Quantum Communication and Networking

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HBO-ICT Technical Computing

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Recent developments

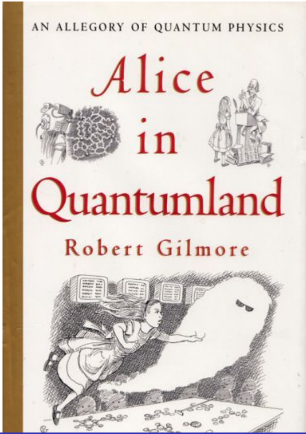
- Revolutionary qubit technology
- Google simulation development
- Record space laser communication

Relevance quantum stack

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

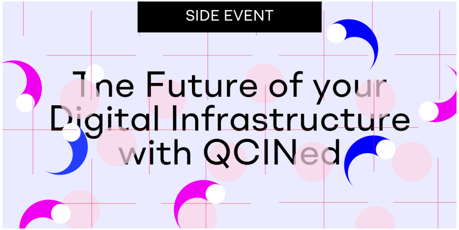
Quantum Internet Hackathons

Quantum Internet Hackthon 2024 Dutch participation with students (with RIPE NCC and Quantum Internet Allliance Use case groupi with SURF involvement)

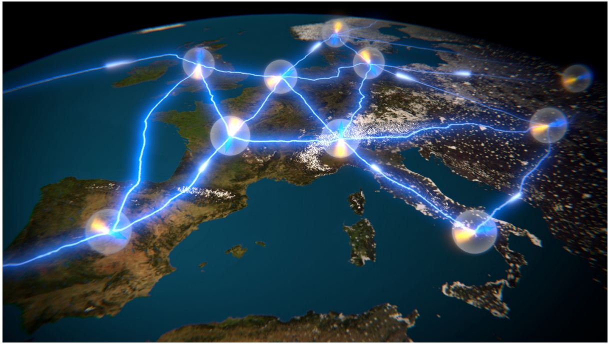


Future of Digital Infrastructure event

Future of quantum internet event part of Quantum meets 2024



activities Europe



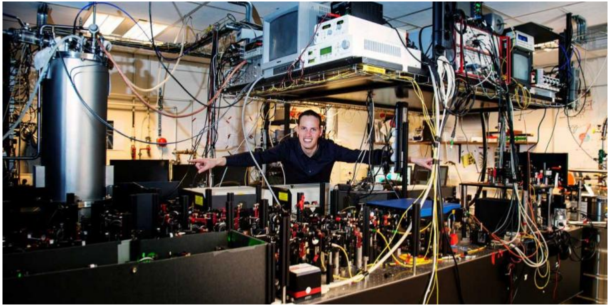
- EU Quantum Flagship projects, Quantum Internet Alliance
- Laiqa: Leap in Advancing of crItical Quantum key distribution-spAce components
- ESA Quantum Technologies

activities Netherlands

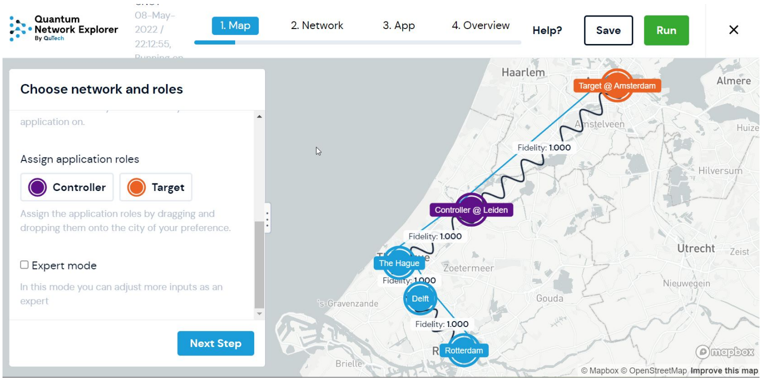
The Netherlands started projects as part of Quantum Dellta NL : Quantum Delta

actvities Qutech

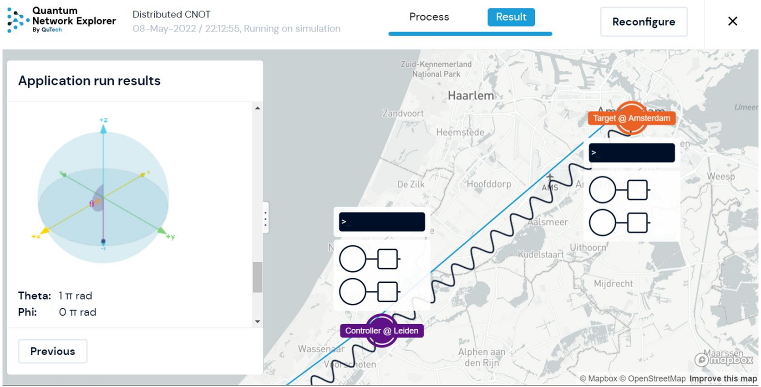
- Milestones Quantum internet
- Quantum internet demonstrator
- Quantum Internet
- development steps
- Ronald Hanson lab
- TNO and quantum internet
- QuTech demonstrator



Quantum Network Explorer, QNE demos



Quantum Network Explorer



Quantum computing and communication

- 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

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

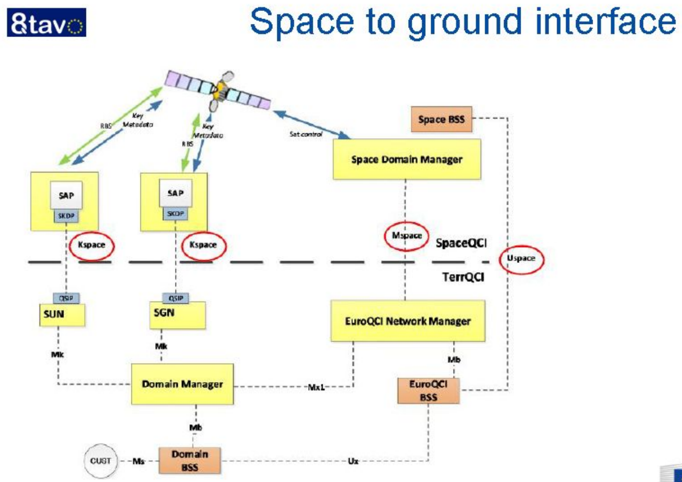
Space

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

Recent ESA activities 1

Recent ESA activities 2

Space QKD plans



EU Quantum Computing Infrastructure

Quantum Computing infrastructure

EuroHPC Joint Undertaking

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

Hardware connection between classical supercomputers and quantum computers → **Use the quantum computer as an accelerator for the supercomputer** → **Develop a software platform for seamless programming of the hybrid system** → **Test and validate hybridisation in key applications** →

Priority use cases
- **Climate modelling**
- **New materials (batteries)**
- **Drug simulation**

European Commission

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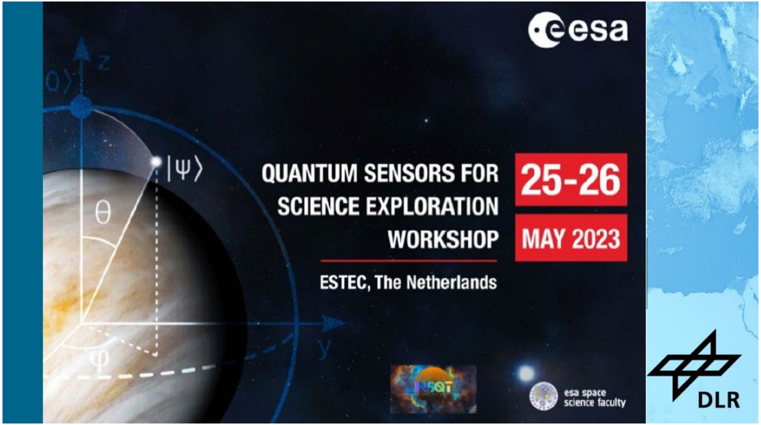
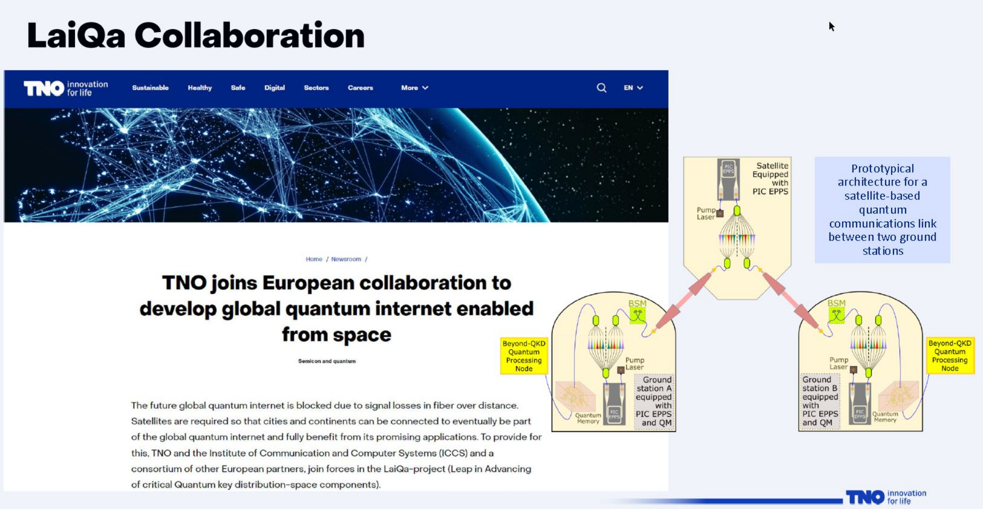
Space exploration and quantum



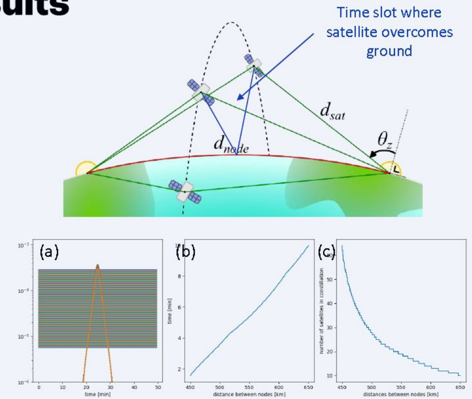
TNO activities 1



TNO actvities 2

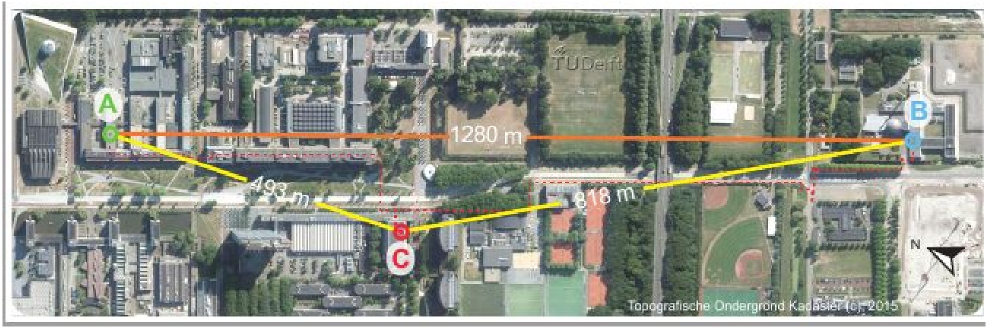
Ground vs Satellite – Results

- 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

[6]



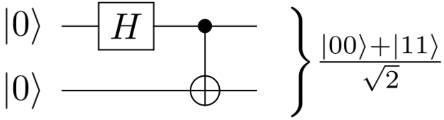
Setup at TUDelft campus

Theory

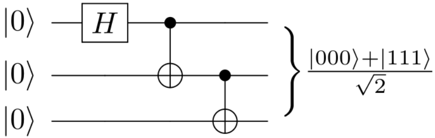
- Quantum Technology Education: A New Approach
- Github tutorials Quantum Communications

Quantum Communications

GHZ-state and Bell-state

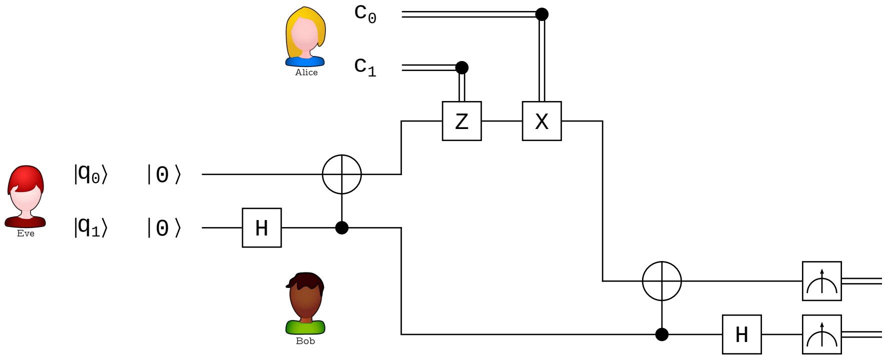


Bell state

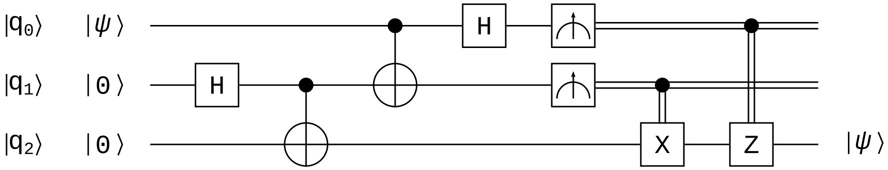


Greenberger–Horne–Zeilinger state

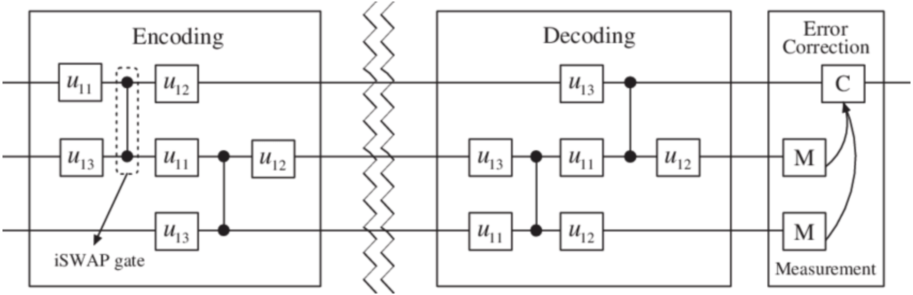
Superdense coding



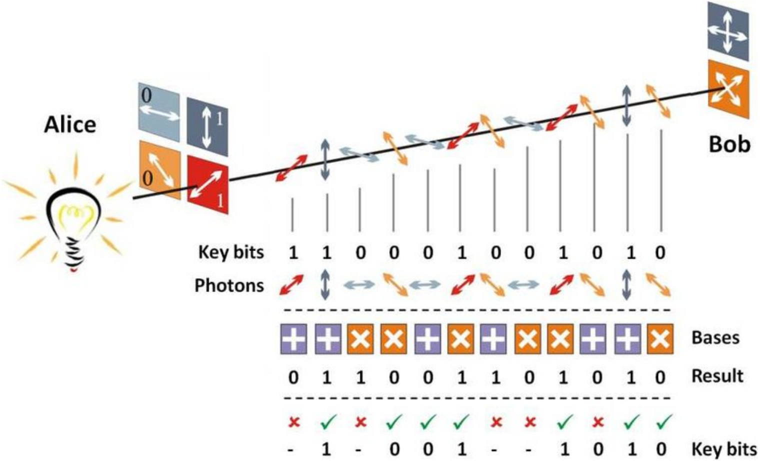
Teleportation



Quantum error correction



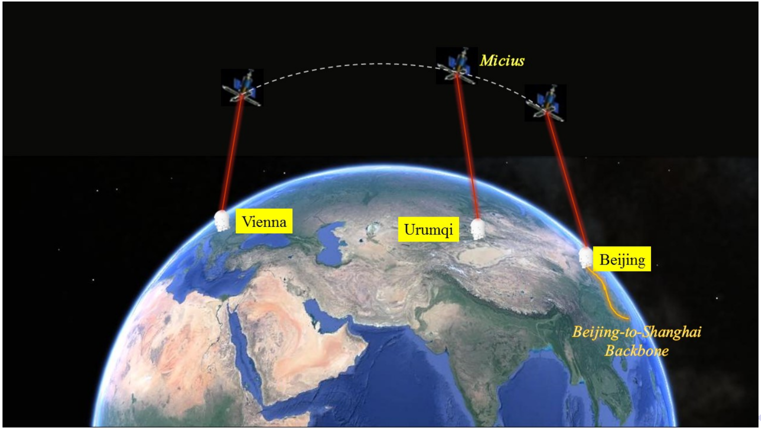
BB84



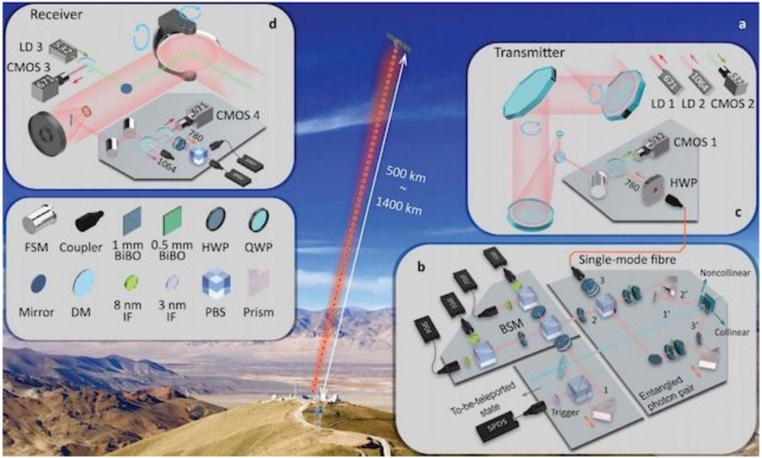
Improvements: E91 and B92 Open Courseware quantum encryption TUDelft

Quantum Key Distribution via Satellite

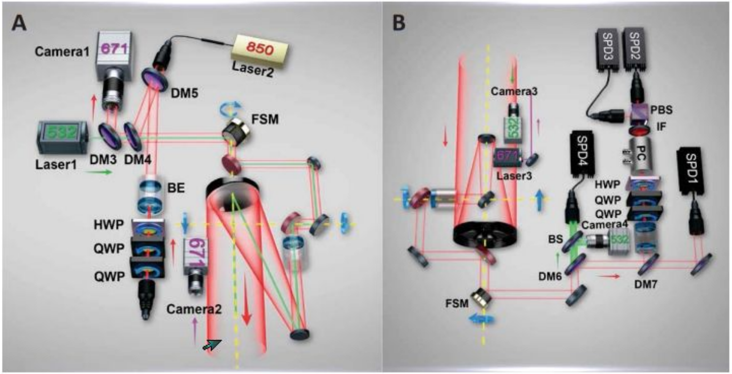
Experiment using entanglement in satellite communication link for quantum key distribution ([7])



Satellite communication components

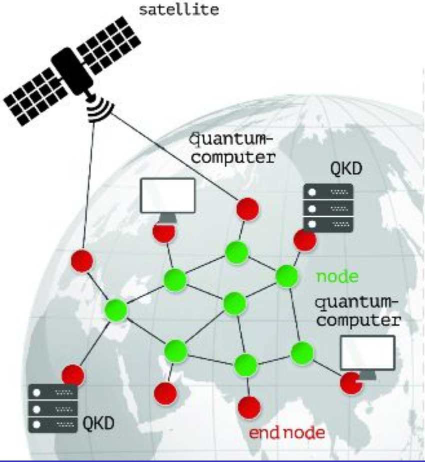


Satellite communication optics



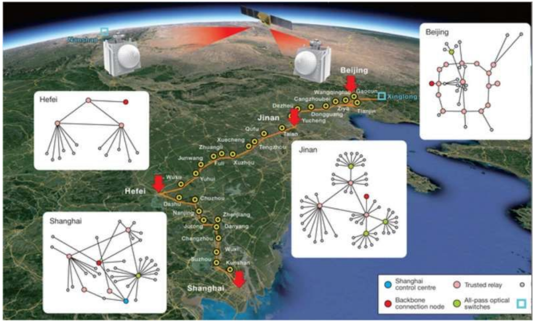
Hybrid networks

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



Integrated space-to-ground quantum communication network

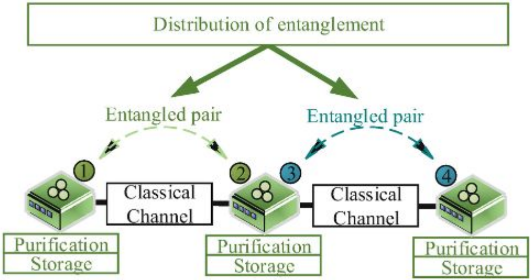
An integrated space-to-ground quantum communication network over 4,600 kilometres



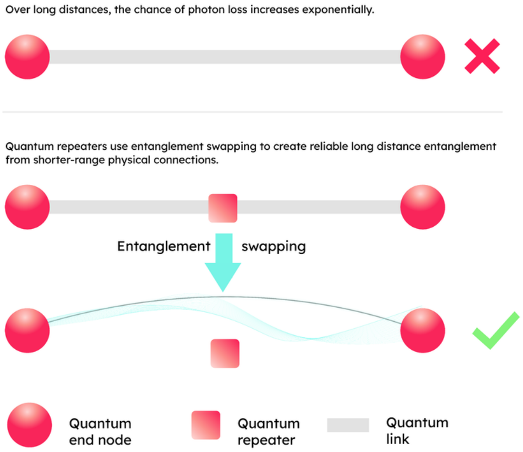
Stack of protocols

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

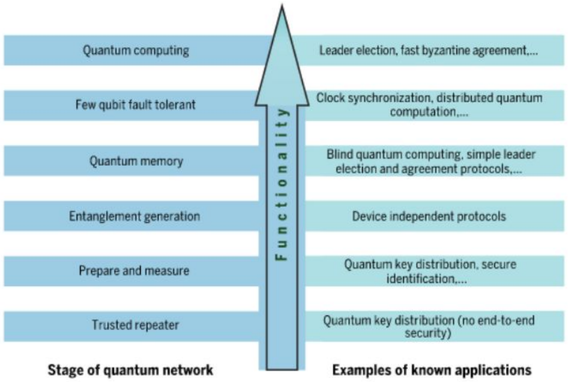
Repeaters


Distribution of entanglement
Entangled pair
Entangled pair
1
2
3
4
Classical Channel
Classical Channel
Purification
Storage
Purification
Storage
Purification
Storage

Repeater implementaton

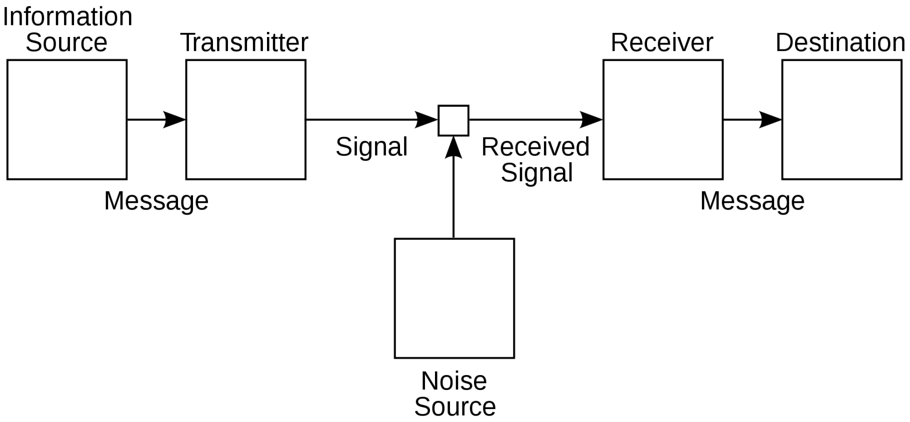


Vision



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.

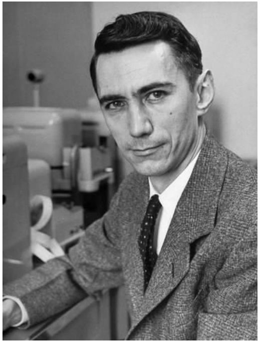
Shannon–Weaver model communication



Communication model used in many disciplines

Father Information theory

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)



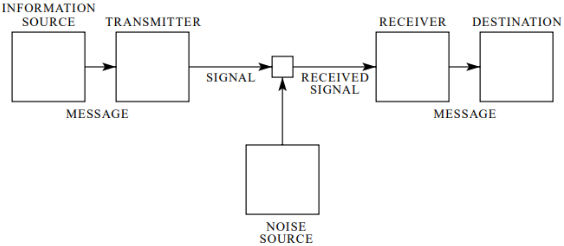
Information and communication theory

Quantum Communication and Networking

Ed Kuijpers

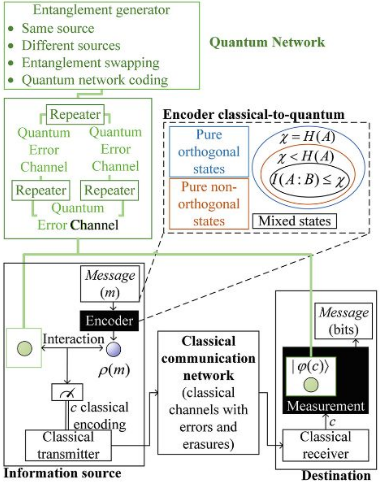
- Model communication in the presence of noise ([8])
- Concept of Information $H = \sum_{i=1}^{N} -p_i \log_2(p_i)$ (1 bit is tossing a coin)
- Entropy and Information related
- Relative entropy $KL(P||Q) = \sum_{x \epsilon X} -P(x) \log Q(x)/\log P(x)$ (Kullback Leiter Divergence/Distance) item Qbits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

Information and Channel capacity



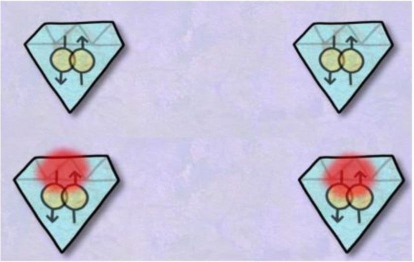
Channel capacity is related to information and noise in channel, $C = Blog_2(1 + \frac{S}{N})$ where C maximum bitrate/s, channel bandwidth, S/N signal to noise power (Shannon–Hartley theorem) and basis for encoding designs

Example configuration



Electron spin qubits

NV centers: electron spin

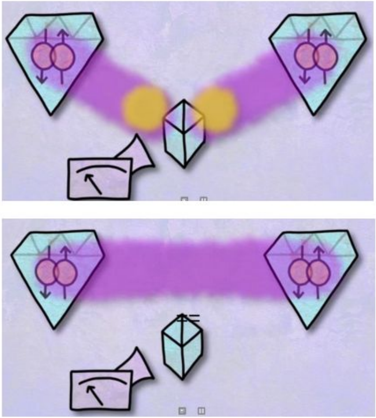


→ electron spin and photon entangled

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



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 enatanglement to NV electrons and potentially NV memories
(try to detect emitted photons, if indistinguishable, then then detection creates entanglement (Bell states) between NV centers)

Bell inequality

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 :

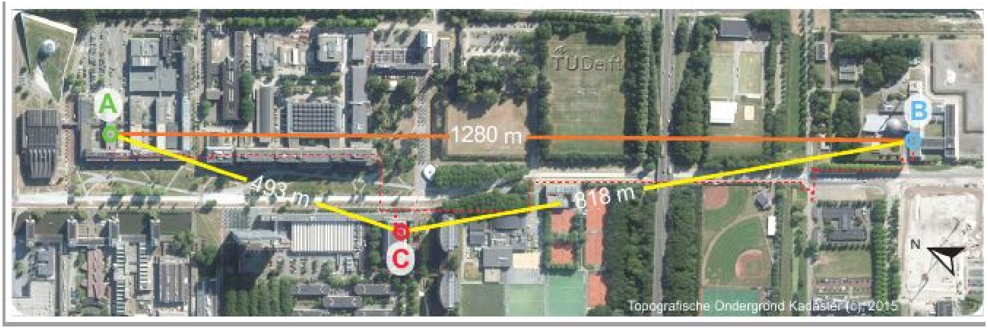
$$S = \langle x \cdot y \rangle_{(0,0)} + \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} - \langle x \cdot y \rangle \_(1,1) \leq 2 \tag{1}$$

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

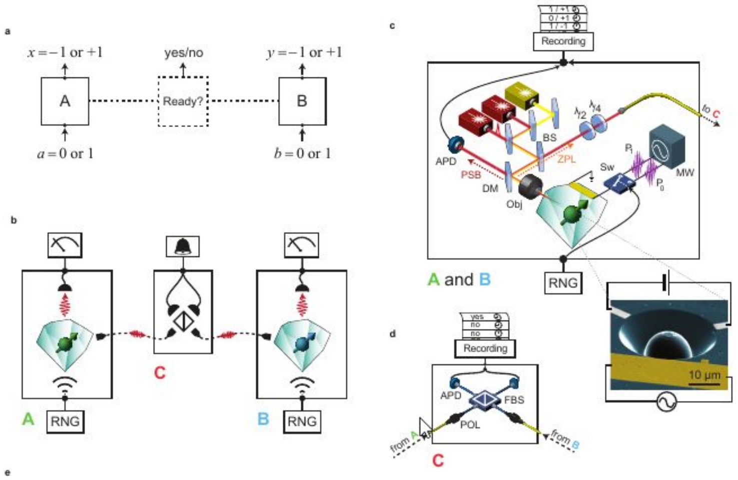
In Qiskit: Local Reality and the CHSH Inequality, Bell's inequality CHSH inequality named after John Clauser, Michael Horne, Abner Shi- mony, and Richard Holt, provides an experimental framework for supporting Bell's theorem.
In Pennylane

Test setup for loophole test



Setup at TUDelft campus

Test setup cont.

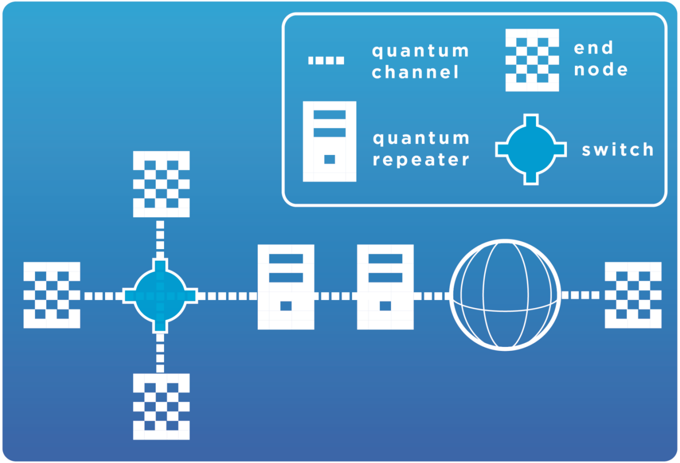


Components

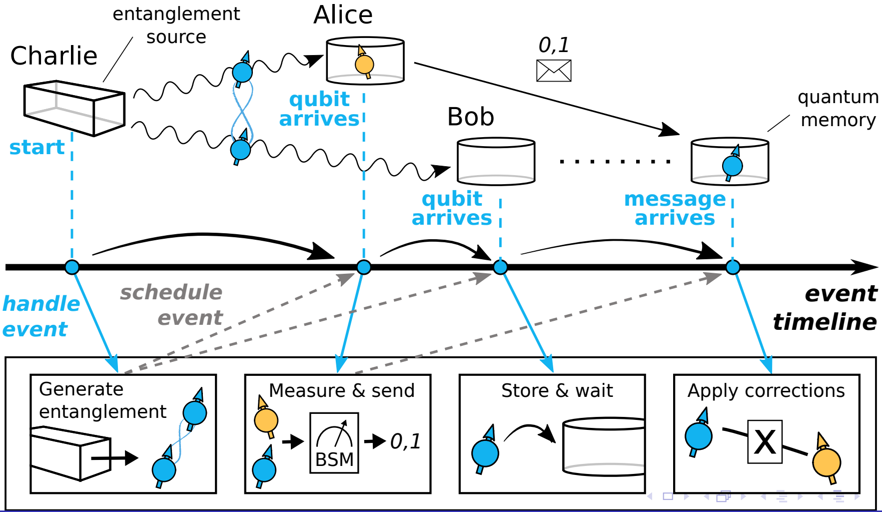
Quantum communication simulation

- 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
- LIQUi$|>$: Language-Integrated Quantum Operations developed at Microsoft
- SeQUeNCe : Simulator of Quantum Network Communcation developed by ARGONNE and univ. Chicago.

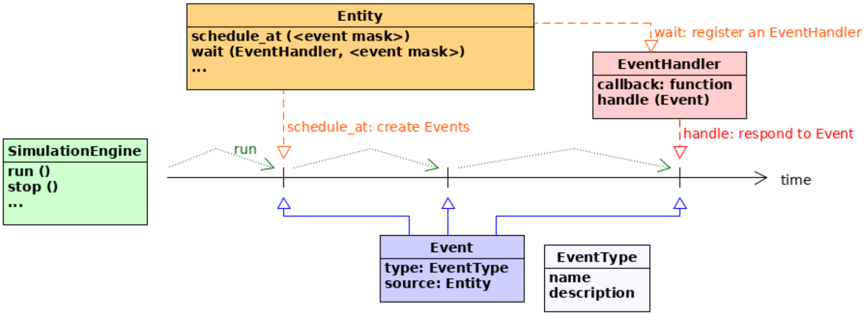
NetSquid



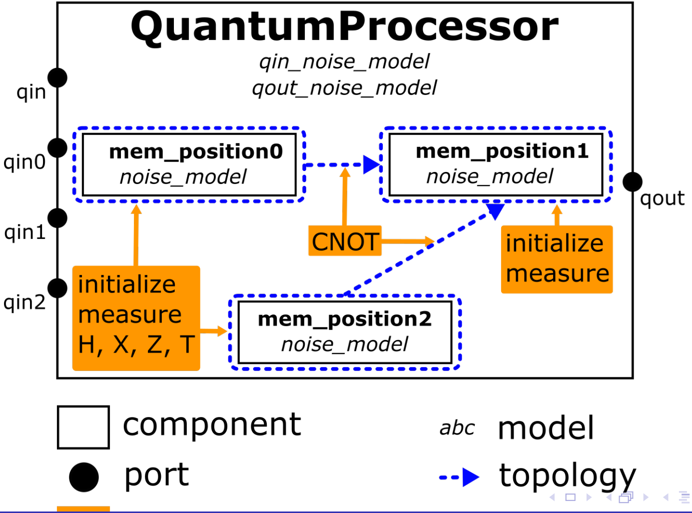
NetSquid event simulation



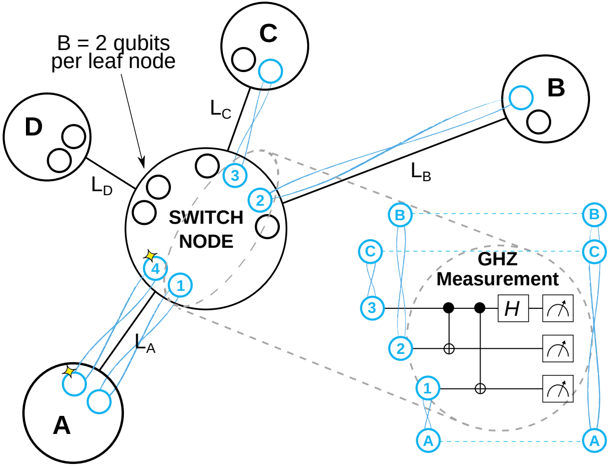
NetSquid design



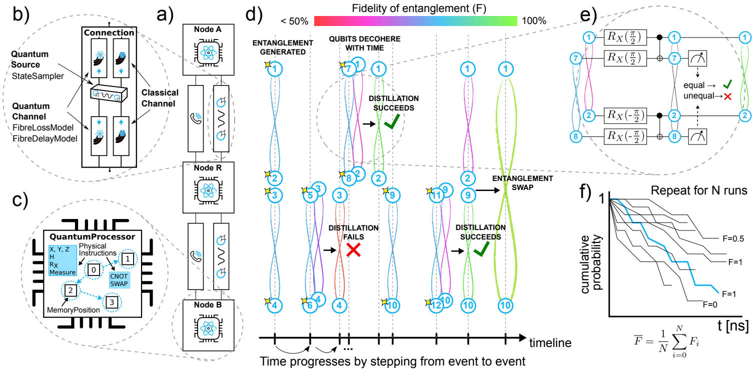
NetSquid nodes



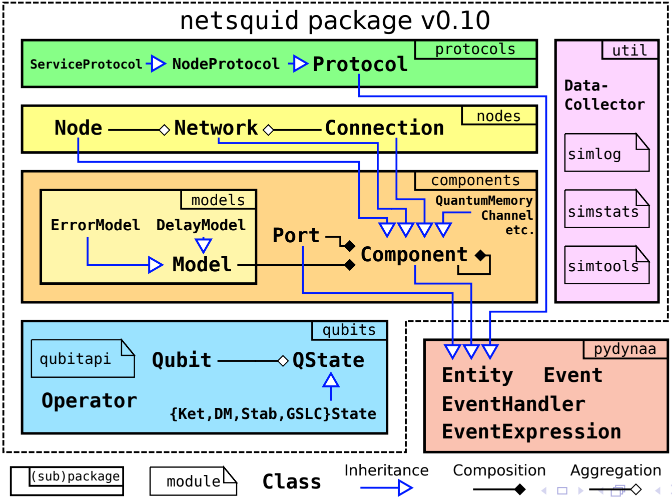
NetSquid example switch

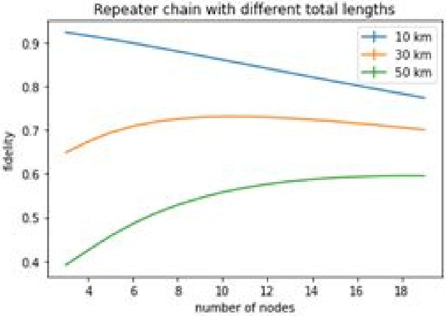


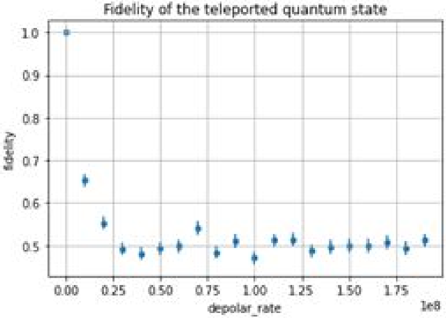
NetSquid Repeater



NetSquid stack







Integration of QNE Application Development Kit:qne-adk

Qiskit and further developments

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

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

Options for papers

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

Further topics

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

References I

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[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. URL: https://doi.org/10.1038%2Fs42005-021-00647-8.