Towards large-scale quantum networks

Kozlowski, Wojciech; Wehner, Stephanie

DOI
10.1145/3345312.3345497

Publication date
2019

Document Version
Final published version

Published in
Proceedings of the 6th ACM International Conference on Nanoscale Computing and Communication, NANOCOM 2019

Citation (APA)
Kozlowski, W., & Wehner, S. (2019). Towards large-scale quantum networks. In C. Contag, & T. Melodia (Eds.), *Proceedings of the 6th ACM International Conference on Nanoscale Computing and Communication, NANOCOM 2019* Article 3345497 (Proceedings of the 6th ACM International Conference on Nanoscale Computing and Communication, NANOCOM 2019). Association for Computing Machinery (ACM). https://doi.org/10.1145/3345312.3345497

Towards Large-Scale Quantum Networks

Wojciech Kozlowski
w.kozlowski@tudelft.nl
QuTech, Delft University of Technology
Delft, Netherlands

Stephanie Wehner
s.d.c.wehner@tudelft.nl
QuTech, Delft University of Technology
Delft, Netherlands

ABSTRACT

The vision of a quantum internet is to fundamentally enhance Internet technology by enabling quantum communication between any two points on Earth. While the first realisations of small scale quantum networks are expected in the near future, scaling such networks presents immense challenges to physics, computer science and engineering. Here, we provide a gentle introduction to quantum networking targeted at computer scientists, and survey the state of the art. We proceed to discuss key challenges for computer science in order to make such networks a reality.

CCS CONCEPTS

• **Networks → Network architectures**; **Network protocols**; **Network components**; • **Computer systems organization → Quantum computing**.

KEYWORDS

networks, quantum networks, quantum internet, network protocols, quantum communications, quantum computing

ACM Reference Format:
Wojciech Kozlowski and Stephanie Wehner. 2019. Towards Large-Scale Quantum Networks. In *The Sixth Annual ACM International Conference on Nanoscale Computing and Communication (NANOCOM '19), September 25–27, 2019, Dublin, Ireland.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3345312.3345497

1 INTRODUCTION

The objective of quantum networks is to fundamentally enhance communication technology by allowing the transmission and manipulation of quantum bits (qubits) between remote locations. Such networks will be embedded within classical networks as shown in Fig. 1 and applications will have access to both quantum and classical channels. Quantum networks will be used to execute protocols that have no classical counterpart or are more efficient than what is possible classically. The range of possible quantum applications will depend on the development stage of the underlying hardware hardware [67]. This new networking paradigm has already opened up a range of new applications, which are provably impossible to realise using classical communication over the internet that we have today. Quantum key distribution (QKD) [2, 19] to ensure secure communication is the most famous example as it is also the only application that is ready for commercialisation and is undergoing standardisation. Whilst QKD will be the main focus for most near-term quantum networks, many other applications have already been put forward, with many more to be expected when such networks become widespread such as secure quantum computing in the cloud [10, 21], clock synchronisation [34], and sensor networks [22, 23].

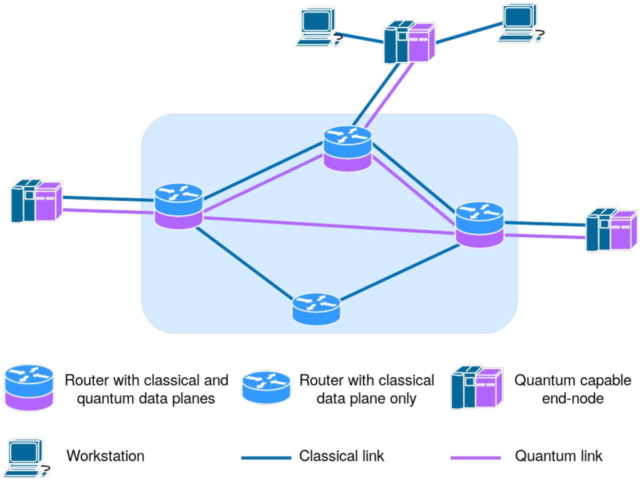


Figure 1: Quantum networks will be embedded within classical networks and use existing infrastructure to send and receive control messages. This can be achieved by adding a quantum data plane to existing networks. Note that the quantum and classical links do not have to coincide.

Using features of quantum mechanics as the underlying physical mechanism for communication opens up many new possibilities, but also introduces considerable new design challenges. Some of these design challenges are due to fundamental differences between quantum and classical information, while others arise from technological limitations in engineering large-scale quantum systems. The first fundamental difference that quantum communication brings with it is the no-cloning theorem [43]. That is, arbitrary quantum data cannot be copied without destroying the original version. This means that it is impossible to use the same solutions that worked for classical networks which rely heavily on the ability to read and copy data for the purposes of retransmission and signal amplification. These limitations make transmitting qubits over long distances particularly challenging. The second fundamental difference arises due to a phenomenon called quantum entanglement. Entanglement is a special state of two or more qubits, that can in principle persist even if they are separated by arbitrary geographical distances and

---

NANOCOM '19, September 25–27, 2019, Dublin, Ireland

ACM ISBN 978-1-4503-6897-1/19/09…$15.00
https://doi.org/10.1145/3345312.3345497

it is the key ingredient that enables long distance quantum communication. This property exists at the physical level and it requires that the location and state of its constituent qubits be known at all times. This is in contrast to classical communication, where signals at the physical layer typically proceed from the sender to the receiver and no state or notion of a connection exists. This introduces new demands for the control of such networks, as quantum data is inherently delocalised across multiple devices.

Design considerations that come from technological and not just fundamental limitations form an integral part of quantum network development and a key issue when considering realistic deployments. The technological challenges are immense, and include — for example — storing qubits for a long time or manipulating a large number of qubits simultaneously.

The remainder of this paper is structured as follows: Section 2 briefly surveys the current state of the art of quantum networked technologies and in Section 3 we give a basic introduction to the quantum physics of such networks. In Sections 4 and 5 we discuss the elements of a quantum network and a possible network stack respectively. Future research challenges are presented in Section 6 and the paper is concluded in 7.

2 STATE OF THE ART

At present, no large-scale quantum networks exist. At short distances (~100 km in telecom fibre), devices that perform QKD are commercially available [16, 20, 22, 32]. Early-stage demonstrations also achieve longer distances in the lab using coiled fibre [5, 29, 39, 57, 66, 72], or through free space communication [54, 61]. QKD devices have been deployed in a variety of field tests and short-distance networks [47, 52, 56, 65].

While no long-distance quantum networks exist, short distance segments have been chained together classically to form so-called trusted repeater or trusted node networks [50, 53]. Such networks do not allow the end to end transmission of qubits, or the generation of entanglement and hence do not offer end-to-end security. They only enable secure communication between two end-points, provided that all the intermediate nodes are trusted. Such links of trusted nodes have been realised [14, 52], but require a high level of physical security to protect the trusted nodes. Such devices only produce short-lived (entanglement is not stored), short-distance entanglement and lack any of the features needed to bridge longer distances.

Long-range quantum communication, as well as the realisations of networks with functionalities more advanced than QKD, are presently still in their infancy. Entanglement between distant sites (~1200 km) has been produced using a satellite [68]. However, data rates (~1 hz for 275 s per day) are still too low to produce a secret key, and the entanglement is short-lived. The present record for producing heralded entanglement between distant sites is 1.3 km in a solid state quantum device (nitrogen-vacancy (NV) centres in diamond) [28]. Longer distances have been observed for nodes in the same lab [70]. Demonstrations of more complex applications such as blind quantum computing [1] and quantum sensing [24] have also been realised in laboratory conditions.

Going forward, we would like to improve early-stage quantum communication in three directions. First, we would like to enable untrusted long-distance communication. Second, we would also like to enable the execution of more complex quantum network applications in order to take full advantage of our ability to transmit qubits. And finally, we would like to improve accessibility by allowing early stage access to such technology. The first realisation of such a network, a four-node demonstration in the Netherlands, is scheduled to be operational within the next 5–6 years. Much essential work is being done to build quantum hardware to make this possible, which is covered at length in the physics literature [41, 51, 67].

3 QUBITS AND ENTANGLEMENT

This subsection will briefly introduce the basic concepts of quantum computing and networking: qubits, quantum gates, and entanglement. For additional information see e.g. [43].

3.1 Qubits

The differences between quantum computation and classical computation begin at the bit-level. A classical computer operates on the binary alphabet $\{0, 1\}$. Mathematically, a quantum bit, a qubit, exists over the same binary space, but unlike the classical bit, it can exist in a so-called superposition of the two possibilities:

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{1}$$

where $|X\rangle$ denotes a quantum state, here the binary 0 and 1, and the coefficients α and β are complex numbers called probability amplitudes satisfying $|\alpha|^2 + |\beta|^2 = 1$.

Upon measurement[1], the qubit loses its superposition and irreversibly collapses into one of the two basis states, either $|0\rangle$ or $|1\rangle$, and yields the corresponding value, 0 or 1, as the measurement readout. The outcome of the measurement is not deterministic, and the probability of measuring 0 and collapsing the state to $|0\rangle$ is $|\alpha|^2$ and similarly the probability of measuring 1 and collapsing the state to $|1\rangle$ is $|\beta|^2$. This randomness is not due to our ignorance of the underlying mechanisms, but rather it is a fundamental feature of a quantum mechanical system.

Many possible realisations of qubits exists. Key to all these representations, is to find a realisation of the classical states $|0\rangle$ and $|1\rangle$, together with a procedure to create arbitrary superpositions $|\Psi\rangle$ thereof. For quantum memories, and quantum computing devices, $|0\rangle$ and $|1\rangle$ typically correspond to states of two different energies in either a natural "atomic system" (e.g. ion traps [27], NV centres in diamond [60], neutral atoms [8] or atomic ensembles [51]), or artificially designed nano-scale systems (e.g. superconducting quantum processors [13]). For transmission, usually optically, qubits can be represented in a variety of ways: the two states $|0\rangle$ and $|1\rangle$ can be encoded in the presence or absence of a photon [11, 31], a time-bin encoding of early and late arrival [7], or the horizontal and vertical polarisation of photons [2, 38].

3.2 Multiple Qubits

We can express the state of an n-qubit quantum state as

$$|\Psi\rangle = \sum_{x \in \{0,1\}^n} \alpha_x |x\rangle \;, \tag{2}$$

---

[1] In the standard basis, given by $\{|0\rangle, |1\rangle\}$

where $\sum_x |\alpha_x|^2 = 1$. We remark that this means that since there are 2^n possible strings $x \in \{0,1\}^n$, we need an exponential number of parameters $\alpha_x \in \mathbb{C}$ in order to describe the definite state $|\Psi\rangle$. This is in sharp contrast to classical computing, where only n parameters are needed (namely a specific string x).

As an example, if we have two qubits A and B, and the first qubit is in a state $|0\rangle_A$ and the second in a state $|1\rangle_B$, then the overall state of the two qubits can be expressed as $|01\rangle = |0\rangle_A|1\rangle_B$. However, there exists multi-qubit states $|\Psi\rangle$ which cannot be written as such a combination of single qubit states. That is, the two qubits can non longer be described independently of each other. The states of the two individual qubits are now correlated beyond what is possible to achieve classically. Such states are called *entangled*. For two-qubits the maximally entangled state can (up to local quantum gates) be written as

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B\right) . \tag{3}$$

Such states have an interesting property that for any measurement on A that probabilistically yields outcome x, there always exists a measurement on B that yields exactly the same outcome x. Very intuitively, such states can hence be understood as the quantum analogue of maximal correlation in the classical domain, only such correlations persist for any measurement. Entanglement enables much stronger than classical correlations, also for more complex scenarios [62]. Interestingly, entanglement cannot be shared, which is also known as the monogamy of entanglement [59].

An entangled state is created from initially unentangled qubits, say $|0\rangle_A|0\rangle_B$. A common scheme to locally create an entangled state is to start by applying the so-called Hadamard operation on A to produce $(|0\rangle_A + |1\rangle_A)|0\rangle_B/\sqrt{2}$. Subsequently a controlled NOT operation (CNOT) is performed which has the effect $\mathrm{CNOT}|x\rangle_A|y\rangle_B = |x\rangle_A|y + x \mod 2\rangle$:

$$\mathrm{CNOT}\frac{1}{\sqrt{2}}\left(|0\rangle_A|0\rangle_B + |1\rangle_A|0\rangle_B\right) = \frac{1}{\sqrt{2}}\left(|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B\right) . \tag{4}$$

The physical implementation depends on the underlying hardware platform. For NV centres in diamond this operation can be implemented using a combination of a microwave and optical pulses [28].

3.3 Teleportation

Qubits may be transmitted directly, or via quantum teleportation [3] using entanglement. To teleport one data qubit $|\Psi\rangle$, we require one entangled pair $|\Phi\rangle$ to be established between the sender and receiver ahead of time. The sender performs a measurement of the data qubit $|\Psi\rangle$ and their qubit A of $|\Phi\rangle$ (see Fig. 2), resulting in two classical bits $y \in \{0,1\}^2$ as the measurement outcome. The sender transmits y to the receiver, who applies a correction depending on y on their qubit in order to recover $|\Psi\rangle$. From the perspective of control of such a network, we remark that this requires that the sender has correctly identified that qubit A belongs to the entangled state $|\Phi\rangle$ shared with the receiver, and that the entanglement is consumed by this process. Deterministic teleportation has been realised, using for example two network nodes based on NV in diamond [48].

Teleportation is crucial for quantum networking. The no-cloning theorem means that retransmitting the data qubit if sending fails is not an option. However, $|\Phi\rangle$ is a known generic state that does not carry any data and can be repeatedly recreated until it has been successfully distributed to the sender and receiver. At this point the sender simply teleports the sensitive data qubit to the receiver without putting it through the network risking its loss.

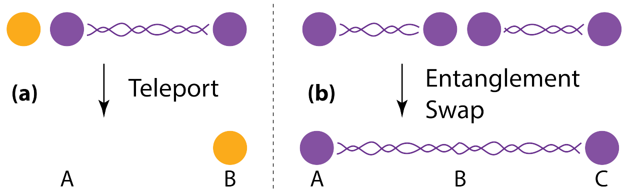


Figure 2: Entangled Bell pairs enable long-distance quantum communication. (a) An unknown data qubit state can be teleported over long distances by consuming a Bell pair that has one qubit at the source and the other qubit at the destination. (b) Two shorter Bell pairs can be combined into a longer Bell pair with an entanglement swap operation.

3.4 Entanglement Swapping

Teleportation also provides a mechanism to extend short-distance entanglement to larger distances [9, 18, 41]. Consider node A which has generated entanglement with node B. Similarly, B has produced entanglement with C. We can now generate entanglement between A and C using the help of B: B teleports the qubit entangled with node A to C, using the entanglement he shares with C. This process is also known as entanglement swapping [9, 73] (see Fig. 2).

Unfortunately, neither the entanglement generation nor the swapping operations are noiseless. Therefore, with each link and each swap the quality of the entanglement, called fidelity, degrades. However, it is possible to create higher fidelity entangled pairs from two or more lower quality pair states through a process called distillation using the Purify-and-Swap algorithm [9]. Therefore, once the quality loss over a given distance become prohibitive, additional redundancy may be used to restore the state fidelity.

4 ELEMENTS OF A QUANTUM NETWORK

Let us provide a high-level overview of the elements of a quantum network [67]. For additional overview of design considerations for quantum networks we also refer to Refs. [15, 62, 64].

End Nodes: Just like in classical networks we need devices at the edge of the network on which applications are run. In the simplest case, these are photonic devices consisting of linear optical elements, photon sources and detectors. These do not have a quantum memory to store qubits, and can also only perform a limited set of quantum operations deterministically. However, these are sufficient to perform all protocols in the prepare and measure stage of quantum network [67] at short distances (presently ~100 km over deployed telecom fibre), such as QKD.

However, they may also be *processing nodes* with an optical interface which are capable of storing qubits, as well as performing universal quantum computation. Examples include NV centres in diamond [4, 28, 58], ion traps [40], and neutral atoms [49]. Such systems can also be used to run application protocols in the quantum memory network stage and eventually above [67].

Quantum repeaters: The objective of quantum repeaters is to transmit qubits over long-distances. Any system that is a quantum processing node, can also be used as a repeater platform. In addition, there exist specific hardware platforms tailored to the task of a quantum repeater. This includes multiplexed quantum repeaters [51] which promise to generate entanglement quickly by temporal and spatial multiplexing. These repeater platforms work — in a possible combination with entanglement distillation steps — by the entanglement swapping principle outlined in Fig. 2. Theoretical proposals for employing forward error correction also exist [42], but they are not possible to realise in the near-term.

The current world record for producing such heralded (i.e. confirmed) entanglement is 1.3 km which has been achieved using NV centres in diamond [28], see Fig. 3. This platform is a few (about 10 [6]) qubit quantum computer with an optical interface capable of executing arbitrary gates and measurements. It has been recently demonstrated that NV centres are capable of memory lifetimes approaching one minute [6] in nodes not yet interfaced to the network. Other platforms exist that are similar on the conceptual level with similar capabilities such as ion traps [33] and neutral atoms [49] (see Table 1 for current parameter trade-offs).

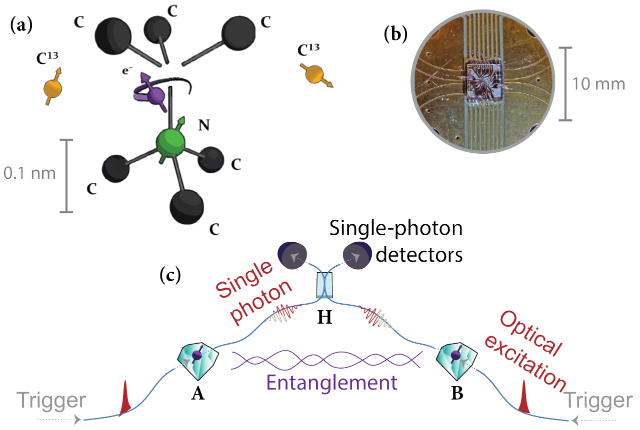


Figure 3: Example of a physical implementation producing entanglement between two quantum processors (NV in diamond). (a) The qubits of the Bell pair are stored in NV centres in diamond on (b) custom chips. (c) Entanglement is generated between the two processors using probabilistic entanglement swapping: entanglement is produced between each processor and a traveling qubit (photon) sent to the mid-point. The mid-point performs entanglement swapping, and sends a confirmation (heralding) signal back to the nodes whether entanglement generation was a success.

Communication lines: Qubits can be sent using photons through fibre, or free space communication [70]. Standard telecom fibre can be used for this purpose, potentially following an appropriate wavelength conversion to the telecom band [17, 71].

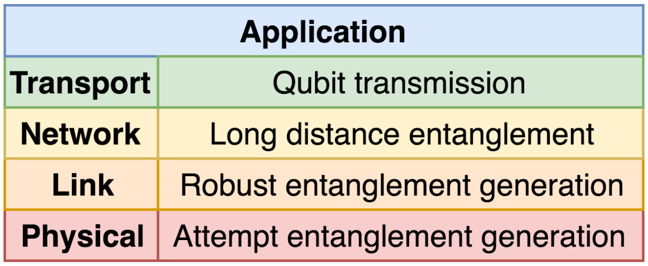
Classical Control Messages. A crucial component of quantum communication is also the ability to send classical data. The control of quantum devices requires quite a number of classical control signals to be exchange, teleportation being just one example. In order to develop functional quantum protocols we will need a way to transmit control information between the quantum repeaters. This means that it is expected that quantum networks will be deployed alongside classical networks with a quantum data plane coexisting with the classical one as shown in Fig. 1.

Table 1: Quantum Link Efficiency (QLE) is given by the ratio of the entangling rate to the decoherence rate, capturing how fast entanglement can be produced in relation to how fast it is lost. A QLE ≥ 1 is required to extend entanglement over long distances.

Platform	QLE
NV Centres	8 [31]
Trapped Ions	5 [30]
Neutral Atoms	2 (projected) [35, 44]

5 A QUANTUM NETWORK STACK

One may wonder whether one can design quantum network protocols without detailed knowledge of the underlying hardware system. Here, we briefly summarise the approach of Ref. [15], because it is defined in terms of service layers rather than protocol layers (see Fig. 4) which gives it a structure that is similar to the classical TCP/IP stack. It also gives a concrete link layer protocol that abstracts away from the underlying hardware system, turning entanglement generation into a well-defined service.



Application	
Transport	Qubit transmission
Network	Long distance entanglement
Link	Robust entanglement generation
Physical	Attempt entanglement generation

Figure 4: Functional allocation in a quantum network stack. The structure mirrors and is inspired by the classical TCP/IP network stack.

Physical. This layer corresponds to the actual quantum hardware devices and physical connections. The physical layer keeps no state related to entanglement production, produced entanglement probabilistically, and has no decision making capabilities. The hardware is solely responsible for tasks such as time synchronisation, photon emission, laser phase stabilisation, and so on, that are required to actually produce entangled Bell pairs.

Link. The task of the link-layer is to utilise the physical layer's ability to produce entanglement between neighbouring nodes reliably. It also integrates the quantum and classical data planes providing sufficient information for higher level protocols and network management. A concrete link layer protocol can be found in [15].

Network. Similar to a network layer in classical networking, the task of the network layer is to enable the generation of entanglement between network nodes which are not directly connected. A protocol to achieve this would utilise the link layer to produce entanglement between neighbouring nodes followed by entanglement swaps to create long distance links.

Transport. One can imagine, that a transport layer could provide the additional service of transmitting qubits to the application layer. This could be realised by, for example, pre-generating entangled pairs of qubits using the network layer, followed by teleportation to ensure reliable end-to-end delivery of qubits.

6 CHALLENGES AND REQUIREMENTS

Quantum networks are still in their early infancy. Realising the necessary quantum hardware is of paramount importance and presents many challenges, but that is only one part of the story. Here, we present some of the challenges beyond hardware accounting for the fundamental differences inherent to quantum communication and mitigating the limitations and imperfections at the physical level. Further design considerations can also be found in [15].

Timely decision making. Quantum memory lifetimes are extremely short even in the most sophisticated setups and this directly impacts our ability to produce long-distance entanglement by means of entanglement swapping. Entanglement swapping requires that both entangled pairs of qubits are available on two separate links at the same time so the intermediate node must be able to store the first pair until it receives the second pair. If one of the qubits decoheres, the pair is lost and the entire process must start over. One approach to increase the likelihood of such a coincidence event lies in proposals to perform massive multiplexing [51] significantly reducing the required storage time. There is also the obvious approach of increasing memory lifetime. NV centres in diamond already exhibit a high QLE, see Table 1, and lifetimes up to a minute have recently been observed in NV nodes not yet connected to a network [6]. Longer memory lifetimes impose less stringent demands on timing at the network layer allowing it to be kept at the physical layer.

Nevertheless, mitigating limited qubit lifetimes is essential and demands fast and reactive control of the network. In a network based on entanglement swapping it also raises the interesting question of whether such entanglement is produced only on-demand, or if there exists a mechanism which continuously generates entangled pairs at all times between certain links of the network.

Extending the network stack. In parallel with the effort of building the physical network links there is a need for work to build up the quantum network stack vertically. The first link-layer protocol has been proposed [15]. However, to go beyond point-to-point connectivity between two directly connected nodes we need a network layer service and the transport layer to provide platform-independent services for distributed quantum applications. The first end-to-end quantum communication protocols have started to appear though they generally assume hardware capabilities beyond what is possible in the near-term future [37, 69].

Routing. In addition to forwarding protocols necessary to actually generate an end-to-end Bell pair there are many other second-level mechanisms necessary for a fully functional quantum internet. The specific question of routing entanglement, i.e. making decisions on how end-to-end entanglement can be established quickly between users in future quantum networks, is seeing more attention [12, 25, 26, 46, 55, 63]. Routing in quantum networks is a non-trivial problem due to the non-local and temporary nature of entangled pairs as well as different physical resource requirements necessary for delivering these pairs with a high enough fidelity.

SDN Integration. Given limited lifetimes, building robust and efficient quantum network routing and management protocols in an entirely distributed manner may be difficult. This could make software-defined networking (SDN) a very attractive direction for quantum networking and has already been considered for QKD [45].

SDN is an architecture for programmable networks that splits the vertical integration of the forwarding and control planes and puts much of the decision-making capabilities in a centralised controller (physically decentralised with appropriate redundancy) [36]. In this approach, the central controller has network-wide visibility and it is responsible for most (or all as is the case for OpenFlow) control plane decisions based on input it receives from the individual nodes in the network. It is plausible that in a quantum network a controller would be responsible for managing the global strategies for the distribution of long-distance Bell pairs (Bell pairs that have been produced as a result of entanglement swaps between separate links), but connection establishment, Bell pair generation, and other localised operations are left to the actual devices who will try to conform to the controller's strategy.

Security. Given that one of the most important features quantum networking brings with it is enhanced security it is crucial that a design for a future quantum network architecture incorporates strong security features itself. Such design considerations should be employed already at the physical layer, to ensure the protection of quantum network nodes. For example, we remark that convincing a remote node to produce entanglement with its neighbour may simply lead to a denial of service attack consuming its resources [15]. This shows that at the very least authentication is necessary for control messages already at the physical layer. Such authentication could be realised using standard classical mechanisms, or also use keys generated by QKD in combination with an information-theoretically secure authentication scheme.

7 CONCLUSION

There is a tremendous amount of work to do to build a fully functional quantum network, both at the physical level and at the systems and software level. Recent experimental progress in entanglement generation rates and memory lifetimes is very promising and the breadth of the combined research effort should result in practical demonstrations very soon. Nevertheless, there are a lot of open questions and research challenges that are unresolved and require a range of expertise from beyond physics such as operating systems, computer networks, and communications. This opens up many new opportunities for researchers from outside the usual circles to contribute to the growing field of quantum networking.

ACKNOWLEDGEMENTS

The authors of this memo acknowledge funding received the EU Flagship on Quantum Technologies, Quantum Internet Alliance, an ERC Starting Grant (SW) and an NWO VIDI Grant (SW). The authors would further like to thank [15] for permission to reuse some of their figures.

REFERENCES

[1] Stefanie Barz, Elham Kashefi, Anne Broadbent, Joseph F Fitzsimons, Anton Zeilinger, and Philip Walther. 2012. Demonstration of blind quantum computing. *science* 335, 6066 (2012), 303–308.

[2] Charles H Bennett and Gilles Brassard. 1984. Quantum cryptography: public key distribution and coin tossing. In *Proceedings of the International Conference on Computers, Systems and Signal Processing*.

[3] Charles H. Bennett, Gilles Brassard, Claude Crépeau, Richard Jozsa, Asher Peres, and William K. Wootters. 1993. Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels. *Phys. Rev. Lett.* 70 (Mar 1993), 1895–1899. Issue 13. DOI:http://dx.doi.org/10.1103/PhysRevLett.70.1895

[4] Hannes Bernien, Bas Hensen, Wolfgang Pfaff, Gerwin Koolstra, MS Blok, Lucio Robledo, TH Taminiau, Matthew Markham, DJ Twitchen, Lilian Childress, and Ronald Hanson. 2013. Heralded entanglement between solid-state qubits separated by three metres. *Nature* 497, 7447 (2013), 86.

[5] Alberto Boaron, Gianluca Boso, Davide Rusca, Cédric Vulliez, Claire Autebert, Misael Caloz, Matthieu Perrenoud, Gaëtan Gras, Félix Bussières, Ming-Jun Li, Daniel Nolan, Anthony Martin, and Hugo Zbinden. 2018. Secure quantum key distribution over 421 km of optical fiber. *Physical review letters* 121, 19 (2018), 190502.

[6] CE Bradley, J Randall, MH Abobeih, RC Berrevoets, MJ Degen, MA Bakker, M Markham, DJ Twitchen, and TH Taminiau. 2019. A 10-qubit solid-state spin register with quantum memory up to one minute. *arXiv preprint arXiv:1905.02094* (2019).

[7] Jürgen Brendel, Nicolas Gisin, Wolfgang Tittel, and Hugo Zbinden. 1999. Pulsed energy-time entangled twin-photon source for quantum communication. *Physical Review Letters* 82, 12 (1999), 2594.

[8] H-J Briegel, Tommaso Calarco, Dieter Jaksch, Juan Ignacio Cirac, and Peter Zoller. 2000. Quantum computing with neutral atoms. *Journal of modern optics* 47, 2-3 (2000), 415–451.

[9] H-J Briegel, Wolfgang Dür, Juan I Cirac, and Peter Zoller. 1998. Quantum repeaters: the role of imperfect local operations in quantum communication. *Physical Review Letters* 81, 26 (1998), 5932.

[10] Anne Broadbent, Joseph Fitzsimons, and Elham Kashefi. 2009. Universal blind quantum computation. In *2009 50th Annual IEEE Symposium on Foundations of Computer Science*. IEEE, 517–526.

[11] C Cabrillo, J Ignacio Cirac, P Garcia-Fernandez, and P Zoller. 1999. Creation of entangled states of distant atoms by interference. *Physical Review A* 59, 2 (1999), 1025.

[12] Marcello Caleffi. 2017. Optimal routing for quantum networks. *IEEE Access* 5 (2017), 22299–22312.

[13] John Clarke and Frank K Wilhelm. 2008. Superconducting quantum bits. *Nature* 453, 7198 (2008), 1031.

[14] Rachel Courtland. 2016. China's 2,000-km quantum link is almost complete [News]. *IEEE Spectrum* 53, 11 (2016), 11–12.

[15] Axel Dahlberg, Matthew Skrzypczyk, Tim Coopmans, Leon Wubben, Filip Rozpędek, Matteo Pompili, Arian Stolk, Przemysław Pawełczak, Robert Knegjens, Ronald Hanson, and Stephanie Wehner. 2019. A Link Layer Protocol for Quantum Networks. *arXiv preprint arXiv:1903.09778* (2019).

[16] Eleni Diamanti, Hoi-Kwong Lo, Bing Qi, and Zhiliang Yuan. 2016. Practical challenges in quantum key distribution. *npj Quantum Information* 2 (2016), 16025.

[17] Anaïs Dréau, Anna Tchebotareva, Aboubakr El Mahdaoui, Cristian Bonato, and Ronald Hanson. 2018. Quantum frequency conversion of single photons from a nitrogen-vacancy center in diamond to telecommunication wavelengths. *Physical Review Applied* 9, 6 (2018), 064031.

[18] W Dür, H-J Briegel, JI Cirac, and P Zoller. 1999. Quantum repeaters based on entanglement purification. *Physical Review A* 59, 1 (1999), 169.

[19] Artur K Ekert. 1991. Quantum cryptography based on BellâĂŹs theorem. *Physical review letters* 67, 6 (1991), 661.

[20] A Extance. 2017. Fibre Systems. (2017). Retrieved May 27, 2019 from www.fibre-systems.com/feature/quantum-security

[21] Joseph F Fitzsimons and Elham Kashefi. 2017. Unconditionally verifiable blind quantum computation. *Physical Review A* 96, 1 (2017), 012303.

[22] Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone. 2004. Quantum-enhanced measurements: beating the standard quantum limit. *Science* 306, 5700 (2004), 1330–1336.

[23] Daniel Gottesman, Thomas Jennewein, and Sarah Croke. 2012. Longer-baseline telescopes using quantum repeaters. *Physical review letters* 109, 7 (2012), 070503.

[24] Xueshi Guo, Casper R Breum, Johannes Borregaard, Shuro Izumi, Mikkel V Larsen, Matthias Christandl, Jonas S Neergaard-Nielsen, and Ulrik L Andersen. 2019. Distributed quantum sensing in a continuous variable entangled network. *arXiv preprint arXiv:1905.09408* (2019).

[25] Laszlo Gyongyosi and Sandor Imre. 2017. Entanglement-gradient routing for quantum networks. *Scientific reports* 7, 1 (2017), 14255.

[26] Laszlo Gyongyosi and Sandor Imre. 2018. Decentralized base-graph routing for the quantum internet. *Physical Review A* 98, 2 (2018), 022310.

[27] Hartmut Häffner, Christian F Roos, and Rainer Blatt. 2008. Quantum computing with trapped ions. *Physics reports* 469, 4 (2008), 155–203.

[28] Bas Hensen, Hannes Bernien, Anaïs E Dréau, Andreas Reiserer, Norbert Kalb, Machiel S Blok, Just Ruitenberg, Raymond FL Vermeulen, Raymond N Schouten, Carlos Abellán, Waldimar Amaya, Valerio Pruneri, Morgan W Mitchell, Michael Markham, Daniel J Twitchen, David Elkouss, Stephanie Wehner, Tim H Taminiau, and Ronald Hanson. 2015. Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres. *Nature* 526, 7575 (2015), 682.

[29] Philip A Hiskett, Danna Rosenberg, Charles G Peterson, Richard J Hughes, S Nam, AE Lita, AJ Miller, and JE Nordholt. 2006. Long-distance quantum key distribution in optical fibre. *New Journal of Physics* 8, 9 (2006), 193.

[30] David Hucul, Ismail V Inlek, Grahame Vittorini, Clayton Crocker, Shantanu Debnath, Susan M Clark, and Christopher Monroe. 2015. Modular entanglement of atomic qubits using photons and phonons. *Nature Physics* 11, 1 (2015), 37.

[31] Peter C Humphreys, Norbert Kalb, Jaco PJ Morits, Raymond N Schouten, Raymond FL Vermeulen, Daniel J Twitchen, Matthew Markham, and Ronald Hanson. 2018. Deterministic delivery of remote entanglement on a quantum network. *Nature* 558, 7709 (2018), 268.

[32] Takahiro Inagaki, Nobuyuki Matsuda, Osamu Tadanaga, Masaki Asobe, and Hiroki Takesue. 2013. Entanglement distribution over 300 km of fiber. *Optics express* 21, 20 (2013), 23241–23249.

[33] IV Inlek, C Crocker, M Lichtman, K Sosnova, and C Monroe. 2017. Multispecies trapped-ion node for quantum networking. *Physical review letters* 118, 25 (2017), 250502.

[34] Peter Komar, Eric M Kessler, Michael Bishof, Liang Jiang, Anders S Sørensen, Jun Ye, and Mikhail D Lukin. 2014. A quantum network of clocks. *Nature Physics* 10, 8 (2014), 582.

[35] Matthias Körber, Olivier Morin, Stefan Langenfeld, Andreas Neuzner, Stephan Ritter, and Gerhard Rempe. 2018. Decoherence-protected memory for a single-photon qubit. *Nature Photonics* 12, 1 (2018), 18.

[36] Diego Kreutz, Fernando MV Ramos, Paulo Verissimo, Christian Esteve Rothenberg, Siamak Azodolmolky, and Steve Uhlig. 2015. Software-defined networking: A comprehensive survey. *Proc. IEEE* 103, 1 (2015), 14–76.

[37] Takaaki Matsuo, Clément Durand, and Rodney Van Meter. 2019. Quantum link bootstrapping using a RuleSet-based communication protocol. *arXiv preprint arXiv:1904.08605* (2019).

[38] Klaus Mattle, Harald Weinfurter, Paul G Kwiat, and Anton Zeilinger. 1996. Dense coding in experimental quantum communication. *Physical Review Letters* 76, 25 (1996), 4656.

[39] M Minder, M Pittaluga, GL Roberts, M Lucamarini, JF Dynes, ZL Yuan, and AJ Shields. 2019. Experimental quantum key distribution beyond the repeaterless secret key capacity. *Nature Photonics* (2019), 1.

[40] DL Moehring, P Maunz, S Olmschenk, KC Younge, DN Matsukevich, L-M Duan, and C Monroe. 2007. Entanglement of single-atom quantum bits at a distance. *Nature* 449, 7158 (2007), 68.

[41] William J Munro, Koji Azuma, Kiyoshi Tamaki, and Kae Nemoto. 2015. Inside quantum repeaters. *IEEE Journal of Selected Topics in Quantum Electronics* 21, 3 (2015), 78–90.

[42] Sreraman Muralidharan, Jungsang Kim, Norbert Lütkenhaus, Mikhail D Lukin, and Liang Jiang. 2014. Ultrafast and fault-tolerant quantum communication across long distances. *Physical review letters* 112, 25 (2014), 250501.

[43] Michael A Nielsen and Isaac L Chuang. 2000. Quantum information and quantum computation. *Cambridge: Cambridge University Press* 2, 8 (2000), 23.

[44] Christian Nölleke, Andreas Neuzner, Andreas Reiserer, Carolin Hahn, Gerhard Rempe, and Stephan Ritter. 2013. Efficient teleportation between remote single-atom quantum memories. *Physical review letters* 110, 14 (2013), 140403.

[45] Y Ou, E Hugues-Salas, F Ntavou, R Wang, Y Bi, SY Yan, G Kanellos, R Nejabati, and D Simeonidou. 2018. Field-trial of machine learning-assisted quantum key distribution (QKD) networking with SDN. In *2018 European Conference on Optical Communication (ECOC)*. IEEE, 1–3.

[46] Mihir Pant, Hari Krovi, Don Towsley, Leandros Tassiulas, Liang Jiang, Prithwish Basu, Dirk Englund, and Saikat Guha. 2019. Routing entanglement in the quantum internet. *npj Quantum Information* 5, 1 (2019), 25.

[47] M Peev, C Pacher, R Alléaume, C Barreiro, J Bouda, W Boxleitner, T Debuisschert, E Diamanti, M Dianati, J F Dynes, S Fasel, S Fossier, M FÃijrst, J-D Gautier, O Gay, N Gisin, P Grangier, A Happe, Y Hasani, M Hentschel, H HÃijbel, G Humer, T LÃďnger, M Legré, R Lieger, J Lodewyck, T LorÃijnser, N LÃijtkenhaus, A

Marhold, T Matyus, O Maurhart, L Monat, S Nauerth, J-B Page, A Poppe, E Querasser, G Ribordy, S Robyr, L Salvail, A W Sharpe, A J Shields, D Stucki, M Suda, C Tamas, T Themel, R T Thew, Y Thoma, A Treiber, P Trinkler, R Tualle-Brouri, F Vannel, N Walenta, H Weier, H Weinfurter, I Wimberger, Z L Yuan, H Zbinden, and A Zeilinger. 2009. The SECOQC quantum key distribution network in Vienna. *New Journal of Physics* 11, 7 (jul 2009), 075001. `DOI`: http://dx.doi.org/10.1088/1367-2630/11/7/075001

[48] Wolfgang Pfaff, BJ Hensen, Hannes Bernien, Suzanne B van Dam, Machiel S Blok, Tim H Taminiau, Marijn J Tiggelman, Raymond N Schouten, Matthew Markham, Daniel J Twitchen, and others. 2014. Unconditional quantum teleportation between distant solid-state quantum bits. *Science* 345, 6196 (2014), 532–535.

[49] Andreas Reiserer and Gerhard Rempe. 2015. Cavity-based quantum networks with single atoms and optical photons. *Reviews of Modern Physics* 87, 4 (2015), 1379.

[50] Louis Salvail, Momtchil Peev, Eleni Diamanti, Romain Alléaume, Norbert Lütkenhaus, and Thomas Länger. 2010. Security of trusted repeater quantum key distribution networks. *Journal of Computer Security* 18, 1 (2010), 61–87.

[51] Nicolas Sangouard, Christoph Simon, Hugues De Riedmatten, and Nicolas Gisin. 2011. Quantum repeaters based on atomic ensembles and linear optics. *Reviews of Modern Physics* 83, 1 (2011), 33.

[52] Masahide Sasaki, M Fujiwara, H Ishizuka, W Klaus, K Wakui, M Takeoka, S Miki, T Yamashita, Z Wang, A Tanaka, K Yoshino, Y Nambu, S Takahashi, A Tajima, A Tomita, T Domeki, T Hasegawa, Y Sakai, H Kobayashi, T Asai, K Shimizu, T Tokura, T Tsurumaru, M Matsui, T Honjo, K Tamaki, H Takesue, Y Tokura, J F Dynes, A R Dixon, A W Sharpe, Z L Yuan, A J Shields, S Uchikoga, M LegrÃĺ, S Robyr, P Trinkler, L Monat, J-B Page, G Ribordy, A Poppe, A Allacher, O Maurhart, T LÃďnger, M Peev, others, and A. Zeilinger. 2011. Field test of quantum key distribution in the Tokyo QKD Network. *Optics express* 19, 11 (2011), 10387–10409.

[53] Valerio Scarani, Helle Bechmann-Pasquinucci, Nicolas J. Cerf, Miloslav Dušek, Norbert Lütkenhaus, and Momtchil Peev. 2009. The security of practical quantum key distribution. *Rev. Mod. Phys.* 81 (Sep 2009), 1301–1350. Issue 3. `DOI`: http://dx.doi.org/10.1103/RevModPhys.81.1301

[54] Tobias Schmitt-Manderbach, Henning Weier, Martin Fürst, Rupert Ursin, Felix Tiefenbacher, Thomas Scheidl, Josep Perdigues, Zoran Sodnik, Christian Kurtsiefer, John G Rarity, Anton Zeilinger, and Harald Weinfurter. 2007. Experimental demonstration of free-space decoy-state quantum key distribution over 144 km. *Physical Review Letters* 98, 1 (2007), 010504.

[55] Eddie Schoute, Laura Mancinska, Tanvirul Islam, Iordanis Kerenidis, and Stephanie Wehner. 2016. Shortcuts to quantum network routing. *arXiv preprint arXiv:1610.05238* (2016).

[56] D Stucki, M Legré, F Buntschu, B Clausen, N Felber, N Gisin, L Henzen, P Junod, G Litzistorf, P Monbaron, L Monat, J-B Page, D Perroud, G Ribordy, A Rochas, S Robyr, J Tavares, R Thew, P Trinkler, S Ventura, R Voirol, N Walenta, and H Zbinden. 2011. Long-term performance of the SwissQuantum quantum key distribution network in a field environment. *New Journal of Physics* 13, 12 (dec 2011), 123001. `DOI`: http://dx.doi.org/10.1088/1367-2630/13/12/123001

[57] Damien Stucki, Nino Walenta, Fabien Vannel, Robert Thomas Thew, Nicolas Gisin, Hugo Zbinden, S Gray, CR Towery, and S Ten. 2009. High rate, long-distance quantum key distribution over 250 km of ultra low loss fibres. *New Journal of Physics* 11, 7 (2009), 075003.

[58] Tim Hugo Taminiau, Julia Cramer, Toeno van der Sar, Viatcheslav V Dobrovitski, and Ronald Hanson. 2014. Universal control and error correction in multi-qubit spin registers in diamond. *Nature nanotechnology* 9, 3 (2014), 171.

[59] Barbara M Terhal. 2004. Is entanglement monogamous? *IBM Journal of Research and Development* 48, 1 (2004), 71–78.

[60] Emre Togan, Yiwen Chu, AS Trifonov, Liang Jiang, Jeronimo Maze, Lilian Childress, MV Gurudev Dutt, Anders Søndberg Sørensen, PR Hemmer, Alexander S Zibrov, and M D Lukin. 2010. Quantum entanglement between an optical photon and a solid-state spin qubit. *Nature* 466, 7307 (2010), 730.

[61] Giuseppe Vallone, Davide Bacco, Daniele Dequal, Simone Gaiarin, Vincenza Luceri, Giuseppe Bianco, and Paolo Villoresi. 2015. Experimental Satellite Quantum Communications. *Phys. Rev. Lett.* 115 (Jul 2015), 040502. Issue 4. `DOI`: http://dx.doi.org/10.1103/PhysRevLett.115.040502

[62] Rodney Van Meter. 2014. *Quantum networking.* John Wiley & Sons.

[63] Rodney Van Meter, Takahiko Satoh, Thaddeus D Ladd, William J Munro, and Kae Nemoto. 2013. Path selection for quantum repeater networks. *Networking Science* 3, 1-4 (2013), 82–95.

[64] Rodney Van Meter and Joe Touch. 2013. Designing quantum repeater networks. *IEEE Communications Magazine* 51, 8 (2013), 64–71.

[65] Shuang Wang, Wei Chen, Zhen-Qiang Yin, Hong-Wei Li, De-Yong He, Yu-Hu Li, Zheng Zhou, Xiao-Tian Song, Fang-Yi Li, Dong Wang, Hua Chen, Yun-Guang Han, Jing-Zheng Huang, Jun-Fu Guo, Peng-Lei Hao, Mo Li, Chun-Mei Zhang, Dong Liu, Wen-Ye Liang, Chun-Hua Miao, Ping Wu, Guang-Can Guo, and Zheng-Fu Han. 2014. Field and long-term demonstration of a wide area quantum key distribution network. *Opt. Express* 22, 18 (Sep 2014), 21739–21756. `DOI`: http://dx.doi.org/10.1364/OE.22.021739

[66] Shuang Wang, De-Yong He, Zhen-Qiang Yin, Feng-Yu Lu, Chao-Han Cui, Wei Chen, Zheng Zhou, Guang-Can Guo, and Zheng-Fu Han. 2019. Beating the fundamental rate-distance limit in a proof-of-principle quantum key distribution system. *arXiv preprint arXiv:1902.06884* (2019).

[67] Stephanie Wehner, David Elkouss, and Ronald Hanson. 2018. Quantum internet: A vision for the road ahead. *Science* 362, 6412 (2018), eaam9288.

[68] Juan Yin, Yuan Cao, Yu-Huai Li, Sheng-Kai Liao, Liang Zhang, Ji-Gang Ren, Wen-Qi Cai, Wei-Yue Liu, Bo Li, Hui Dai, Guang-Bing Li, Qi-Ming Lu, Yun-Hong Gong, Yu Xu, Shuang-Lin Li, Feng-Zhi Li, Ya-Yun Yin, Zi-Qing Jiang, Ming Li, Jian-Jun Jia, Ge Ren, Dong He, Yi-Lin Zhou, Xiao-Xiang Zhang, Na Wang, Xiang Chang, Zhen-Cai Zhu, Nai-Le Liu, Yu-Ao Chen, Chao-Yang Lu, Rong Shu, Cheng-Zhi Peng, Jian-Yu Wang, and Jian-Wei Pan. 2017. Satellite-based entanglement distribution over 1200 kilometers. *Science* 356, 6343 (2017), 1140–1144. `DOI`: http://dx.doi.org/10.1126/science.aan3211 arXiv:https://science.sciencemag.org/content/356/6343/1140.full.pdf

[69] Nengkun Yu, Ching-Yi Lai, and Li Zhou. 2019. Protocols for Packet Quantum Network Intercommunication. *arXiv preprint arXiv:1903.10685* (2019).

[70] Yong Yu, Fei Ma, Xi-Yu Luo, Bo Jing, Peng-Fei Sun, Ren-Zhou Fang, , Chao-Wei Yang, Hui Liu, Ming-Yang Zheng, Xiu-Ping Xie, Wei-Jun Zhang, Li-Xing You, Zhen Wang, Teng-Yun Chen, Qiang Zhang, Xiao-Hui Bao, and Jian-Wei Pan. 2019. Entanglement of two quantum memories via metropolitan-scale fibers. *arXiv preprint arXiv:1903.11284* (2019).

[71] Sebastian Zaske, Andreas Lenhard, Christian A Keßler, Jan Kettler, Christian Hepp, Carsten Arend, Roland Albrecht, Wolfgang-Michael Schulz, Michael Jetter, Peter Michler, and others. 2012. Visible-to-telecom quantum frequency conversion of light from a single quantum emitter. *Physical review letters* 109, 14 (2012), 147404.

[72] Xiaoqing Zhong, Jianyong Hu, Marcos Curty, Li Qian, and H-K Lo. 2019. Proof-of-principle experimental demonstration of twin-field type quantum key distribution. *arXiv preprint arXiv:1902.10209* (2019).

[73] Marek Zukowski, Anton Zeilinger, Michael A Horne, and Aarthur K Ekert. 1993. Event-ready-detectors"Bell experiment via entanglement swapping. *Physical Review Letters* 71 (1993), 4287–4290.