SURF

Driving innovation together

Whitepaper - Introducing the concept of Quantum Communication

Celebrating the International Year of Quantum Science and Technology by exploring its potential impact on education and research

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1 Introduction

The UN resolution "Invites the United Nations Educational, Scientific and Cultural Organization (UNESCO) to act as the lead agency and focal point for the International Year of Quantum Science and Technology, and invites all Member States of the United Nations, members of the specialised agencies, observers of the General Assembly, as well as organisations within the United Nations system and other international and regional organisations, academia, civil society, the private sector and other relevant stakeholders to observe 2025 as the International Year of Quantum Science and Technology".

The scientific community recognises the importance of quantum science and is coming together to raise awareness of its past and future impacts. This supports the International Year of Quantum, commemorating 100 years of quantum mechanics. Given the anticipated value of quantum technology in the upcoming years, SURF aims to become an early adopter of quantum technology for the benefit of research and education in the Netherlands.

It is an important moment in advancing and recognising quantum technologies worldwide. As nations race to harness the full potential of quantum technology, the stakes have never been higher. The quantum phenomena have been studied for decades, with various applications such as lasers, transistors, atomic clocks, and quantum information technologies. Among the transformative technologies, quantum communication stands out as a groundbreaking means of securing and enhancing our Internet infrastructure.

In line with the International Year of Quantum Science and Technology[1], we have tried to demystify quantum by focussing on quantum communication and its potential for education and research. This white paper is written for interested readers who are not working in or engaging with quantum technologies regularly.

1.1 Structure and Approach

We have tried to demystify quantum by focussing on quantum communication and its potential for education and research. This report is written for interested readers who are not working in or engaging with quantum technologies regularly. The aim of this white paper is to:

1. Understand (the basics of) quantum communication
2. Generate an overview of quantum communication initiatives in the Netherlands and European Union
3. Explore global initiatives of quantum communication
4. Grasp quantum communication's role in shaping the future of education and research

Our special thanks

[1] https://quantum2025.org

This white paper synthesises insights obtained via desk research with those gained from consultations with experts and other people working in and around the field. It offers a comprehensive overview of the quantum communication landscape. The consulted individuals are listed below:

- Clara Osorio Tamayo, senior scientist at TNO and lead of Quantum Delta NL's Quantum Sensing Applications Programme
- Marten Teitsma, professor and program manager of Applied Quantum Computing at the Amsterdam University of Applied Sciences and initiator of the Talent and Learning Centre at Quantum Delta NL
- Lolke Boonstra, ICT research expert at the Innovation department of ICT, TU Delft

1.2 Some definitions

- Quantum Computing (QC): the behaviour of quantum physics applied to computing.
- Quantum Communication: an emerging communication paradigm that encodes information in a quantum state.
- Quantum Key Distribution (QKD): a quantum communication protocol that enables the distribution of a secret key between two points/people that cannot be intercepted.
- Quantum Network: the physical infrastructure that enables quantum communication.
- Quantum Sensors: a type of sensors where quantum mechanical effects, like coherence and entanglement, translate stimuli into electric signals.
- Qubits: building blocks of quantum data (qubits instead of classical bytes).

2 What is Quantum communication?

Quantum communication is rapidly growing in maturity and importance. It enables new types of connectivity by utilising the principles of quantum mechanics. Quantum communication uses quantum states to encode, transmit, and decode information. Its three main characteristics are:

1. stronger-than-classical correlations;
2. privacy and security guarantees at the physical level;
3. connecting quantum devices.

2.1 Stronger-than-classical correlations

Classically (i.e. without quantum mechanics), throwing two fair coins in two separate locations would result in two series of random, but uncorrelated, outcomes. That is, the result of each coin throw in one location would be perfectly random but would not tell you anything about the result of any coin throw in the other location. With quantum mechanics, you can achieve correlations that are not possible classically. It is possible to construct a quantum equivalent of our thought experiment in which the results of the coin throws remain perfectly random, but which are also perfectly correlated. That is, the result of a coin flip at one location, while perfectly random, would always be the same as the result of the corresponding coin flip at the other location. This effect generalises beyond two locations and to more complicated correlations and leads to opportunities for tasks that require coordination.

2.2 Privacy and security guarantees at the physical level

Classical data can be read and copied without any side effects on the data itself. This is fundamentally not possible for quantum data. Performing a measurement on an unknown piece of quantum data will modify the state of the quantum system, and a process for copying quantum data is simply physically not possible. It is also possible to construct quantum states that physically cannot be shared between arbitrarily many parties effectively creating untappable connections. This means that quantum data is protected at the physical level in ways that classical data can never be, leading to opportunities in the domain of privacy and security.

2.3 Connecting quantum devices

Quantum devices can be easily connected over the classical Internet, much like quantum computing in the cloud is made available today. However, this communication is limited to the classical inputs and outputs of quantum processes. Quantum data created in the processes cannot be communicated using classical channels. Therefore, in order to have quantum processes in two independent devices interact with each other at the quantum level quantum communication is needed. This makes quantum communication a key enabler for distributed and networked quantum computing as well as other networks of quantum devices, such as networks of quantum sensors.

3 Quantum communication in the Netherlands and Europe

3.1 Developments in the Netherlands

The Netherlands envisions becoming a global leader in quantum innovation by fostering an ecosystem that integrates cutting-edge research, technology development, and real-world applications. They are pursuing an ambitious quantum strategy to become a top 3 quantum economy by 2035 (QDNL, 2023). Building on its pioneering national quantum strategy and key initiatives like QuTech, QuSoft, and Quantum Delta NL, the country is poised to accelerate quantum technology advancements and commercialisation. The current focus is on deploying a secure national quantum network coordinated by Quantum Delta NL through various initiatives, such as QCINed. Quantum Delta NL is funded by the national growth fund (615,2M Euros[2]), highlighting the government's commitment to linking quantum breakthroughs with the broader digital infrastructure ecosystem.

In the next few years, the Netherlands envisions world-class research institutions, test facilities and production lines for quantum technologies. This needs to be backed up by workforce and industry support. New educational programs have been introduced to promote quantum technology education. One of the challenges with the future of quantum communication is the lack of skilled labour and workforce to build the technology (Bogobowicz et al., 2023). The talent pool remains limited thereby creating a bottleneck for innovation and large-scale deployment.

Additionally, QuSoft's dedication to developing novel algorithms and applications underscores our emphasis on software innovation to complement its hardware achievements. QDNL mentions four main priorities to achieve this vision of establishing the Netherlands as a leader in quantum technology (QDNL, 2023):

1. Technology acceleration: building programs that foster innovation, collaboration, competition, and drive advancements in quantum technology.
2. Commercialisation: a strong emphasis is placed on technology transfer, industry engagement and startup development to facilitate the transition of ideas from educational and knowledge institutions.
3. Internationalisation: building international partnerships and attracting talent and companies from the outside in the Dutch ecosystem.
4. Fabrication: building fabrication facilities that are required for pilot projects, mid and high-level production. Since academic infrastructure is mainly for research, development and prototyping, it would be useful to have dedicated facilities for larger scale productions.

[2] https://www.nationaalgroeifonds.nl/overzicht-lopende-projecten/thema-sleuteltechnologieen-en-valorisatie/quantum-delta-nl

3.2 Europe's quantum initiatives and investments

The European Union is positioning itself as a leader in quantum communication by actively integrating quantum communication initiatives into their broader digital strategy. Through these initiatives, the EU envisions a future where quantum communication technologies become a cornerstone of its digital sovereignty and economic growth (*The European Quantum Communication Infrastructure (EUROQCI) Initiative*, 2024). The EU is advancing through its Quantum Flagship program and pan-European collaborations, outlined in Section 3.2, with Germany, France, and the Netherlands as the largest players in terms of initiatives (Ministry of Economic Affairs and Climate Policy, 2024). One of those comprehensive initiatives is EuroQCI, aimed to establish ultra-secure communication channels across member states (Choucair, 2024). This initiative not only enhances the security of critical communications but also fosters a thriving European quantum ecosystem, driving innovation, market expansion, and the development of new industries in the quantum sector.

The EU Commission has also been working on building agreements such as the Framework Partnership Agreement (FPA) in quantum communication. The goal of initiating these agreements is to establish stable and structured partnerships between the Commission and the institutions and organisations, who commit themselves to establishing, maintaining and implementing the road map in communication technologies. Examples of FPAs are:

- The Quantum Internet Alliance (QIA), a pan-European collaborative effort works towards developing technology to make the quantum internet a reality. The aim is to enable advanced applications beyond QKD through scalable software and network stacks.
- Quantum Secure Network Partnerships (QSNP) focuses on further developing quantum cryptography technologies to secure internet communications, ensuring resilience against future cyber threats.

4 Global developments in quantum communication

Looking ahead, the potential of quantum communication is promising. McKinsey's Quantum Technology Monitor (2023) estimates quantum communication to have a global market share of around 7 to 9 billion dollars by 2040. Quantum communication robustly protects sensitive information in healthcare, financial systems, and military operations as quantum computers are expected to break classical encryption protocols in the next few years. Quantum communication could account for an estimated $8 billion in revenue by 2030 (*Shaping the Long Race in Quantum Communication and Quantum Sensing*, 2021). These innovations also have transformative potential in space-based systems like satellites, which could serve as nodes in a global quantum network, facilitating secure communications across continents.

Major players in quantum communication include China, the United States, and the European Union, each making significant strides. Emerging players like Russia, India, Japan, and Canada may play pivotal roles.

4.1 China

China is noteworthy for its achievements, such as the Micius Satellite its extensive QKD network infrastructure, and state-driven initiatives (Krause, 2024). In 2017, the Micius satellite helped stage the world's first intercontinental, QKD-secured video conference between Beijing and Vienna. The longest QKD network in China boasts a 2032 km ground link between Beijing and Shanghai. Banks and other financial companies are currently using it to transmit private data.

4.2 The United States

The United States follows with government-led efforts like the National Quantum Initiative Act and QNext, alongside contributions from private companies, startups, and military research into quantum-secure communication. A startup in the US, Quantum Xchange is working on building an 88,87 km QKD network linking Manhattan and New Jersey to support the large data centres that banks have in these locations (Giles, 2024).

4.3 Geopolitics

Strategically, quantum communication has implications for cybersecurity, defence, global standards, and governance. It also raises ethical challenges and risks of weaponisation, underscoring the need for international collaboration and responsible development. In 2023, the United Nations Institute for Disarmament Research (UNIDIR) organised a multi-stakeholder dialogue on quantum technologies. The discussion centered on identifying potential threats posed by quantum advancements and exploring strategies to address them. Policymakers face challenges balancing innovation, global collaboration, and security in advancing quantum technologies. This also involves maintaining the relationship between governments and the private sector, if companies which already dominate the global cloud computing market are going to offer quantum compute resources over the cloud, existing structural dependencies on these companies may solidify (The Quantum Race: U.S.-Chinese Competition for Leadership in Quantum Technologies - IGCC, 2024).

5 Potential impact on education and research

There are opportunities for applications in the semiconductor industry and photonics, cybersecurity technology and post-quantum cryptography (Ministry of Economic Affairs and Climate Policy, 2024). There are social benefits expected in education and research. Marten Teitsma mentioned that it is unclear how quantum communication will be useful, especially with new technologies such as AI already changing the teaching and learning landscape. In this part, we'll try to grasp how or where we might see the applications of quantum communication in education and research.

5.1 Cybersecurity for institutions

One of the key benefits of quantum communication is its ability to enhance cybersecurity for universities and research institutions. As cyber threats grow, protecting sensitive student data, research findings, and academic resources becomes increasingly important. This could protect research on topics such as photonics and food security. Additionally, it could prevent cyber-attacks on student records, online exams, and university databases while enabling safe international collaborations.

5.2 Decentralised infrastructures

Quantum communication has the potential to enhance our abilities for coordination between multiple devices. In an ever more connected world this could lead to completely new applications based on infrastructures that are technologically not feasible today, either because they would be insecure or because they cannot scale to the size of the internet. For example, with a quantum network it will be possible to collect statistical data without having any of the participants reveal their values to each other. This potentially opens opportunities for decentralized infrastructures by reducing our need for a central authority thus enabling research and education institutes to collaboratively build their own digital infrastructures.

5.3 Virtual classrooms and real-time collaboration

Education could also be transformed by quantum communication. Virtual classrooms could be enhanced with secure, real-time connections, allowing students to interact with experts worldwide without concerns about data security or their privacy. Quantum communication could drive the concept of virtual worlds for a seamless integration of physical and digital worlds together with XR and AI technologies.

6 Conclusion

This whitepaper explored the geopolitical narratives surrounding this emerging technology, which could influence its growth, adoption, and global competition. However, the full extent of its capabilities and integration into education, research, and society remains uncertain. Overall, the potential of quantum communication is vast, with applications that will become clear over time. The development of quantum networks – a network secure on the physical level - could reshape how information is shared and protected. However, there are also innovations in the classical network such as clock synchronisation, lowering the latency and light path connectivity up to 800 Gbit/s.

The developments and breakthroughs in quantum communication will continue. Preparing the workforce and educating students in this field will be a crucial step to contribute to quantum technologies development and help bridge the gap between research and practical implementation. As quantum communication continues to evolve, policy discussions will be essential in shaping a secure and efficient quantum-powered future.

Regardless of the advancements, investments and politics, we must continue our exploration. The realisation of the concept of quantum communication is only a matter of time. To better understand, anticipate, prepare, we must ask ourselves what futures with quantum communication could look like.

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Editor(s)
Akcaova, Gül
Brugmans-Slot, Dorien

Year of publication
2025

Version
1.0