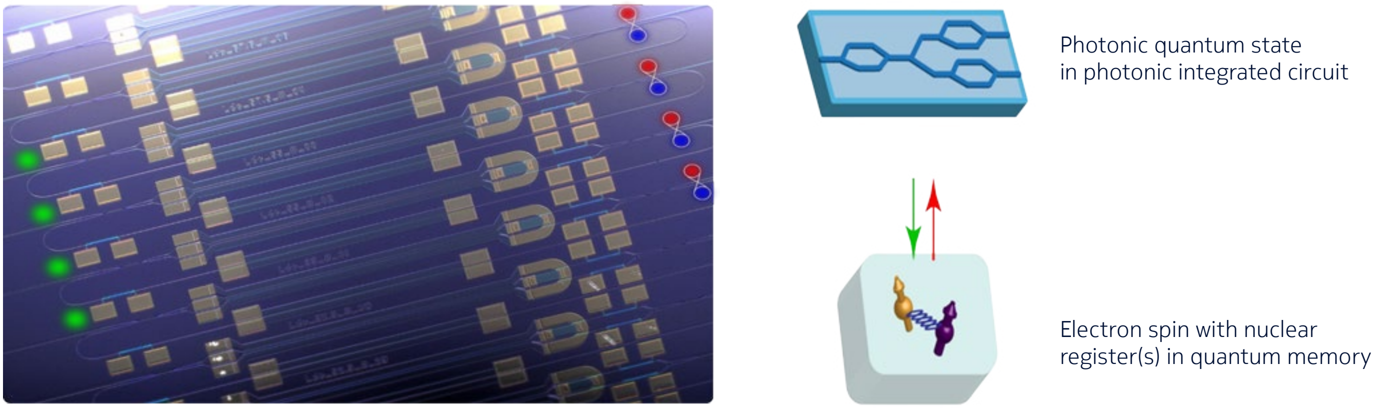
Exploration research on future quantum networks

The actualization of quantum networks still requires research to overcome many unsolved challenges, most importantly the realization of a quantum repeater as shown in Figure 7. The following research problems include building blocks of a quantum repeater, network system concepts and possible applications:

1. **Entangled-photon source:** The entangled photon source that Aspect used is not realistic for future deployments. At Nokia Bell Labs, we are leveraging our experience with Thin Film Lithium Niobate / Tantalate (TFLN/TFLT) and other materials used for high-speed optical modulators. We exploit their non-linearity to efficiently generate entangled photon pairs in a scalable manner.

   (For the specialists: we use the high second-order and third-order linearity to generate entangled photons through three-wave mixing and four-wave mixing processes, respectively [21]. The devices offer stable and high-speed tuning of generated photons along with the ability to create entangled photon pairs at vastly different wavelengths, such as one photon at ~980nm (suited for quantum memory wavelength) and the other at ~1550nm suited for low-loss transmission on optical fibers in long-distance quantum networks.)

Figure 8. (a) Optical microscope image of TFLT based photonic chip for entangled photon pair generation realized at Nokia Bell Labs. (b) Concept of quantum memory (bottom) coupled with optical quantum state in a photonic quantum function (top).



(a)

(b)

2. **Quantum memory:** Various research groups have demonstrated quantum memory operation using optically interfaced solid-state spins [22]. Their spin-photon interface enables the transfer of information in photon states to and from electron and nuclear spin states, forming the basis of operation for quantum network repeaters as well as quantum memories in distributed quantum computing and sensing. At Nokia Bell Labs, we have built on our photonic integration and electronic integrated circuit expertise to integrate such quantum memories with on-chip entangled photon sources, optical modulators, lasers, detectors and microwave signal generators. The on-chip optical components facilitate the initialization and readout of the quantum memory while microwave and radio-frequency pulses at specific frequencies and intervals perform “write” operations [23].
3. **Single-photon detector:** Different types of single-photon detectors are commercially available, like single-photon avalanche photon detectors (SPADs) (similar to Geiger counters but for photons) and superconducting-nanowire single-photon detectors (SNSPDs) [24]. Our research explores how they can efficiently be integrated on a device with other quantum functions. In quantum experiments, they are mostly cooled to 4 K with liquid helium to achieve high detection efficiency. It is not subject of current research at Nokia Bell Labs, but there is an additional need for single photon detectors that can efficiently operate at higher temperature than 4 K, ideally at room temperature, so that quantum repeaters can be practically deployed in a network. It is worth noting that a retina cell in a human eye functions as a single photon detector, which can serve as inspiration for the direction of this research.
4. **Physical-layer system:** We study the transport of quantum states over large distances, which is a challenge for optical networks because of channel attenuation and decoherence from various sources of noise present in the channel. The two main ways to distribute quantum information are through optical fibers and through free space, the latter mainly through satellites. Quantum technologies can also be used to extend the reach of classical data transmission, achieving record low power levels such that 14.5 bits can be reliably detected per photon received [26].

   (For the specialists: Transmission over optical fibers introduces decoherence from Raman noise due to vibrational modes present in the material and rapid polarization and phase fluctuations. In free space, loss occurs due to beam diffraction and background noise from the Sun or other ambient light sources. Distribution of entangled photons and the performance of quantum teleportation to link quantum processors or computers become an important challenge under these conditions. Choosing the type of quantum degree of freedom — like polarization, time-bin, spatial mode, etc. — that is best suited for each medium and developing stabilization techniques is critical.)
5. **Quantum cryptography:** For practical deployment of quantum-safe networks, especially for metropolitan and short-to-medium-distance network links, we are investigating the continuous variable QKD approach as a promising route toward cost-effective and scalable deployment of quantum key exchange. As mentioned in the section on QKD, the benefit of CV-QKD is that it can be realized with commercial lasers and coherent receivers. Leveraging coherent technologies, it can offer high secret-key rates over short-to-medium fiber distances [25].
6. **Quantum network stack:** We are researching the control and system aspects of a future quantum network, such as the quantum repeater and router protocols that take care of the Bell State distribution between any pair of nodes in the network, as well as the system architecture of such quantum nodes. While waiting for a functional physical layer, we are testing our concepts on an in-house quantum network simulator, using an abstract model of the quantum physical behavior of the hardware and a realistic model of our designed protocols, taking into account network delays for message exchanges [27].

7. **Quantum network applications:** Beyond QKD, future quantum networks will enable other applications such as distributed quantum computing, blind quantum computing, quantum-enhanced measurement networks [14], which are distributed quantum algorithms running on top of them. In collaboration with academic partners, we are researching new applications for quantum networks with new quantum advantages, and we are studying how to implement them in the quantum networks we design [27].

It has been a long journey since the EPR thought experiment of Einstein and the first real experiments of quantum entanglement. A lot of research is still required before we see the first practical quantum networks in the next decade. We expect the first application to be QKD. Other possible applications are interconnected quantum computers to scale their capacity and distributed sensing to enhance precision of combined quantum sensors.

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Document code: (April) CID215397