



Quantum Communication and Networking

Ed Kuijpers¹

HBO-ICT Technical Computing

June 6, 2024

¹e.a.kuijpers@hva.nl



Table of contents

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- ① Introduction
- ② Space
- ③ Theory
- ④ Communication background
- ⑤ Quantum communication
- ⑥ Bell inequality loophole test
- ⑦ Simulation
- ⑧ Conclusion and further work



Recent developments

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- Revolutionary qubit technology
- Google simulation development
- Record space laser communication



Relevance quantum stack

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- 1.) Distributed Quantum Computers
- 2.) Secure interfacing
- 3.) Interfacing sensors
- 4.) Spin-off technologies
- 5.) New applications



Quantum Internet Hackathons

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

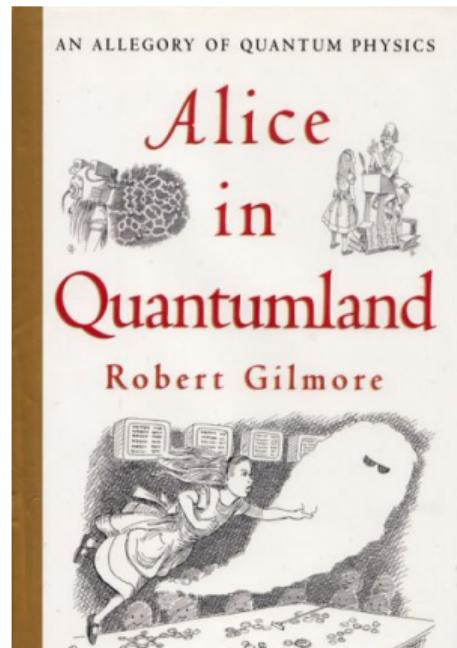
Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

[Quantum Internet Hackthon 2024 Dutch participation with students \(with RIPE NCC and Quantum Internet Alliance Use case group\) with SURF involvement](#)





Future of Digital Infrastructure event

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Future of quantum internet event part of Quantum meets 2024





activities Europe

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work



- EU Quantum Flagship projects, Quantum Internet Alliance
- Laiqa: Leap in Advancing of critical Quantum key distribution-space components
- ESA Quantum Technologies



activities Netherlands

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work



The Netherlands started projects as part of Quantum Delta NL : [Quantum Delta](#)



activities Qutech

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

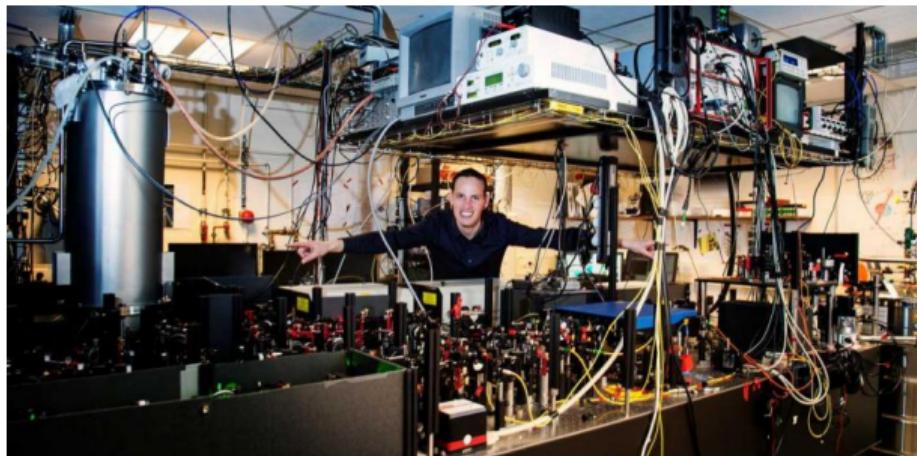
Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- Milestones
 - Quantum internet
- Quantum internet demonstrator
- Quantum Internet
- development steps
- Ronald Hanson lab
- TNO and quantum internet
- QuTech demonstrator





Quantum Internet Explorer 1

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Quantum Network Explorer, QNE demos

The screenshot shows the Quantum Network Explorer (QNE) interface. At the top, there is a navigation bar with tabs: 1. Map (selected), 2. Network, 3. App, 4. Overview, Help?, Save, Run, and a close button (X). The main area is titled "Choose network and roles". It contains a sidebar with the text "application on." and a section titled "Assign application roles" with two buttons: "Controller" (purple circle) and "Target" (orange circle). Below this, it says "Assign the application roles by dragging and dropping them onto the city of your preference." There is also a checkbox for "Expert mode" with the description "In this mode you can adjust more inputs as an expert". At the bottom of the sidebar is a "Next Step" button. The main map area shows several cities in the Netherlands: Haarlem, Almere, Amstelveen, Hilversum, Utrecht, Zeist, Nieuwegein, Gouda, Zoetermeer, Delft, The Hague, Rotterdam, Brielle, and Hoek van Holland. A connection path is drawn from "Controller @ Leiden" (purple circle) through The Hague and Delft to "Target @ Amsterdam" (orange circle). The path is labeled "Fidelity: 1.000". The map includes a legend for "mapbox" and "OpenStreetMap" and a link to "Improve this map". At the bottom right, there is a set of small navigation icons.



Quantum Internet Explorer 2

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Quantum Network Explorer

Quantum Network Explorer
By Qutech

Distributed CNOT
08-May-2022 / 22:12:55, Running on simulation

Process Result Reconfigure X

Application run results

Theta: 1π rad
Phi: 0π rad

Previous

A screenshot of the Quantum Network Explorer interface. On the left, a window titled 'Application run results' displays a 3D Bloch sphere with axes labeled x, y, z. Below the sphere are the values 'Theta: 1π rad' and 'Phi: 0π rad'. At the bottom of this window is a 'Previous' button. To the right of this window is a map of the Netherlands, specifically the western part including Haarlem, Zandvoort, Heemstede, De Zilk, Hoofddorp, Almere, Uithoorn, Mijdrecht, and Vreeswijk. Two nodes are highlighted: 'Controller @ Leiden' at the bottom left and 'Target @ Amsterdam' at the top right. A blue line with a wavy pattern connects these two nodes across the map. Below the map, there are two small circuit diagram icons. At the very bottom of the interface are several navigation icons.



Quantum computing and communication

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- Towards Large Scale Quantum Networks [1]
- Qutube: [Quantum internet](#)
- Qutube: [Applications](#)
- Qutube: [Repeaters and difficulty](#)
- [First quantum network Delft'](#)
- [Researchers establish the first entanglement-based quantum network\(\[2\]\)](#)
- Theory: [3], [4]
- Popular: [5]



Quantum internet tasks

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- Key distribution
- Clock synchronization
- Baseline telescopes
- Anonymous transmission
- Byzantine agreement (distributed processing with unreliable components)
- Blind computing



Space

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- **ESA Quantum Technology**
- Samples on following pages based on conferences presentations



Recent ESA activities 1

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Highlights of the past 12 months

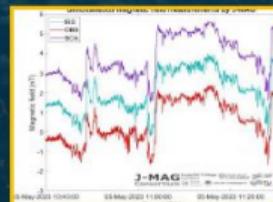


14 April 2023: Juice launches to Jupiter with quantum sensor MAGSCA

MAGSCA measures the absolute strength of the magnetic field. It uses the Zeeman effect, which causes a splitting of electron energy levels in proportion to the strength of the magnetic field. The quantum effect is generated by specifically modulated laser light interfering with rubidium atoms in the glass cell of the sensor.

Testing quantum entanglement in zero-g

A quantum test setup was built into the Air Zero-G aircraft for the tests during an ESA parabolic flight. The results of the parabolic flight experiment demonstrate that quantum entanglement is remarkably robust - no effect due to the changes of acceleration was observed.





Recent ESA activities 2

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Highlights of the past 12 months



Cold atom interferometers as supplementary navigation solutions

A NAVISP project consortium has developed a compact 3-axis Cold Atom Interferometer sensor, aimed for use aboard boats, aircraft and boats as well as at fixed sites.

SAGA Phase B1 Studies

Two competitive industry studies and technology developments defining the QKD space segment for the EC led EuroQCI. SAGA will be the space segment of the EC governmental QKD service.

First ESA activities on novel quantum topics for space

Quantum memories (proposals received); quantum internet (call for proposals published).



To be
continued
...



THE EUROPEAN SPACE AGENCY





Space QKD plans

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

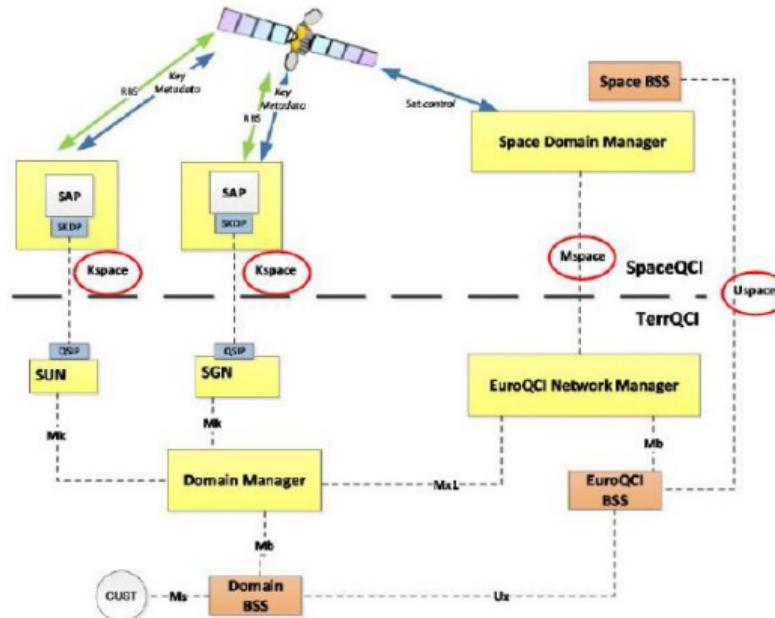
Bell inequality
loophole test

Simulation

Conclusion
and further
work

8tav

Space to ground interface





EU Quantum Computing Infrastructure

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Quantum Computing infrastructure



	2019 & 2020	2021	2022	2023	2024	2025	2026	2027
Quantum Infrastructure	1 st round 2 quantum simulators interfacing with HPC systems	2 nd round 6 quantum computers + quantum simulators interfacing with HPC systems (17 participating states and € 100 M+ procurement budget)				3 rd round new generation of quantum computers + quantum simulators most advanced platforms € 300 M)		





Space exploration and quantum

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Quantum Sensors for Science Exploration Workshop

25-26 MAY 2023

ESTEC, The Netherlands

esa

INSTIT

esa space science faculty

DLR



TNO activities 1

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

LaiQa Collaboration

TNO innovation for life

Sustainable Healthy Safe Digital Sectors Careers More ▾

EN ▾

Prototypical architecture for a satellite-based quantum communications link between two ground stations

TNO joins European collaboration to develop global quantum internet enabled from space

Beyond and quantum

The future global quantum internet is blocked due to signal losses in fiber over distance. Satellites are required so that cities and continents can be connected to eventually be part of the global quantum internet and fully benefit from its promising applications. To provide for this, TNO and the Institute of Communication and Computer Systems (ICCS) and a consortium of other European partners, join forces in the LaiQa-project (Leap in Advancing of critical Quantum key distribution-space components).

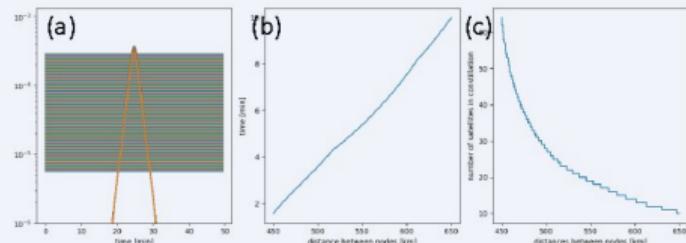
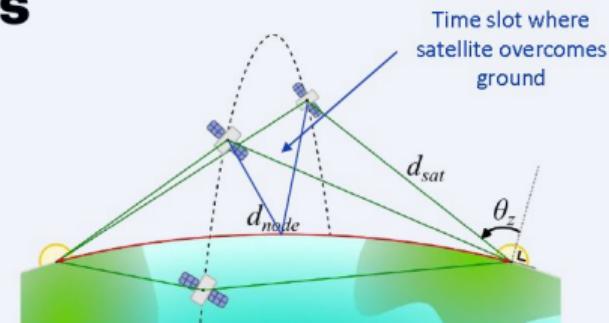
TNO innovation for life

June 6, 2024 20 of 65



Ground vs Satellite – Results

- When the orbit is taken into account, the average entanglement distribution rate per second drops
- It is interesting to observe how, within the orbit, the rates achieved by the satellite change and become better/worse than the static ground link (a)
- It is possible to extract the timeslot within which the satellite overcomes the ground link (b)
- With the above information, one can determine the minimum number of satellites required in the constellation to ensure optimal satellite coverage (c).





Test setup for loophole test

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

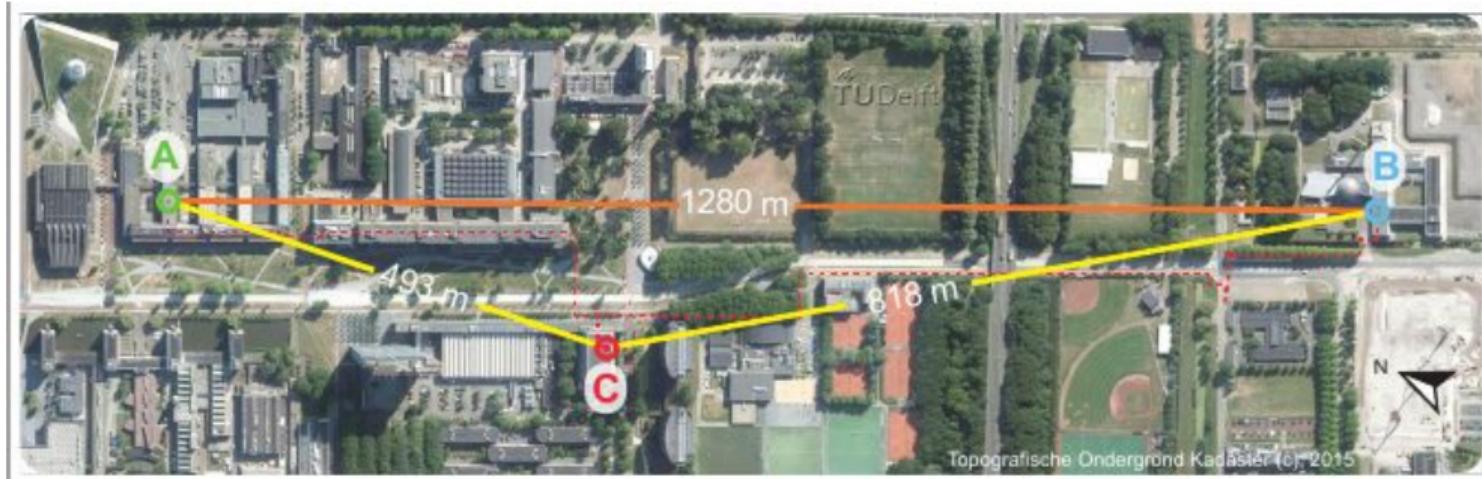
Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

[6]



Setup at TU Delft campus



Theory

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- Quantum Technology Education: A New Approach
- Github tutorials Quantum Communications

Quantum Communications



GHZ-state and Bell-state

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

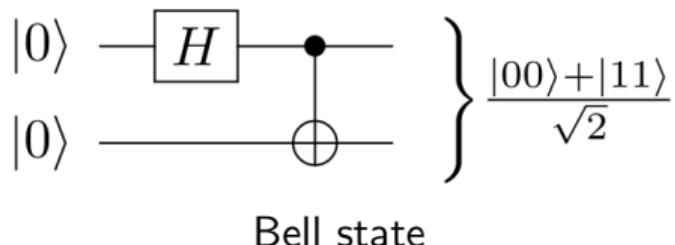
Communication
background

Quantum
communication

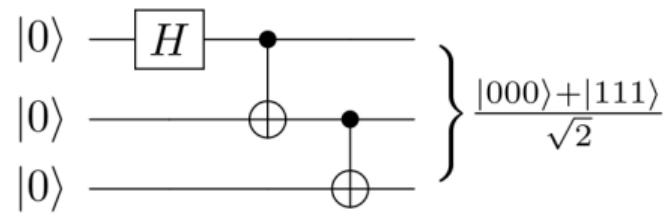
Bell inequality
loophole test

Simulation

Conclusion
and further
work



Bell state



Greenberger–Horne–Zeilinger state



Superdense coding

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

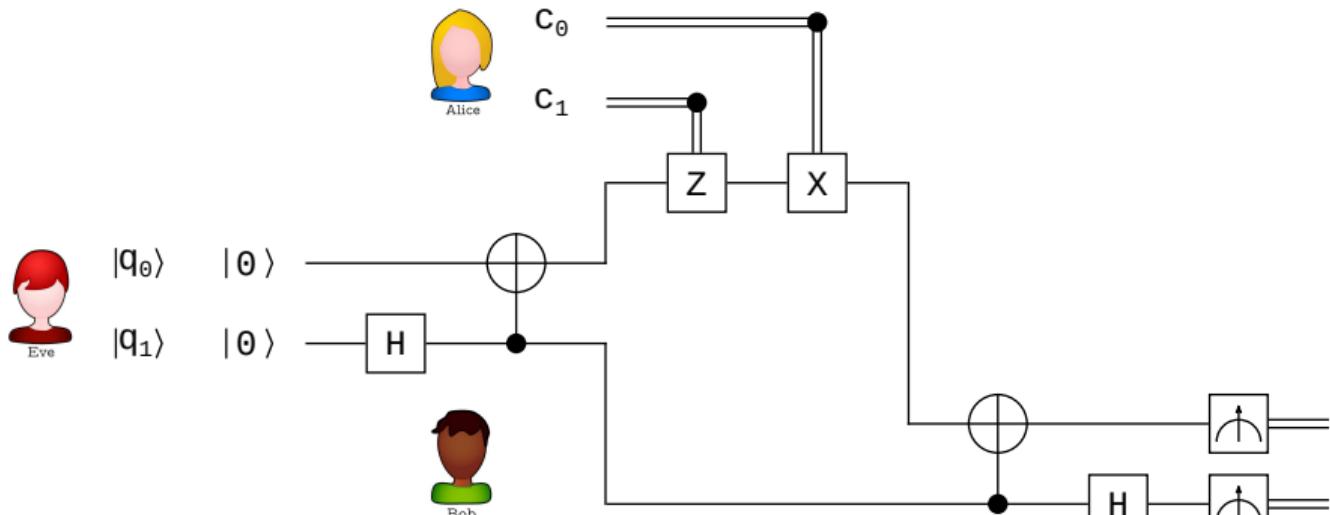
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





Teleportation

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

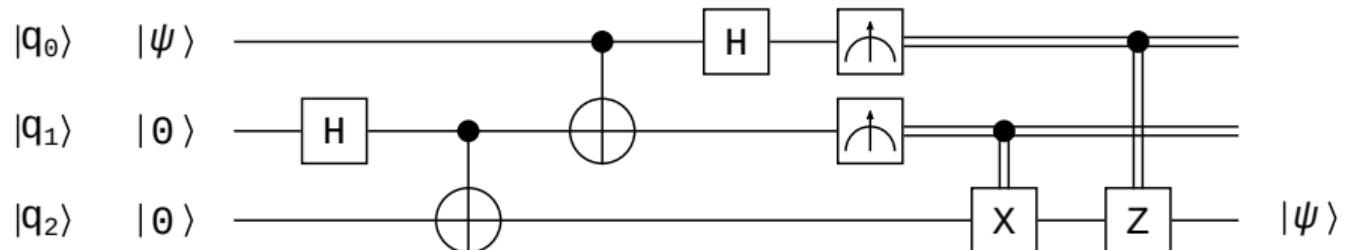
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





Quantum error correction

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

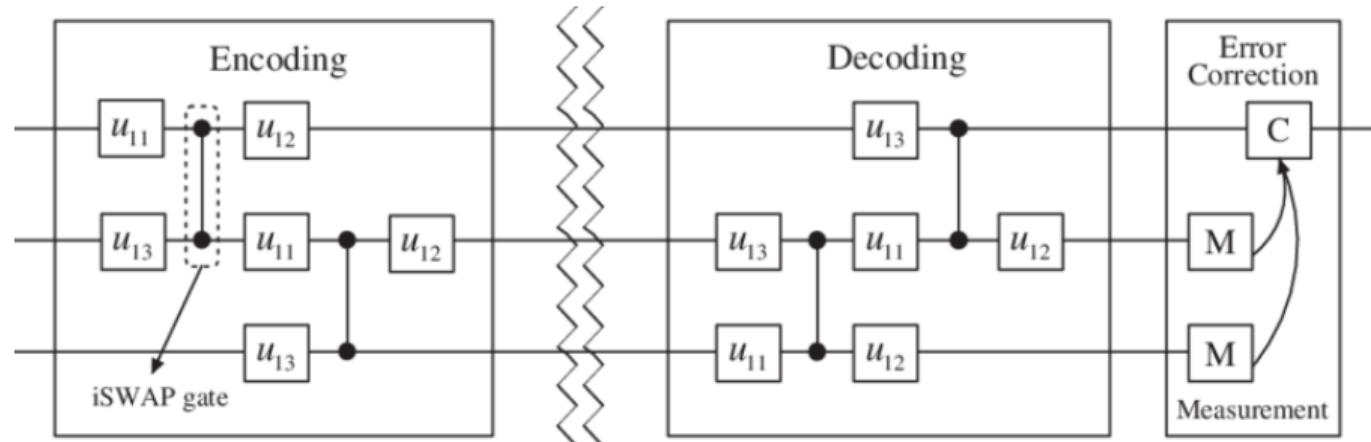
Communication
background

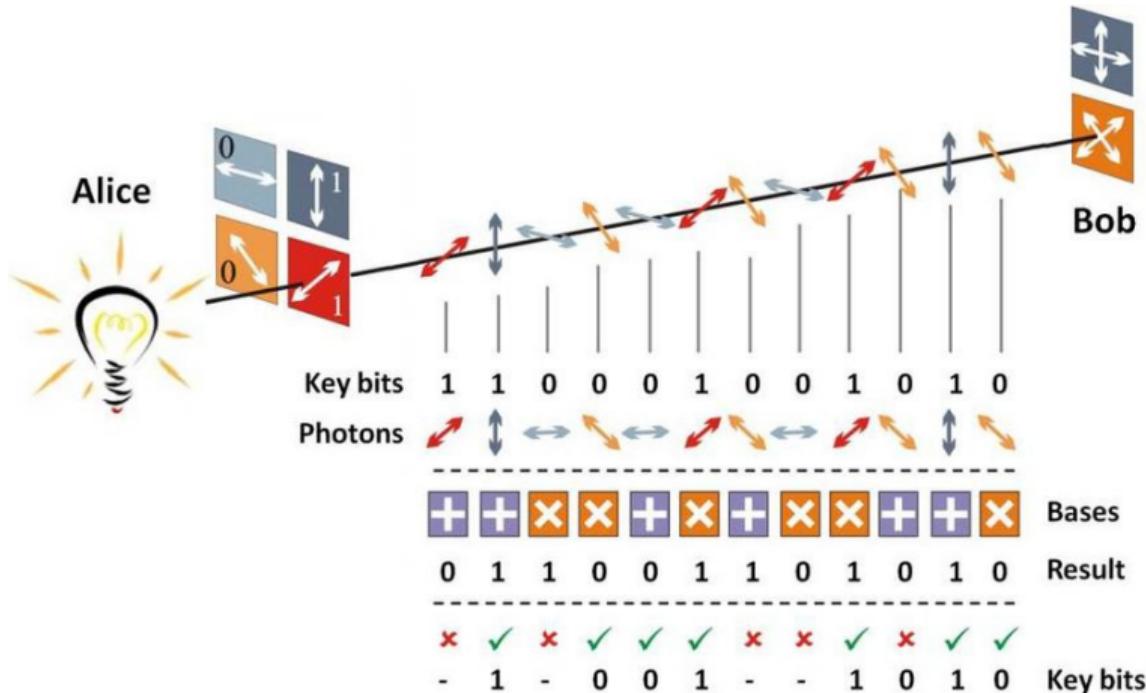
Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





Improvements: E91 and B92 [Open Courseware quantum encryption](#) TU Delft



Quantum Key Distribution via Satellite

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

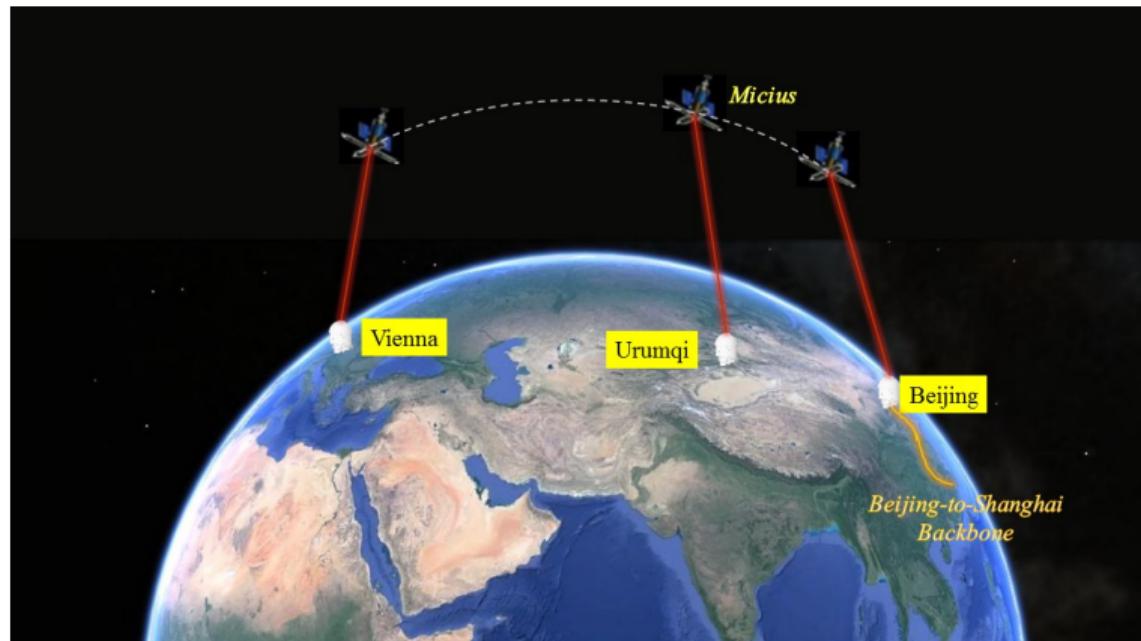
Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Experiment using entanglement in satellite communication link for quantum key distribution ([7])





Satellite communication components

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

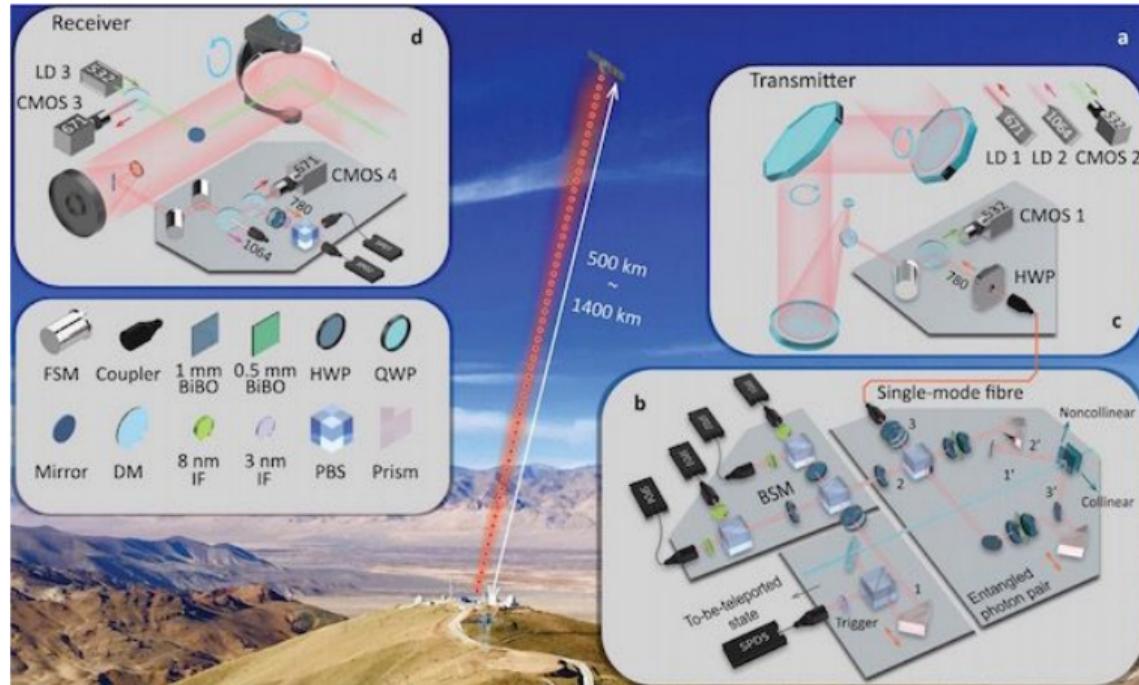
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





Satellite communication optics

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

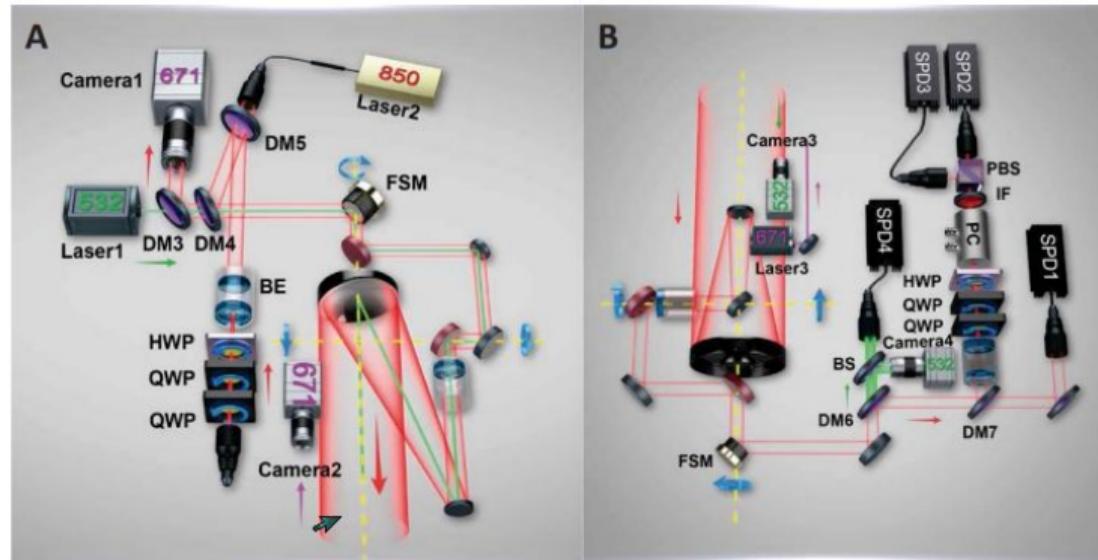
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





Hybrid networks

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

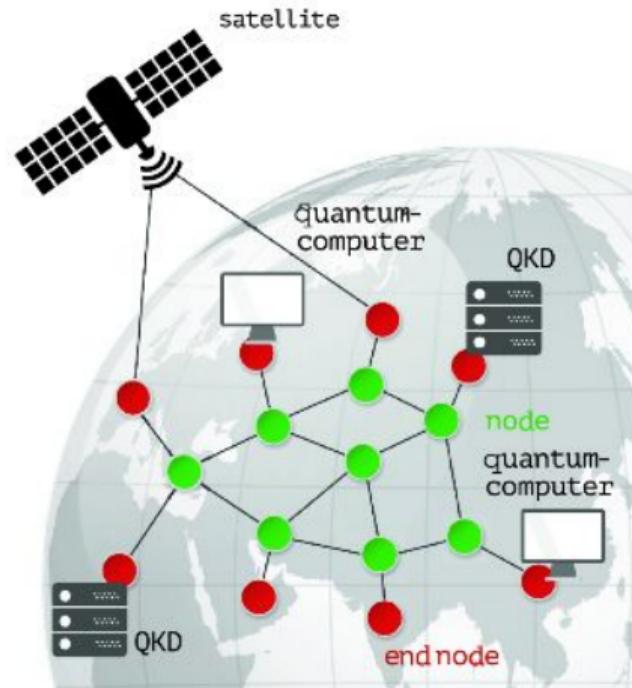
Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Direct path to satellite vs link via optical fibers using repeaters([5])





Integrated space-to-ground quantum communication network

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

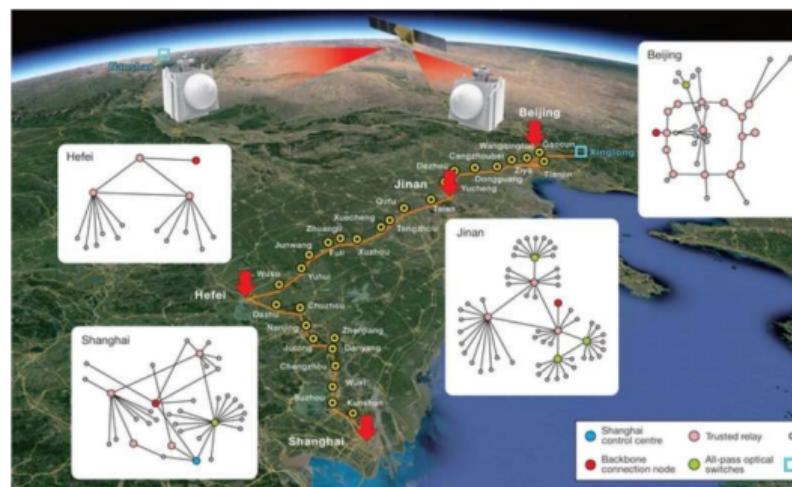
Quantum
communica-
tion

Bell inequality
loophole test

Simulation

Conclusion
and further
work

An integrated space-to-ground quantum communication network over 4,600 kilometres





Stack of protocols

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

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



Repeaters

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

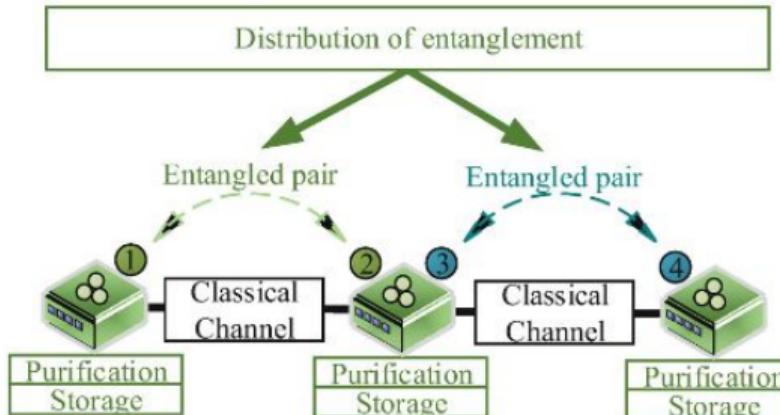
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





Repeater implementation

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

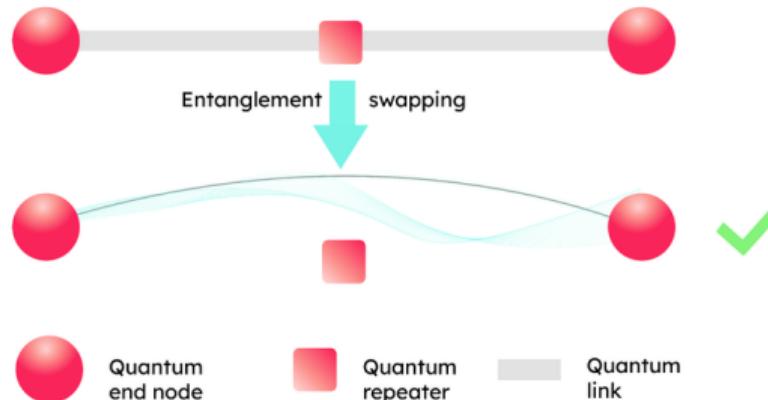
Simulation

Conclusion
and further
work

Over long distances, the chance of photon loss increases exponentially.



Quantum repeaters use entanglement swapping to create reliable long distance entanglement from shorter-range physical connections.





Vision

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

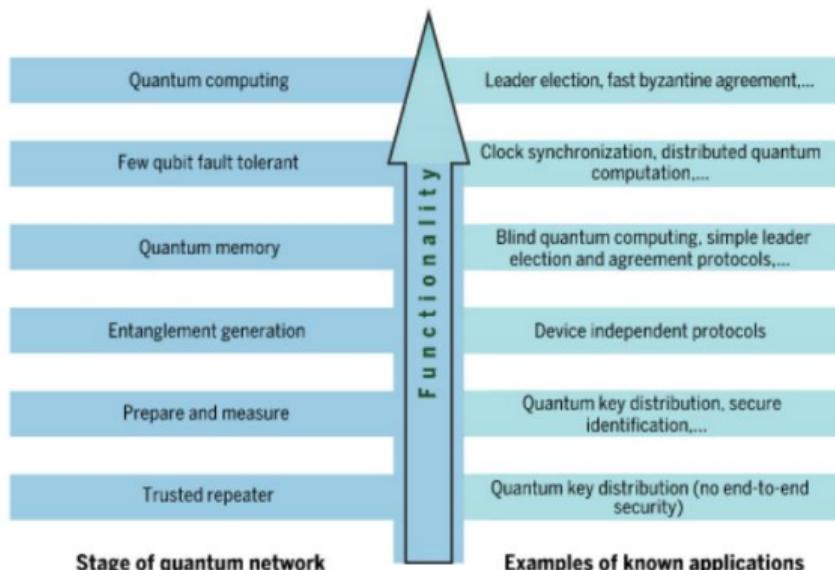
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work



Stages in the development of a quantum internet. Each stage is characterized by an increase in functionality at the expense of greater technological difficulty. This Review provides a clear definition of each stage, including benchmarks and examples of known applications, and provides an overview of the technological progress required to attain these stages.



Shannon–Weaver model communication

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

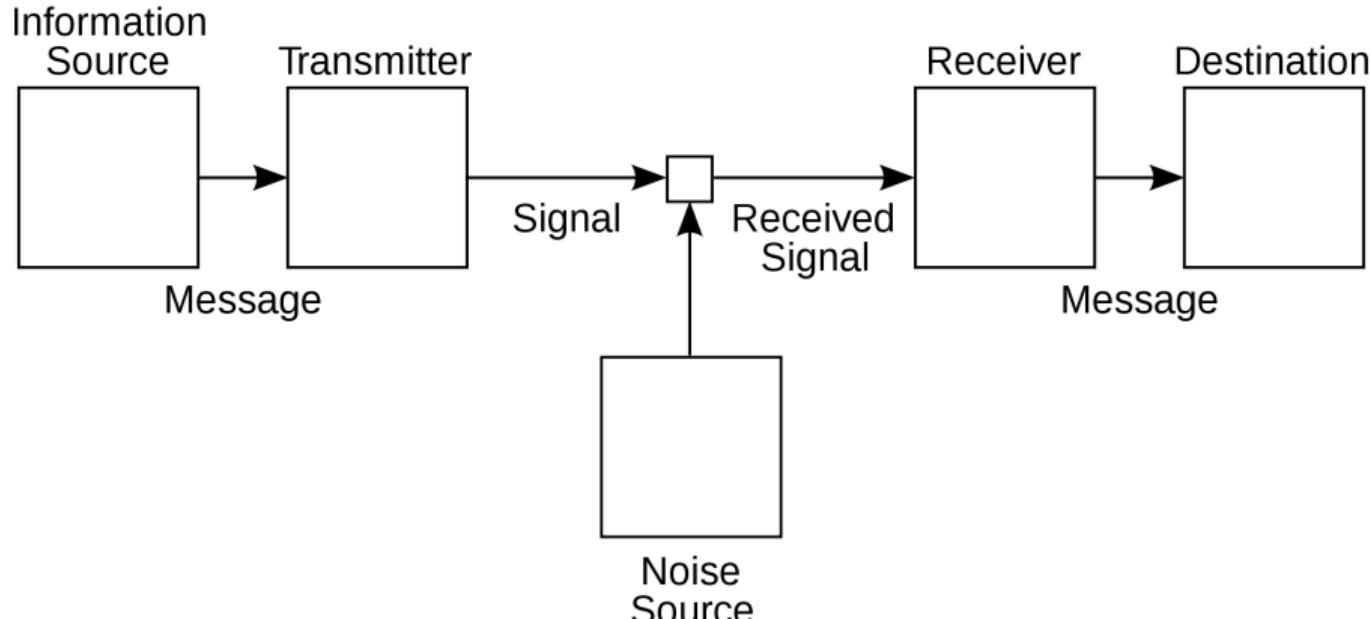
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work



Communication model used in many disciplines



Father Information theory

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Claude Elwood Shannon (April 30, 1916 – February 24, 2001) was an American mathematician, electrical engineer, and cryptographer known as a father of information theory.

([Claude Shannon - The Bit Player Movie Trailer](#))





Information and communication theory

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- Model communication in the presence of noise ([8])
- Concept of Information $H = \sum_{i=1}^N -p_i \log_2(p_i)$ (1 bit is tossing a coin)
- Entropy and Information related
- Relative entropy $KL(P||Q) = \sum_{x \in X} -P(x) \log Q(x)/\log P(x)$ (Kullback Leiter Divergence/Distance) item Qbits (continuous) instead of bits(digital)
- Von Neuman entropy concept used in Quantum Computing
- $S = \sum_{i=1}^N -\eta_i \ln(\eta_i)$ where η_i are eigenvalues.
- $\rho = \sum_j \eta_j |j\rangle \langle j|$, $S = -\text{tr}(\rho \ln \rho)$
- entropy of entanglement defines how states are related
- Basis for calculation channel capacity, error correction, for analogue and digital systems



Information and Channel capacity

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

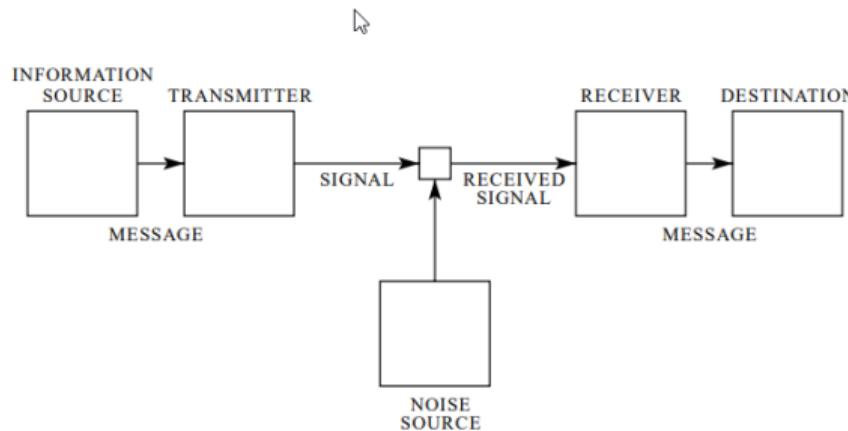
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work



Channel capacity is related to information and noise in channel, $C = B \log_2(1 + \frac{S}{N})$ where C maximum bitrate/s, channel bandwidth, S/N signal to noise power (Shannon–Hartley theorem) and basis for encoding designs



Example configuration

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

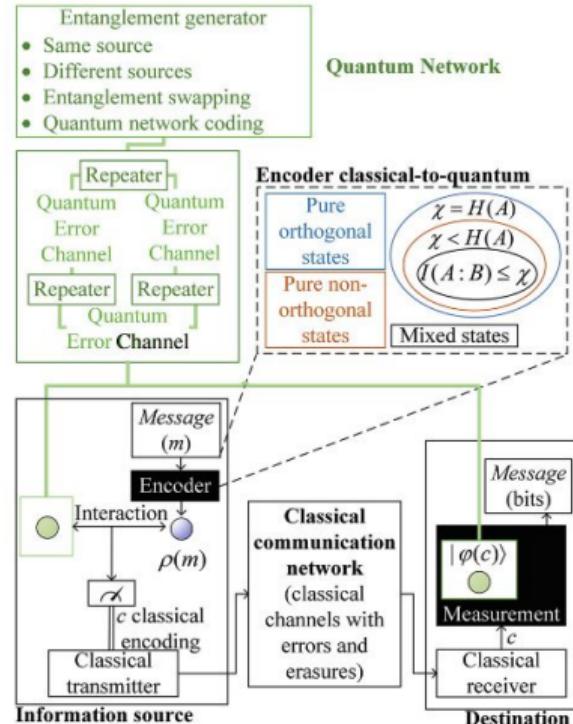
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





Electron spin qubits

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

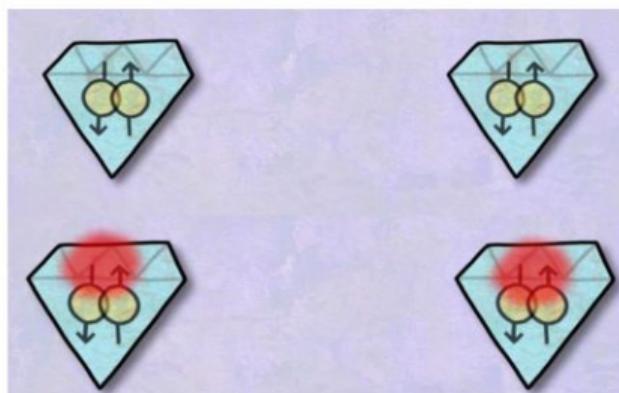
Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

NV centers: electron spin



→ electron spin and photon entangled

1. We prepare two electron spin qubits in a superposition state in distant places A and B

we can control spin with microwave pulses (rotate it), half the way is in superposition

2. We entangle them with a photon qubit:
We shine them with a laser (532 nm), which excites them and they emit photon (600-800 nm)



Photon communication

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

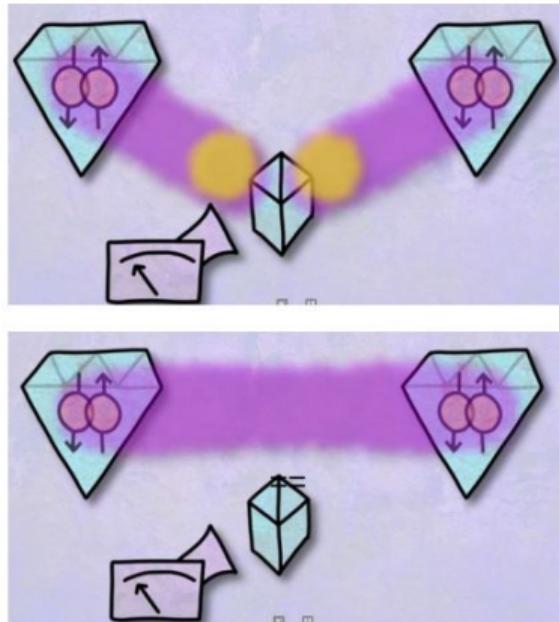
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work



4. Photons created are sent to via eg. optical fiber to a middle point where they interact
(interfere photons using semi transparent mirror, pass them through beam splitter)

5. We detect the photons, if entangled, then detection propagates entanglement to NV electrons and potentially NV memories
(try to detect emitted photons, if indistinguishable, then detection creates entanglement (Bell states) between NV centers)



Bell inequality

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

The remarkable discovery made by Bell is that in any theory of physics that is both local (physical influences do not propagate faster than light) and realistic (physical properties are defined prior to and independent of observation) these correlations are bounded more strongly than in quantum theory. In particular, if the input bits can be considered free random variables (condition of “free will”) and the boxes are sufficiently separated such that locality prevents communication between the boxes during a trial, the following inequality holds under local realism :

$$S = \langle x \cdot y \rangle_{(0,0)} + \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} - \langle x \cdot y \rangle_{-(1,1)} \leq 2 \quad (1)$$

where $\langle x \cdot y \rangle_{-(a,b)}$ denotes the expectation value of the product of x and y for input bits a and b .



Implementations

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

In Qiskit: [Local Reality and the CHSH Inequality](#), Bell's inequality CHSH inequality named after John Clauser, Michael Horne, Abner Shimony, and Richard Holt, provides an experimental framework for supporting Bell's theorem.

In PennyLane



Test setup for loophole test

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

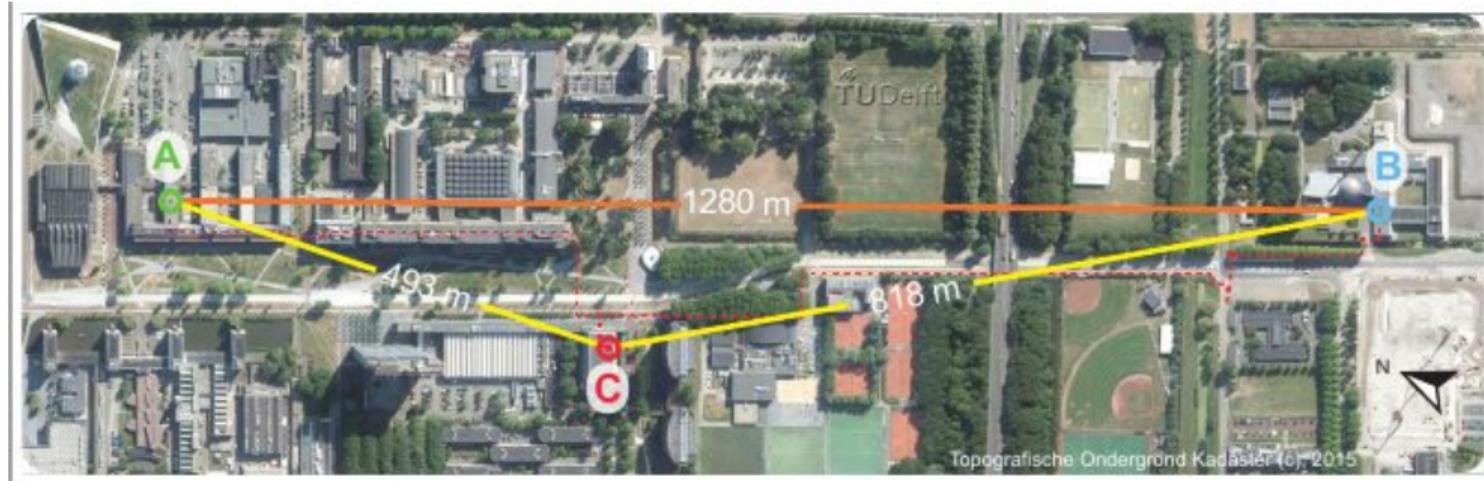
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work



Setup at TU Delft campus



Test setup cont.

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

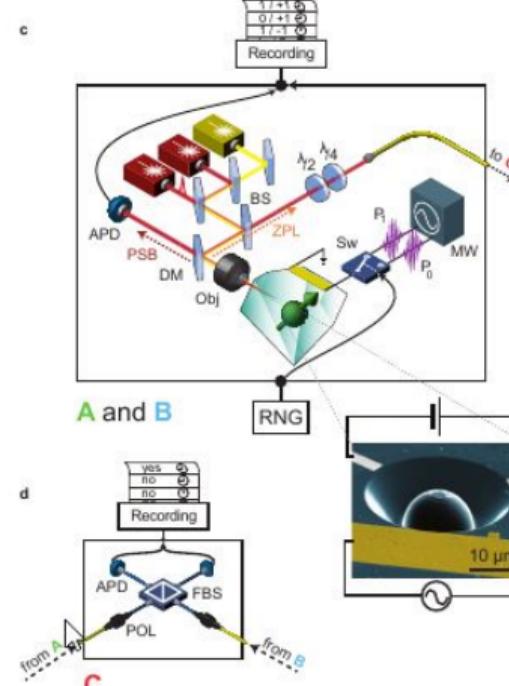
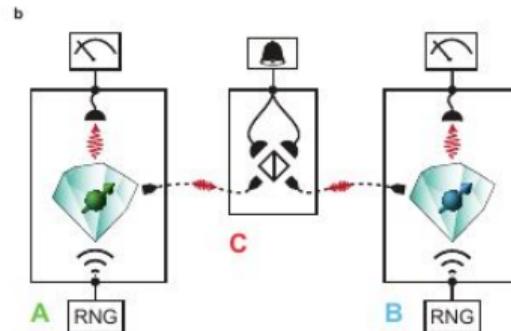
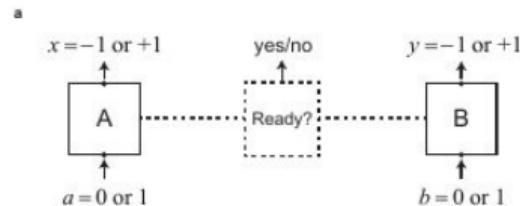
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work



Components



Quantum communication simulation

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

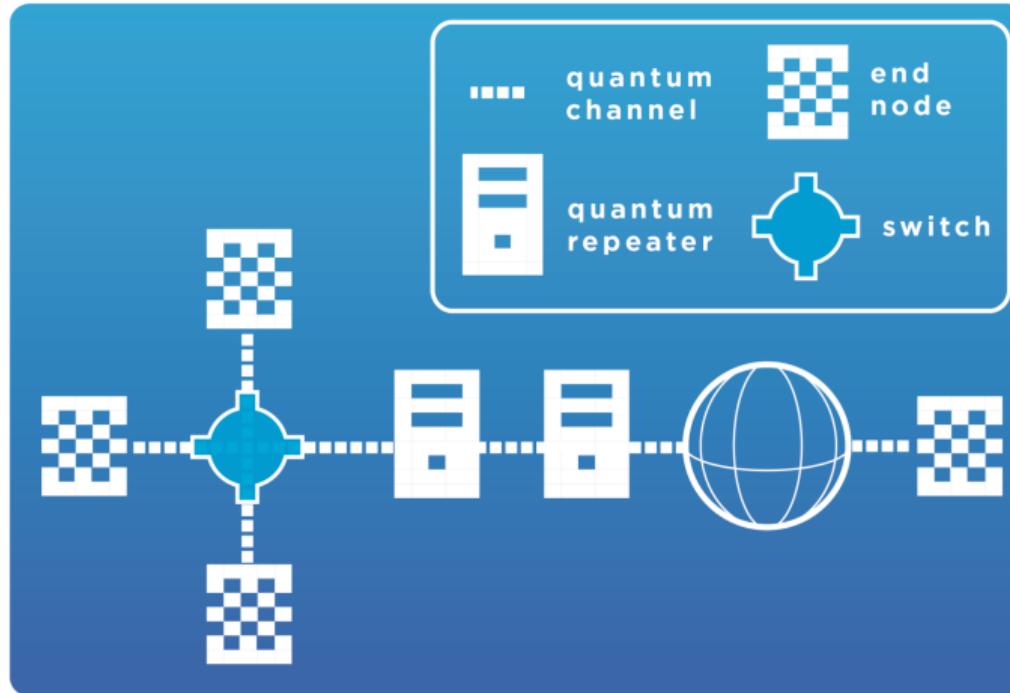
Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- [Simalcron](#): designed by QuTech at TUDelft, written in Python and Twisted
- [NetSquid \(\[9\]\)](#): collaboration between the Netherlands Organization for Applied Science Research (TNO) and the TU Delft, discrete-event simulator, focusing on quantum repeater chains and simulation of link-layer protocol. See also [Quantum Network Explorer](#) and [QNE-ADK](#)
- [NetQASM](#)
- [QuNetSim](#): the Quantum Network Simulator is a Python based simulation framework for quantum networking simulations developed in Munich.
- [Quisp](#): Quantum Internet Simulation Package developed in Japan.
- [SQUANCH](#): Simulator for Quantum Networks and Channels developed at Stanford University
- [LIQULi|>](#): Language-Integrated Quantum Operations developed at Microsoft
- [SeQUENCe](#) : Simulator of Quantum Network Communication developed by ARGONNE and univ. Chicago.





NetSquid event simulation

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

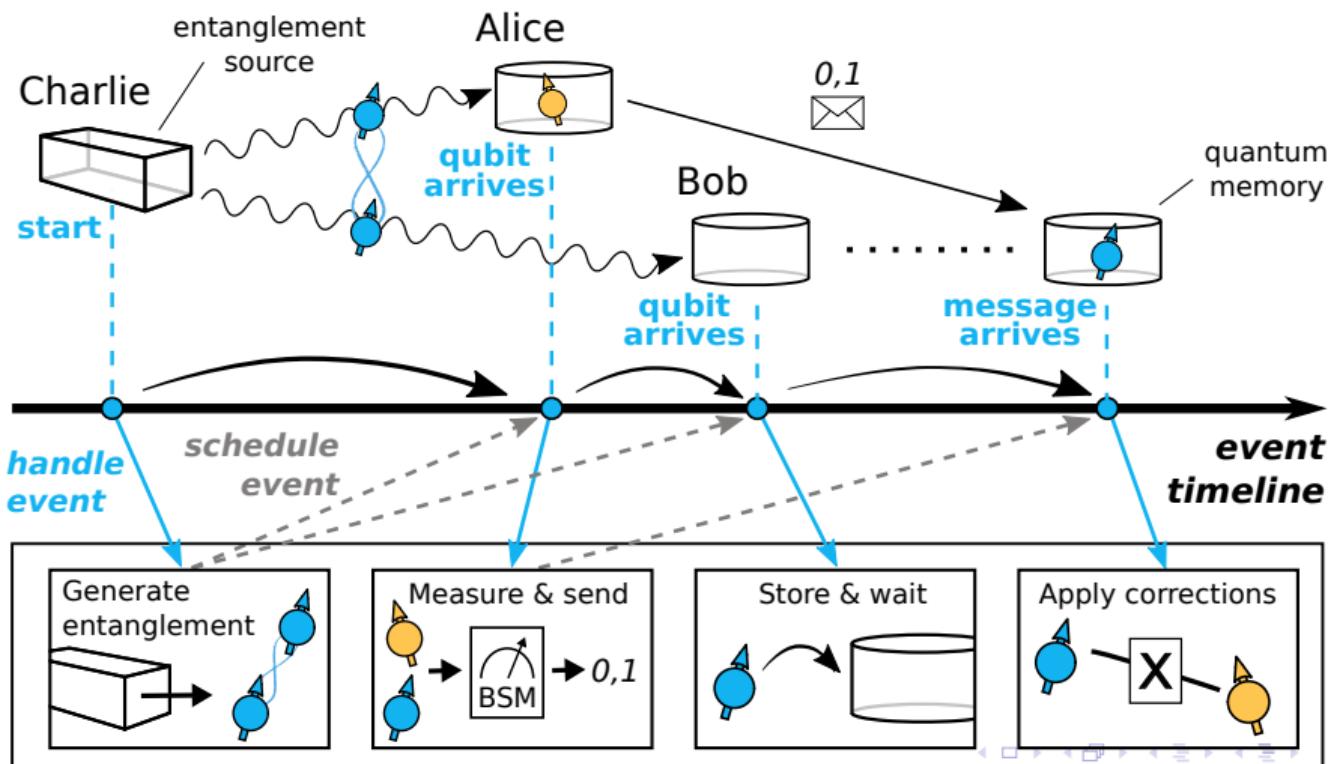
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





NetSquid design

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

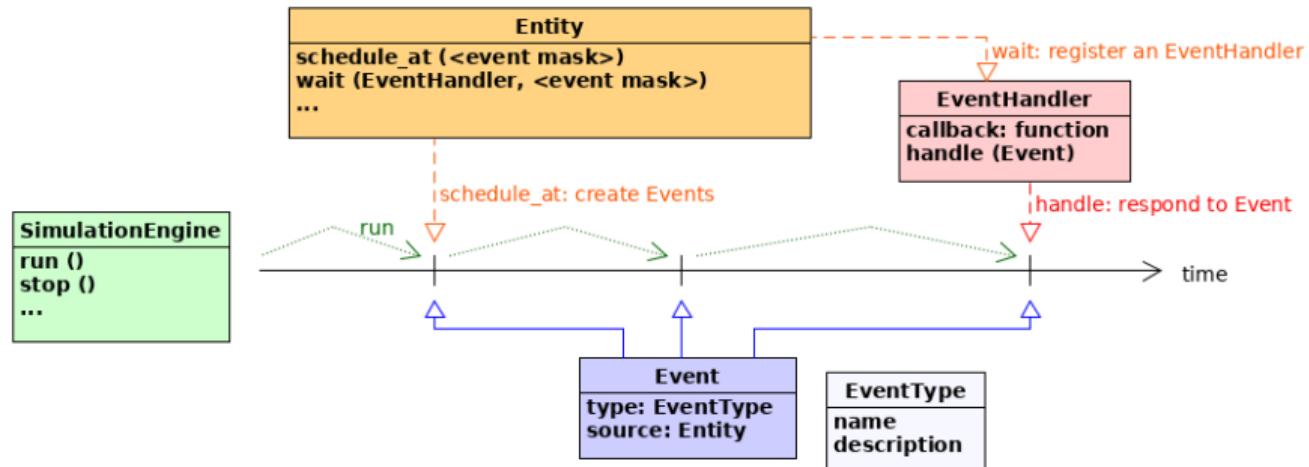
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





NetSquid nodes

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

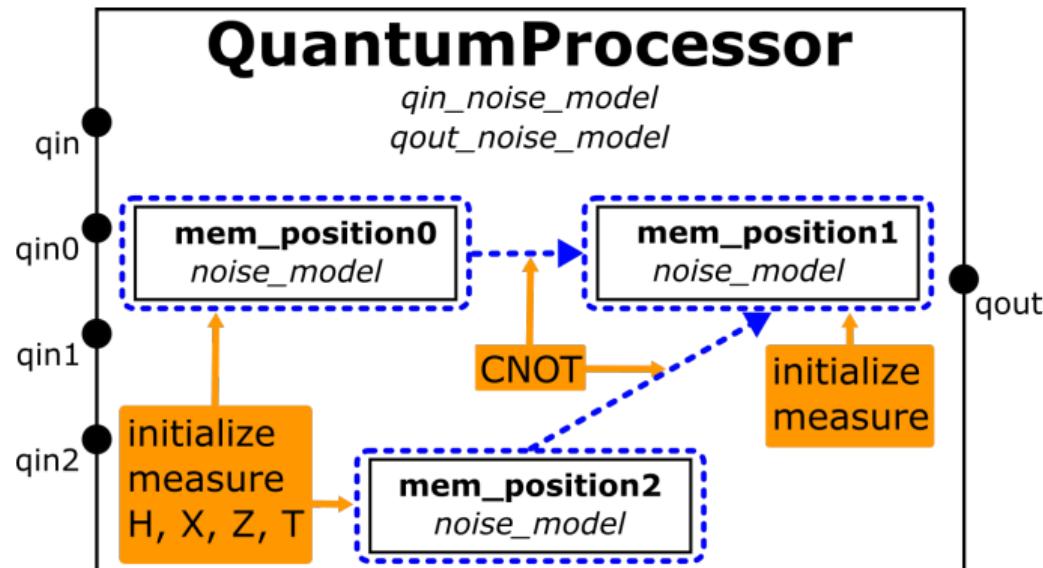
Communication
background

Quantum
communication

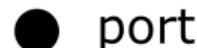
Bell inequality
loophole test

Simulation

Conclusion
and further
work



component



port

abc

model

→

topology



NetSquid example switch

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

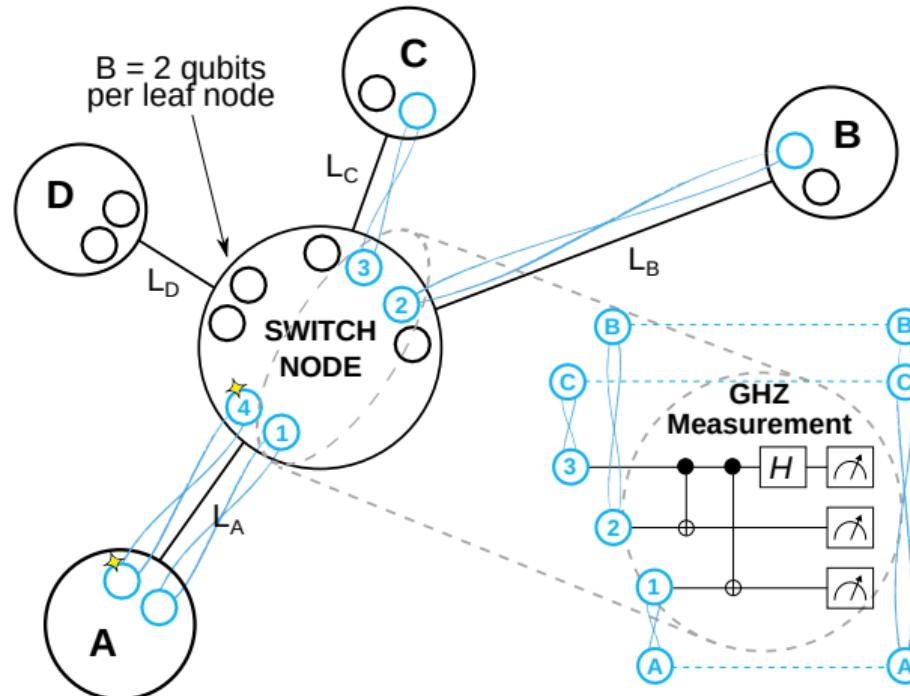
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





NetSquid Repeater

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

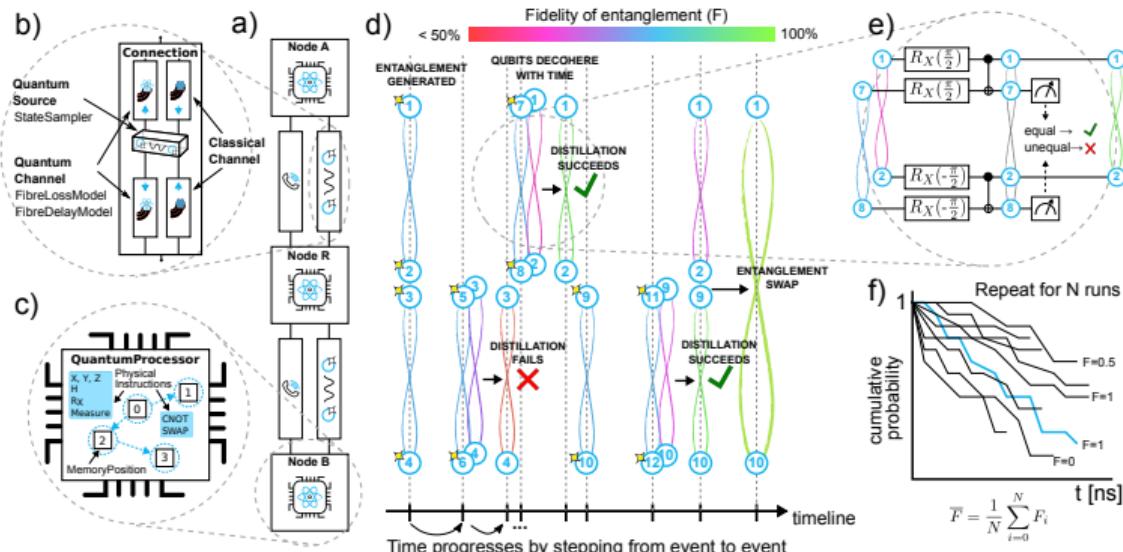
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work





NetSquid stack

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

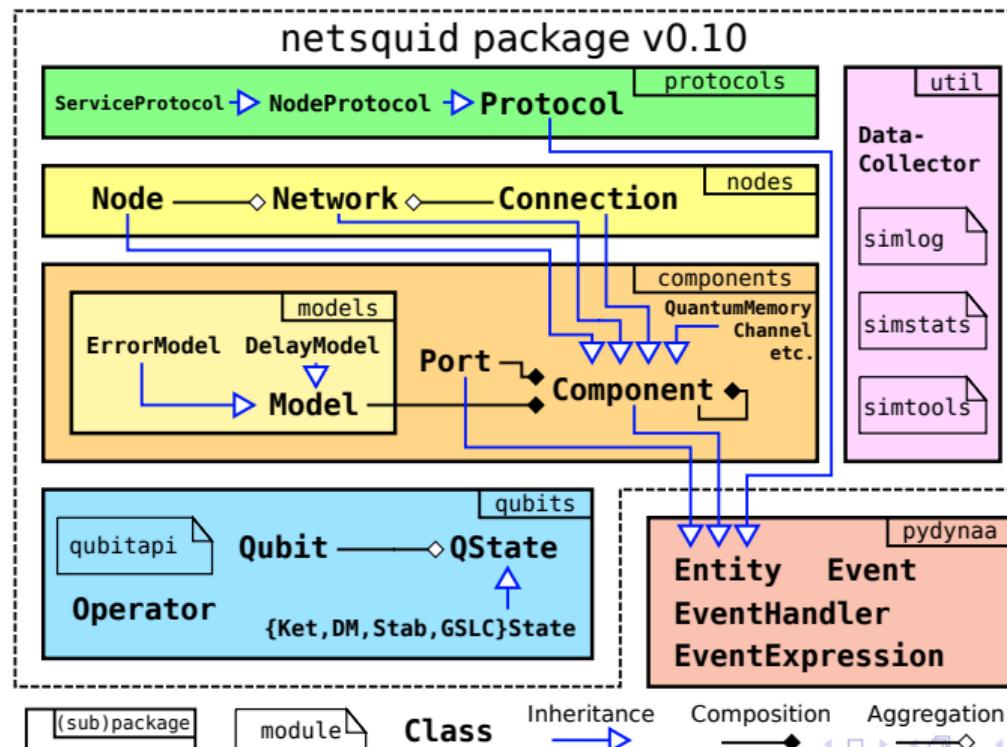
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work



(sub)package

module

Class

Inheritance

Composition

Aggregation





NetSquid Quantum internet simulations

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

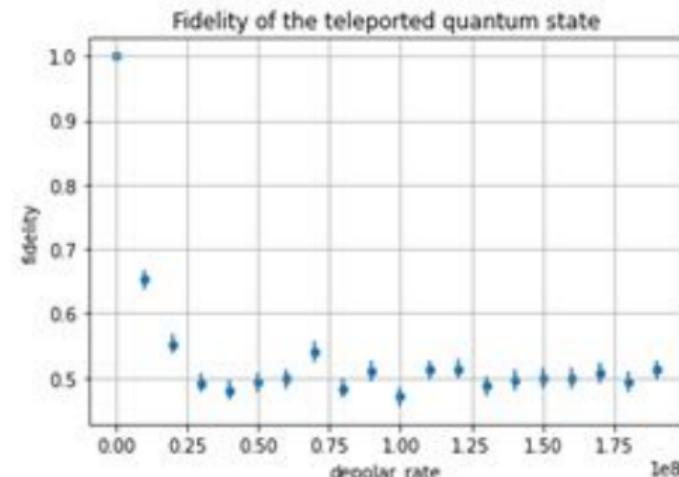
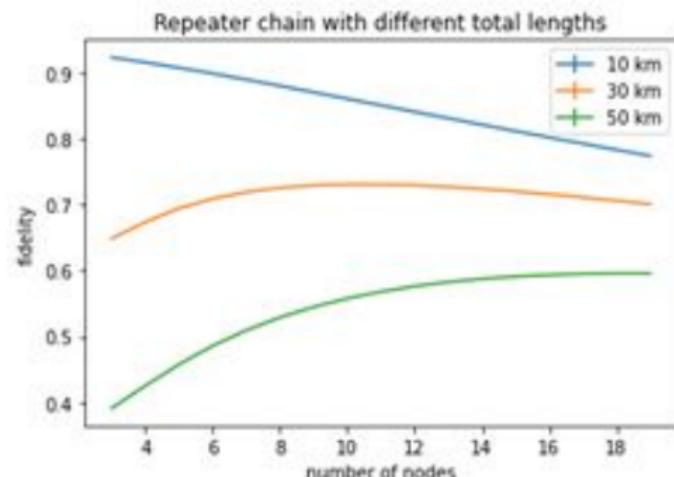
Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work



Integration of QNE Application Development Kit:[qne-adk](#)



Qiskit and further developments

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

Various import updates have become available:

- [Tutorials](#) :
 - Simulators: Device backend noise simulations, Building Noise Models
 - Quantum system error analysis
- [Quantum Error Analysis Tutorials](#)
- [Pulse schedules](#)
- [Qiskit overview: Nature docs, Optimization docs](#)
- [Qiskit Metal: Quantum device design](#)



Conclusion

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- Limited number of qubits needed in quantum stack
- Communication difficult on ground
- Communication via satellites investigated
- EU and ESA cooperation on hybrid solutions in Europe
- Simulation research tool pending real implementations
- Real quantum communication in progress in the Netherlands



Options for papers

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- Security impacts of quantum internet
- Bell inequality and implications
- Review new Qiskit extensions
- etc.



Further topics

Quantum
Communication and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- See Quantum Stack literature references
- Feedback for future activities
- Questions and feedback ?



References I

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- [1] Wojciech Kozlowski and Stephanie Wehner. "Towards Large-Scale Quantum Networks". In: *Proceedings of the Sixth Annual ACM International Conference on Nanoscale Computing and Communication*. NANOCOM '19. Dublin, Ireland: Association for Computing Machinery, 2019. ISBN: 9781450368971. DOI: [10.1145/3345312.3345497](https://doi.org/10.1145/3345312.3345497). URL: <https://doi.org/10.1145/3345312.3345497>.
- [2] M. Pompili, S. L. N. Hermans, S. Baier, et al. "Realization of a multinode quantum network of remote solid-state qubits". In: *Science* 372.6539 (2021), pp. 259–264. DOI: [10.1126/science.abg1919](https://doi.org/10.1126/science.abg1919). eprint: <https://www.science.org/doi/pdf/10.1126/science.abg1919>. URL: <https://www.science.org/doi/abs/10.1126/science.abg1919>.



References II

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- [3] Riccardo Bassoli, Holger Boche, Christian Deppe, et al. *Quantum Communication Networks*. Vol. 23. Springer, 2021. ISBN: 978-3-030-62937-3.
DOI: [10.1007/978-3-030-62938-0](https://doi.org/10.1007/978-3-030-62938-0). URL:
<https://doi.org/10.1007/978-3-030-62938-0>.
- [4] Mohsen Razavi. *An Introduction to Quantum Communications Networks*. 2053-2571. Morgan & Claypool Publishers, 2018. ISBN: 978-1-6817-4653-1.
DOI: [10.1088/978-1-6817-4653-1](https://dx.doi.org/10.1088/978-1-6817-4653-1). URL:
<https://dx.doi.org/10.1088/978-1-6817-4653-1>.



References III

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- [5] Gösta Fürnkranz. “The Quantum Internet”. In: *The Quantum Internet: Ultrafast and Safe from Hackers*. Cham: Springer International Publishing, 2020, pp. 83–189. ISBN: 978-3-030-42664-4. DOI: [10.1007/978-3-030-42664-4_2](https://doi.org/10.1007/978-3-030-42664-4_2). URL: https://doi.org/10.1007/978-3-030-42664-4_2.
- [6] Bas Hensen, Hannes Bernien, Anaïs E Dréau, et al. “Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres”. In: *Nature* 526.7575 (2015), pp. 682–686.
- [7] Juan Yin, Yuan Cao, Yu-Huai Li, et al. “Satellite-Based Entanglement Distribution Over 1200 kilometers”. In: (2017). DOI: [10.48550/ARXIV.1707.01339](https://arxiv.org/abs/1707.01339). URL: <https://arxiv.org/abs/1707.01339>.



References IV

Quantum
Communication
and
Networking

Ed Kuijpers

Introduction

Space

Theory

Communication
background

Quantum
communication

Bell inequality
loophole test

Simulation

Conclusion
and further
work

- [8] Claude E. Shannon. “A Mathematical Theory of Communication”. In: *The Bell System Technical Journal* 27 (July 1948), pp. 379–423, 623–656. URL: <https://www.itsoc.org/about/shannon-1948>.
- [9] Tim Coopmans, Robert Knegjens, Axel Dahlberg, et al. “NetSquid, a NETwork Simulator for QUantum Information using Discrete events”. In: *Communications Physics* 4.1 (July 2021). DOI: [10.1038/s42005-021-00647-8](https://doi.org/10.1038/s42005-021-00647-8). URL: <https://doi.org/10.1038%2Fs42005-021-00647-8>.