Welcome

“Quantum Networks: From a Physics Experiment to a Network System”

Stephanie Wehner

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Quantum Networks: From a Physics Experiment to a Network System

Speaker: Stephanie Wehner

Moderator: Travis Humble

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Quantum Networks
From a Physics Experiment to a Network System

Stephanie Wehner

QuTech

QIA

http://quantum-internet.team

erc NWO

Entanglement for everyone

Enabling quantum communication between local quantum processors anywhere on earth.

Classical

0

1

Quantum

0+1

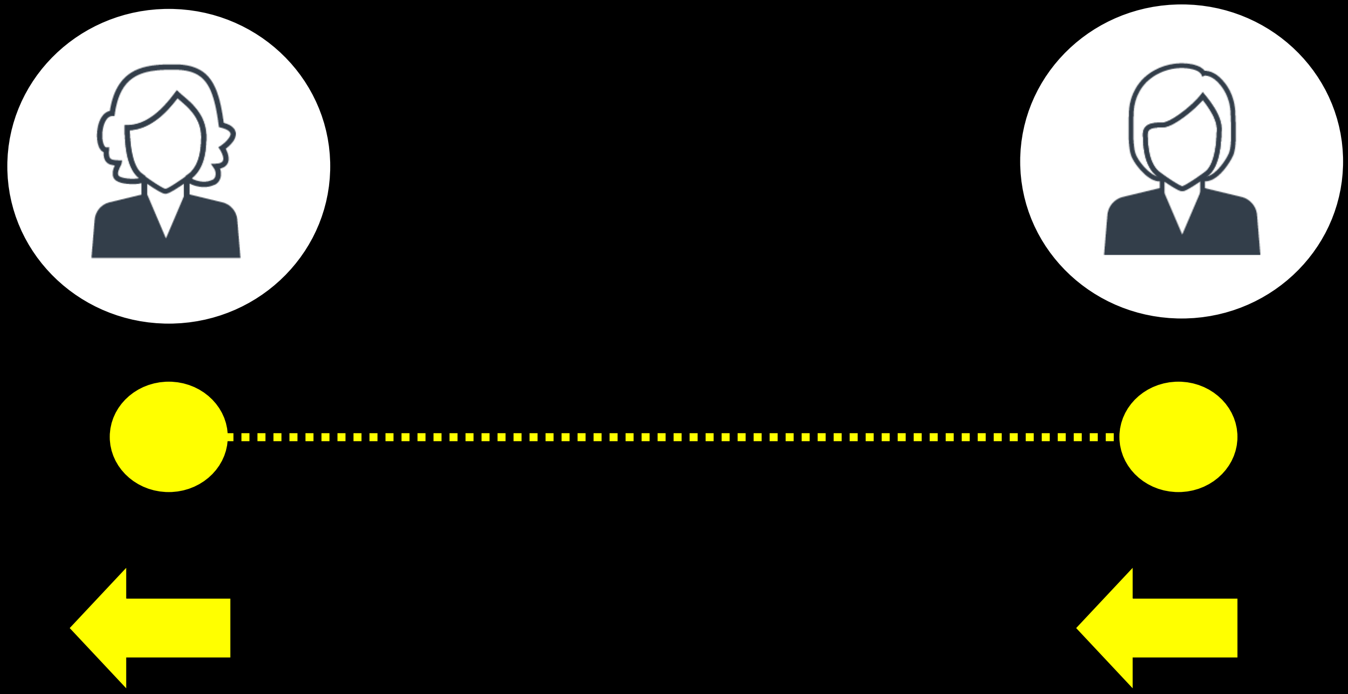
Secure Communication

Secure Quantum Computing in the Cloud

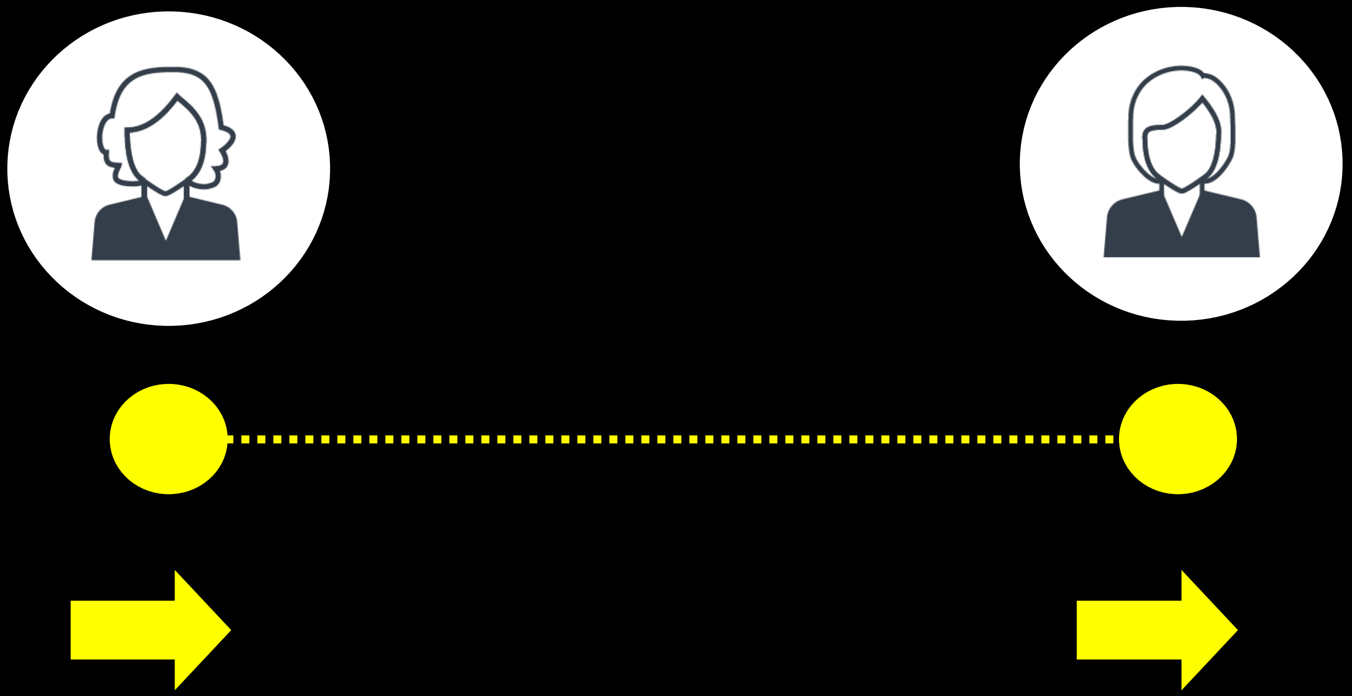
Clock synchronization, Password Identification, Position Verification, Online Games….

Quantum Computing Clusters

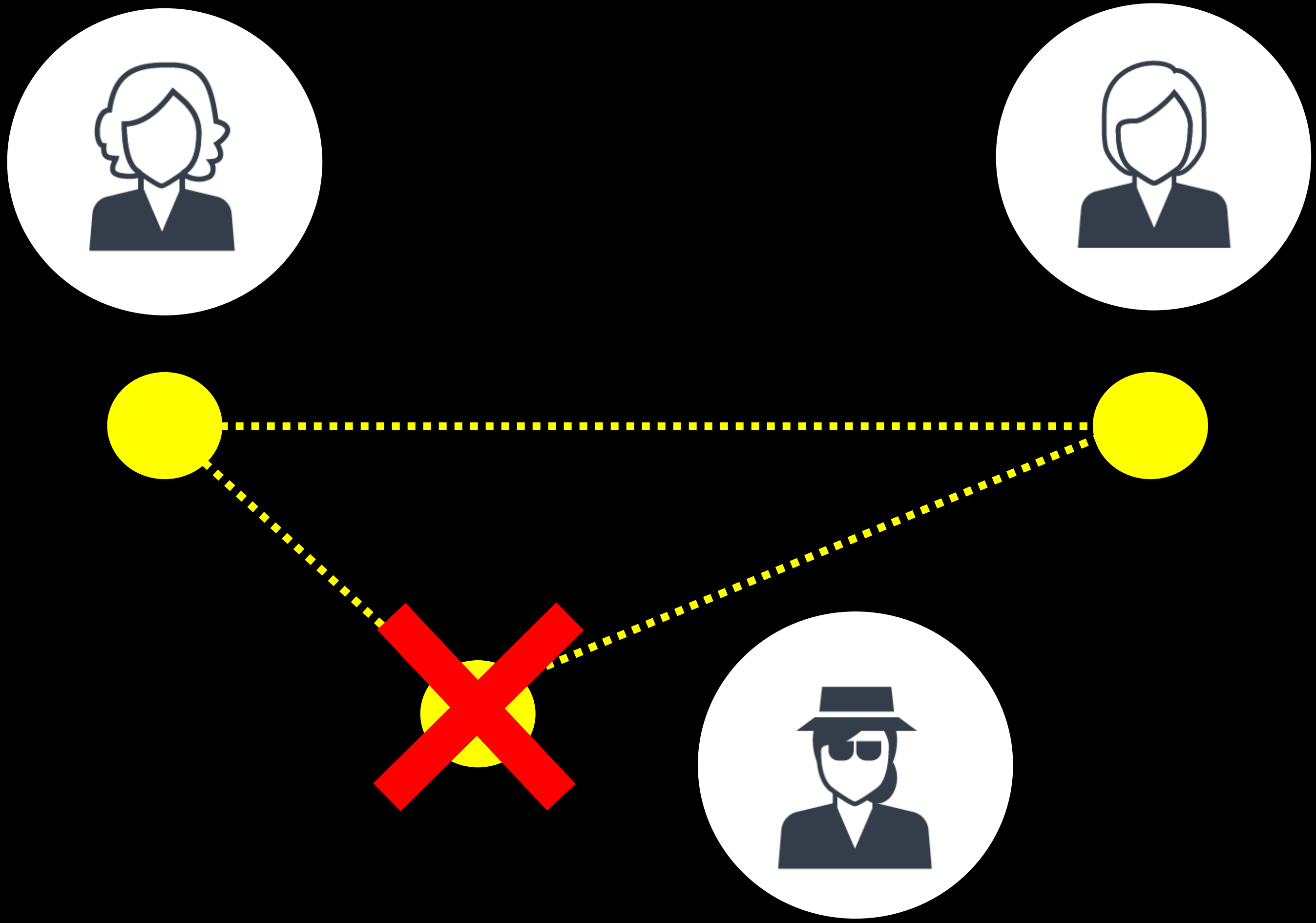
Maximal coordination



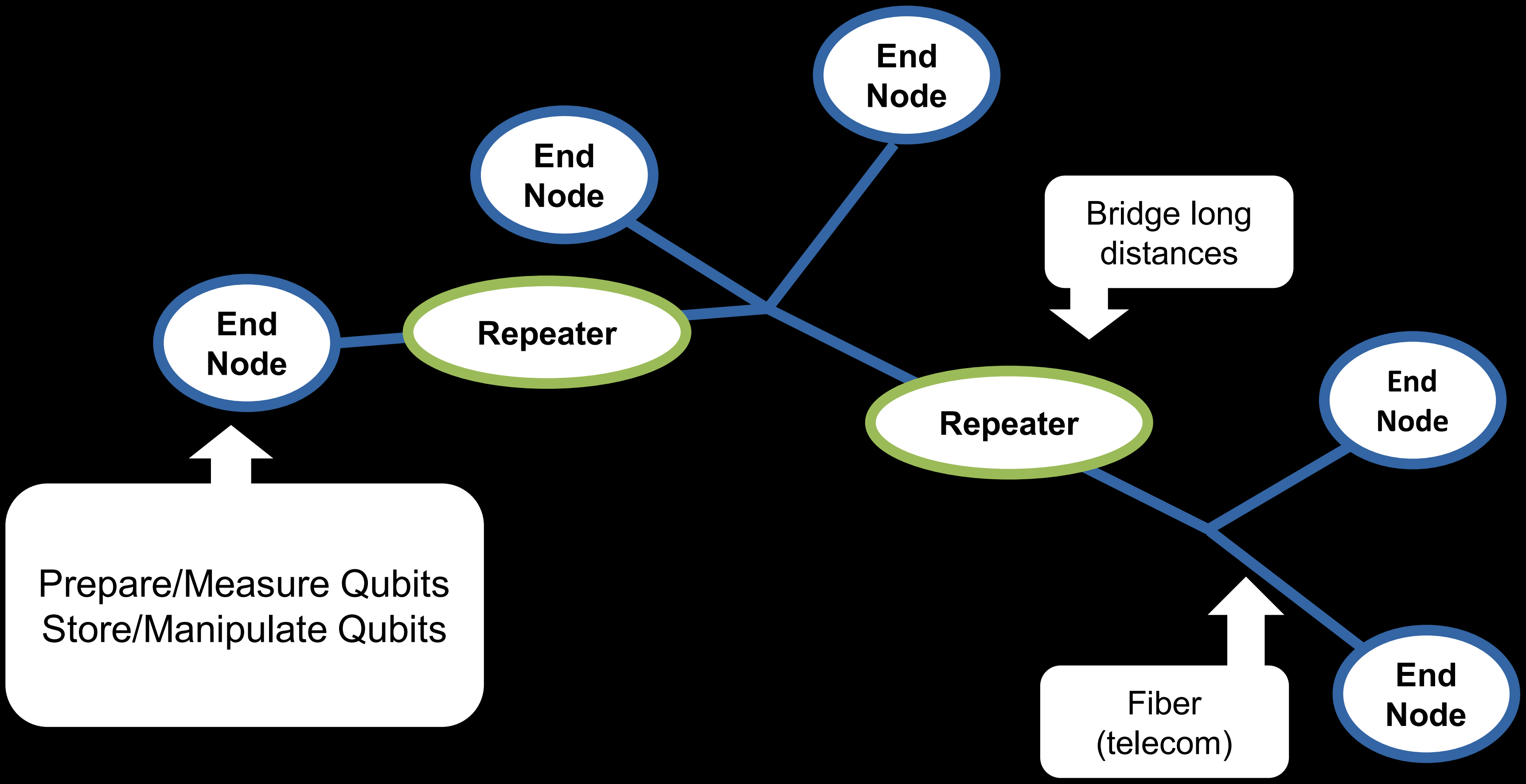
Maximal coordination



Inherently private

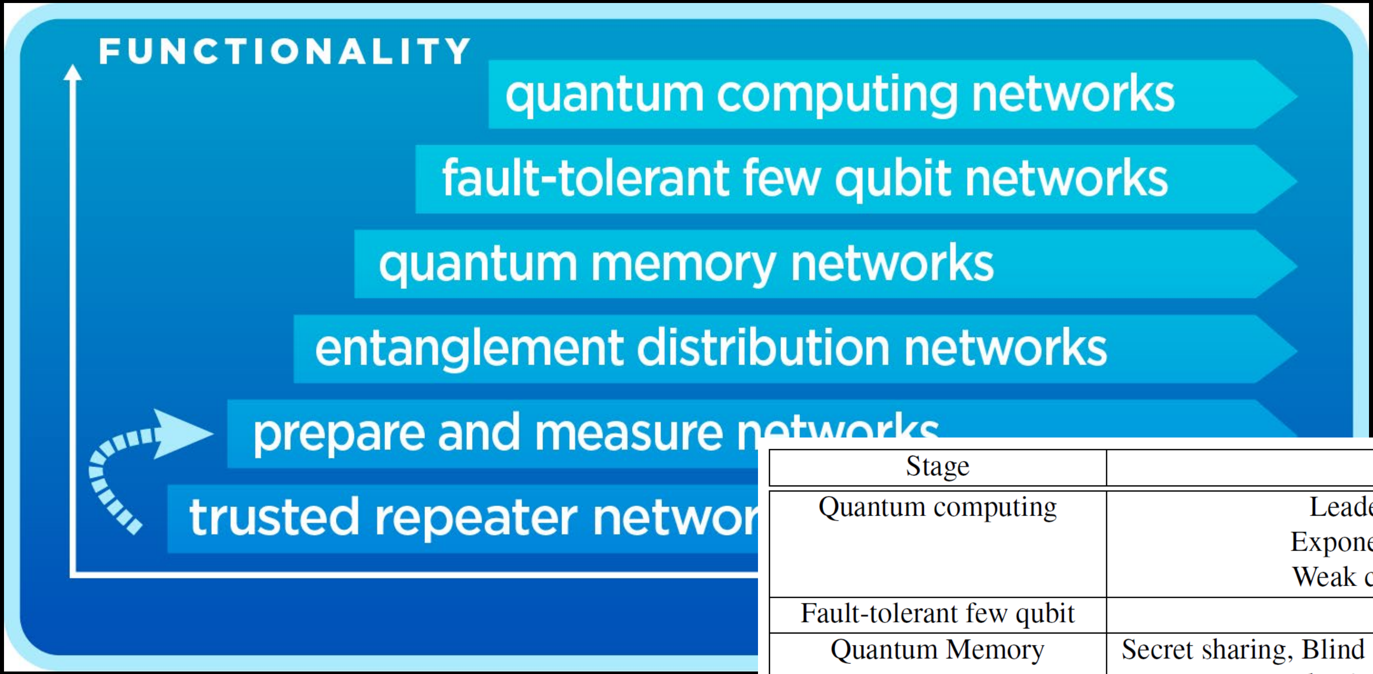


What is a quantum network?



Functionality driven stages of a quantum internet

S. Wehner, D. Elkouss, R. Hanson - *Science* - *362, 6412 (2018)*



Stage	Examples of known protocols
Quantum computing	Leader election, Fast byzantine agreement Exponential savings for communication tasks Weak coin flipping with arbitrarily small bias
Fault-tolerant few qubit	Clock synchronization
Quantum Memory	Secret sharing, Blind quantum computing (using remote quantum servers), Improved coin flipping, Anonymous quantum transmissions, Extending baseline of telescopes, Simple leader election and agreement protocols, Time limited clock synchronization
Entanglement Distribution	Device independence for QKD and other protocols in the prepare and measure stage
Prepare and Measure	Quantum key distribution (QKD), Two-party cryptography, Position verification, Imperfect coin flipping

Where are we now?

Quantum communication –state of the art

Quantum Cryptography (QKD) – non DI: Key Distribution

Status:

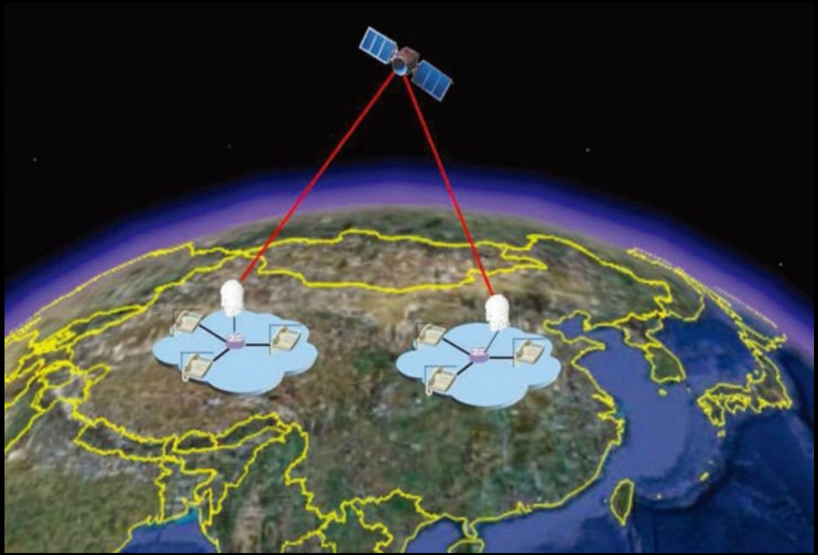
- Commercial at short (~100kms) distances
  (idQuantique, Huawei, Toshiba, NEC, Mitsubishi, ….)
- Lab ~300kms

Survey by Alleaume et al, Theoretical Computer Science, 560 (2014), pp. 62-81

Grand Challenges:

- **Distance – want to communicate over long distances**
- **Functionality – want to do more than QKD**

Quantum communication – state of the art in space



Entanglement over a distance of > 1200km via satellite

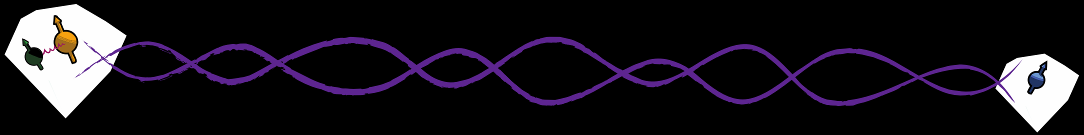
Pan Group, Science, July 2017

Yin et al. 2017. Satellite-based entanglement distribution over 1200 kilometers. Science 356, 6343 (jun 2017), 1140–1144

Quantum communication towards long on the ground

Hanson Taminiau Wehner Elkouss

QuTech Quantum Internet Team

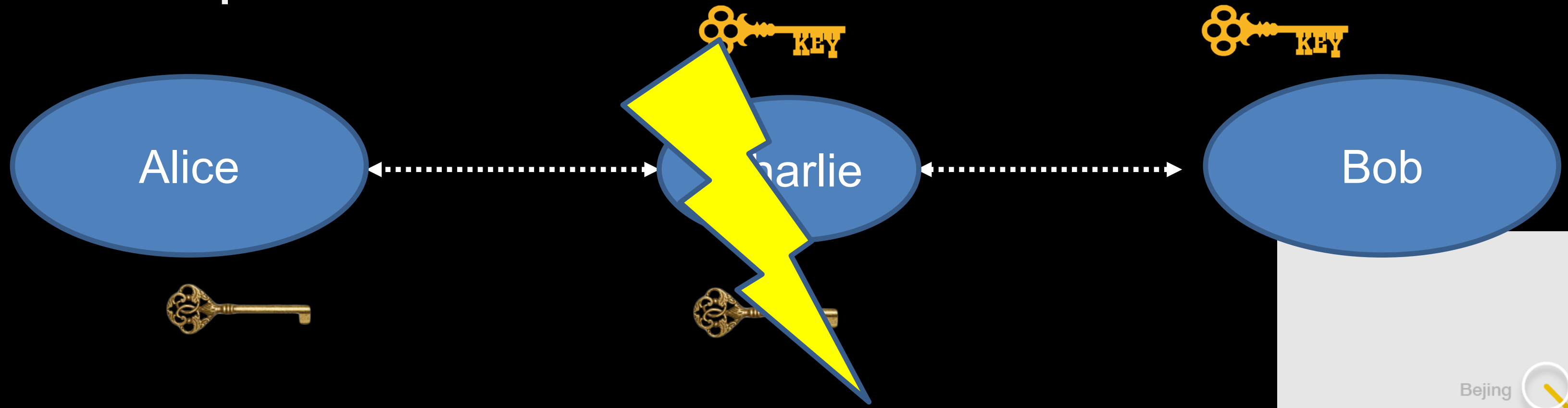


Two quantum processors at the distance of 1.3km:
Loophole-free Bell inequality violation using electron spins separated by 1.3 kms
B. Hensen, H. Bernien, A. Dreau, A. Reiserer, N. Kalb, M. Blok, J. Ruitenberg, R. Vermeulen, R. Schouten, C. Abellan, W. Amaya, V. Pruneri, M. Mitchell, M. Markham, D. Twitchen, D. Elkouss, S. Wehner, T. Taminiau, R. Hanson
Nature, 526, 682-686 (2015)

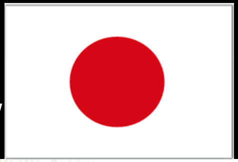
Two quantum memories in the same lab, 50km fiber
Yu et al. Nature, volume 578, pages240–245(2020)

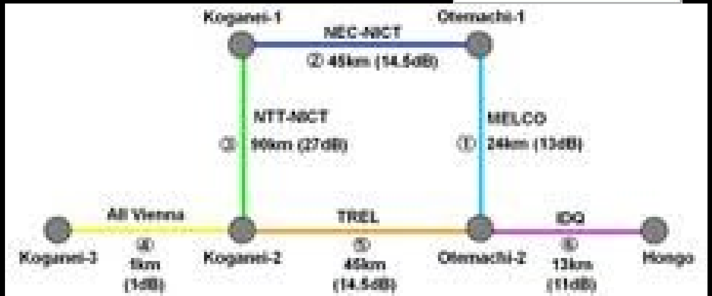
1 Quantum processor and photon traveling 50km,
Krutyanskiy et al, npj Quantum Information 5, 72 (2019)

Trusted repeater networks



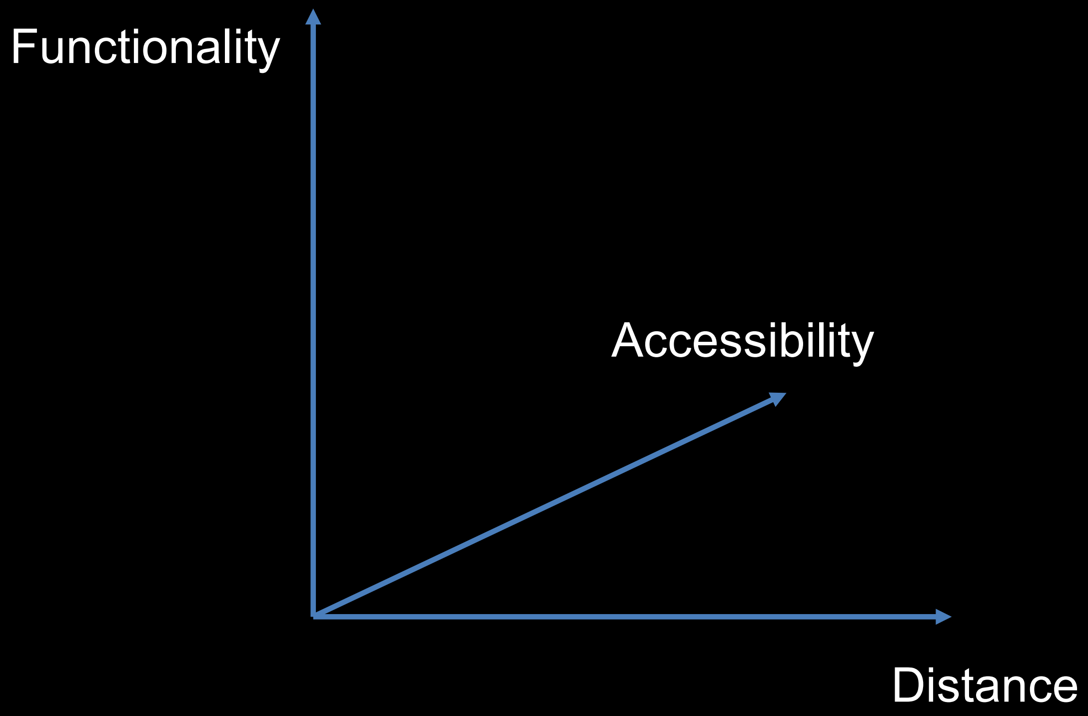
http://www.uqcc.org/QKDnetwork/





Zhang et al, Optics Express, 26(18), pp. 24260-24273 (2018)

Going forward



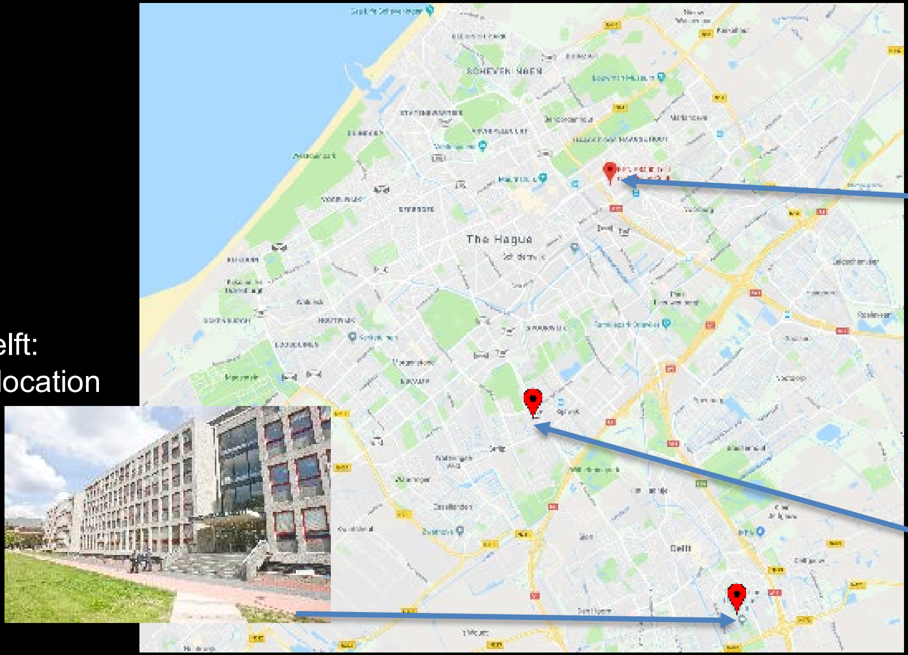
Quantum Networks
@
QuTech

Beyond trusted repeaters

Planned test link Delft – Den Haag

KPN PB400: node location

TU Delft:
node location



KPN telephone exchange:
detector location

- Make 2 processor nodes that are prepared for future upgrades
  - World record in linking quantum processors at a distance

- Make use of existing telecom (dark) fibers
- Generation of entanglement between the 2 nodes
- Gain experience

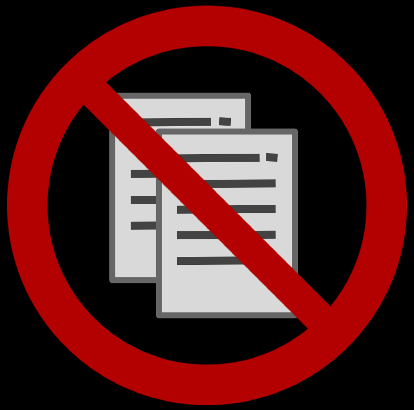
Possible Network Expansion

- Upgrade existing nodes – form a network
- World's first network connecting quantum computers
  - Multiple processor nodes
- Direct QKD links between neighbouring nodes to authenticate control traffic
- World's first quantum network stack demonstration
  - Including universal programmability
- Make platform available on the internet

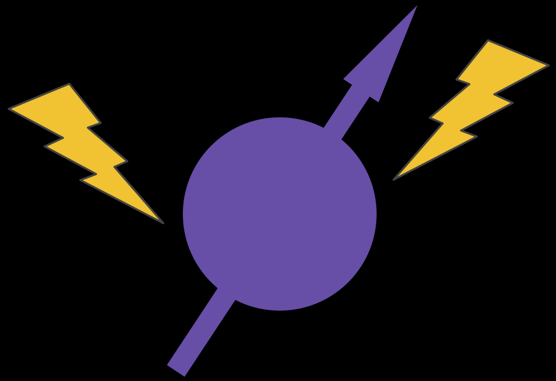
RIPE NCC
RIPE NETWORK COORDINATION CENTRE
amsix
amsterdam internet exchange
SURF NET
kpn

Why is it difficult to bridge long distances?

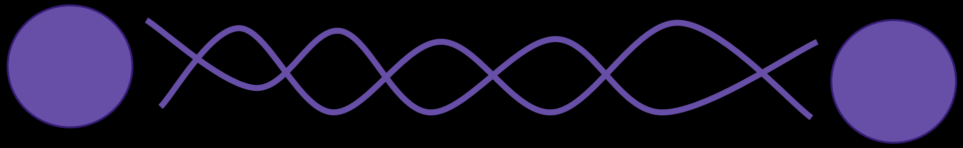
Quantum is different



No copying!

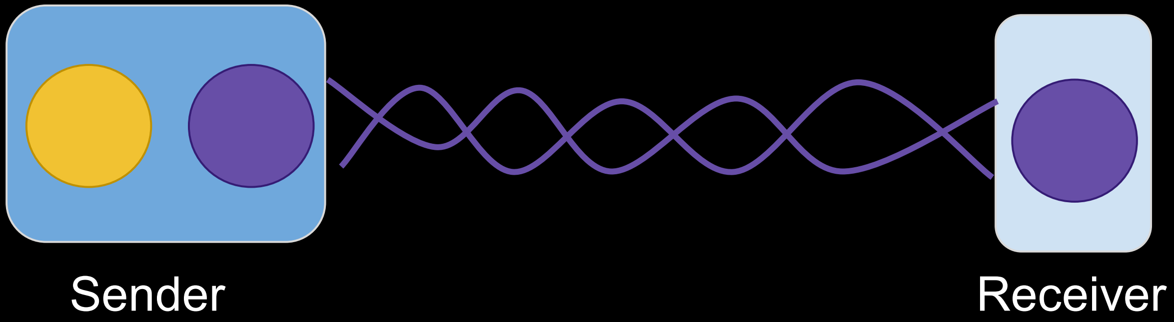


Short lifetimes, difficult to manipulate many qubits

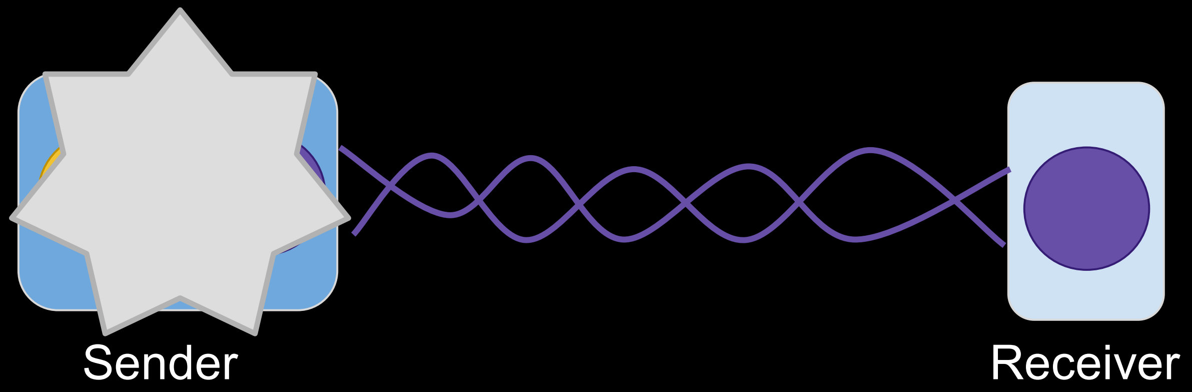


Entanglement works differently - Inherently connected!

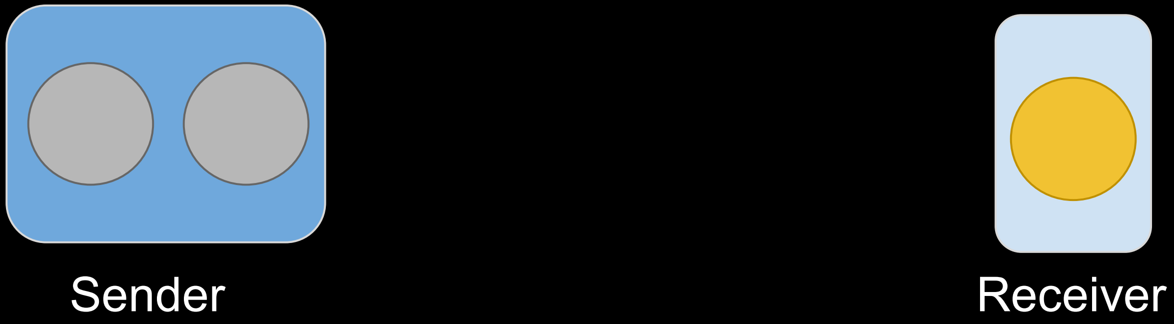
Sending Qubits via Entanglement



Sending Qubits via Entanglement

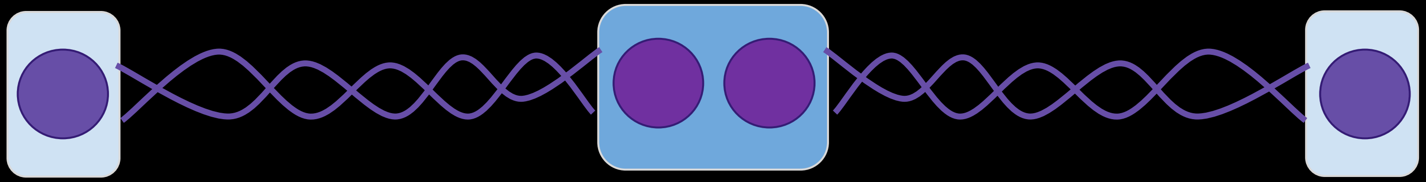


Sending Qubits via Entanglement

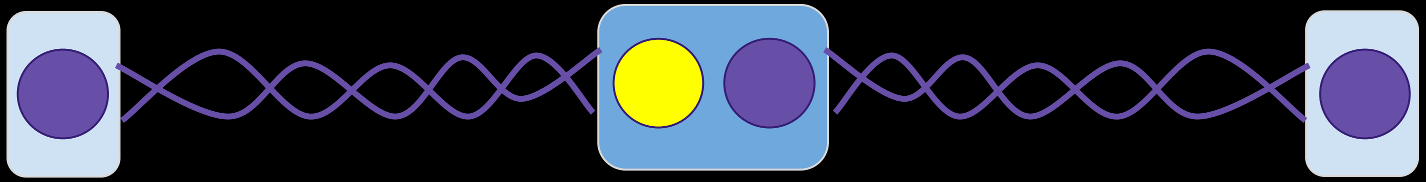


- Consumes the entanglement
- Requires 2 bits of forward communication to the receiver

Key ingredient for a quantum repeater: Entanglement Swapping



Key ingredient for a quantum repeater: Entanglement Swapping



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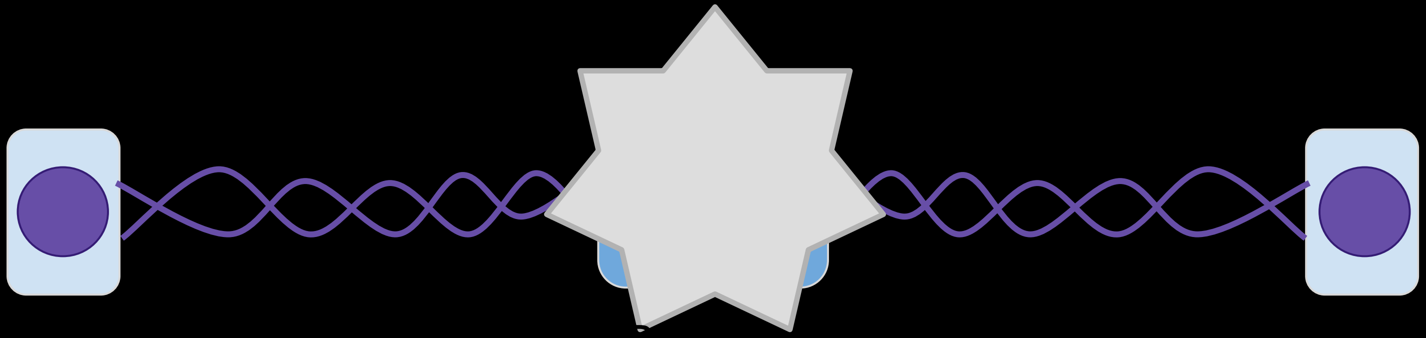

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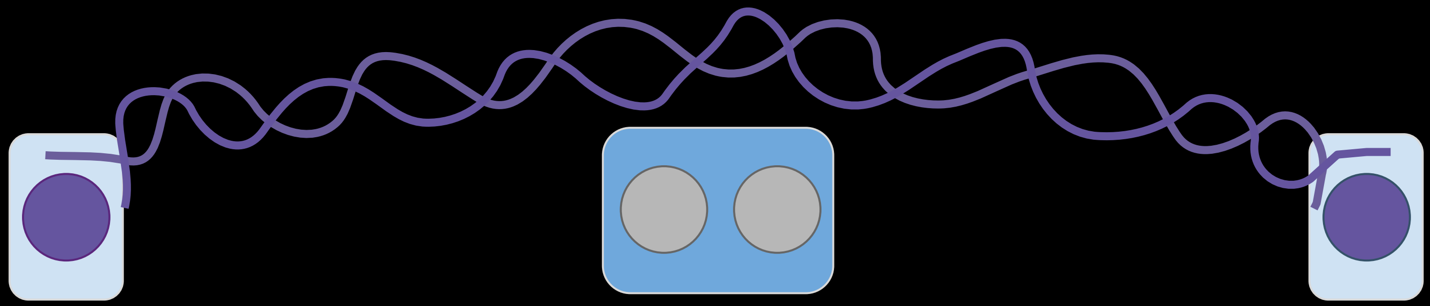
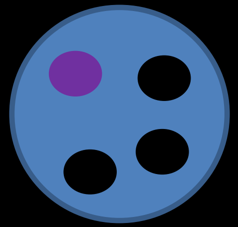
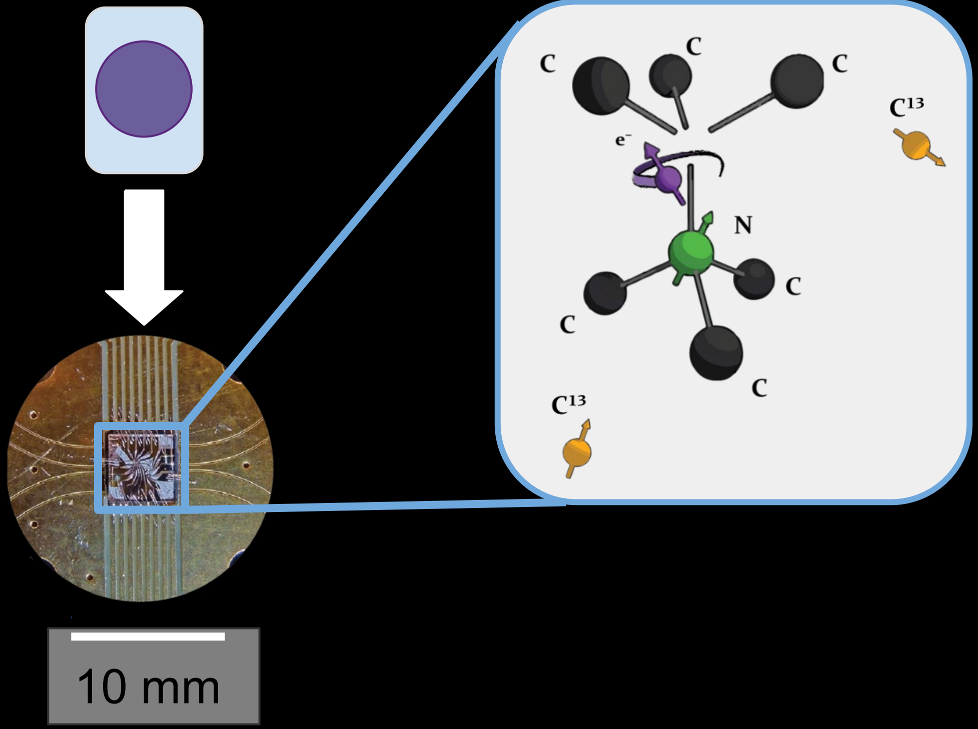


Resources:

- Timing coordination: qubits arriving at the same time at the mid point
- Or, storage: wait until both qubits arrived
- Classical communication from the mid point to the end points
- Original entanglement is consumed

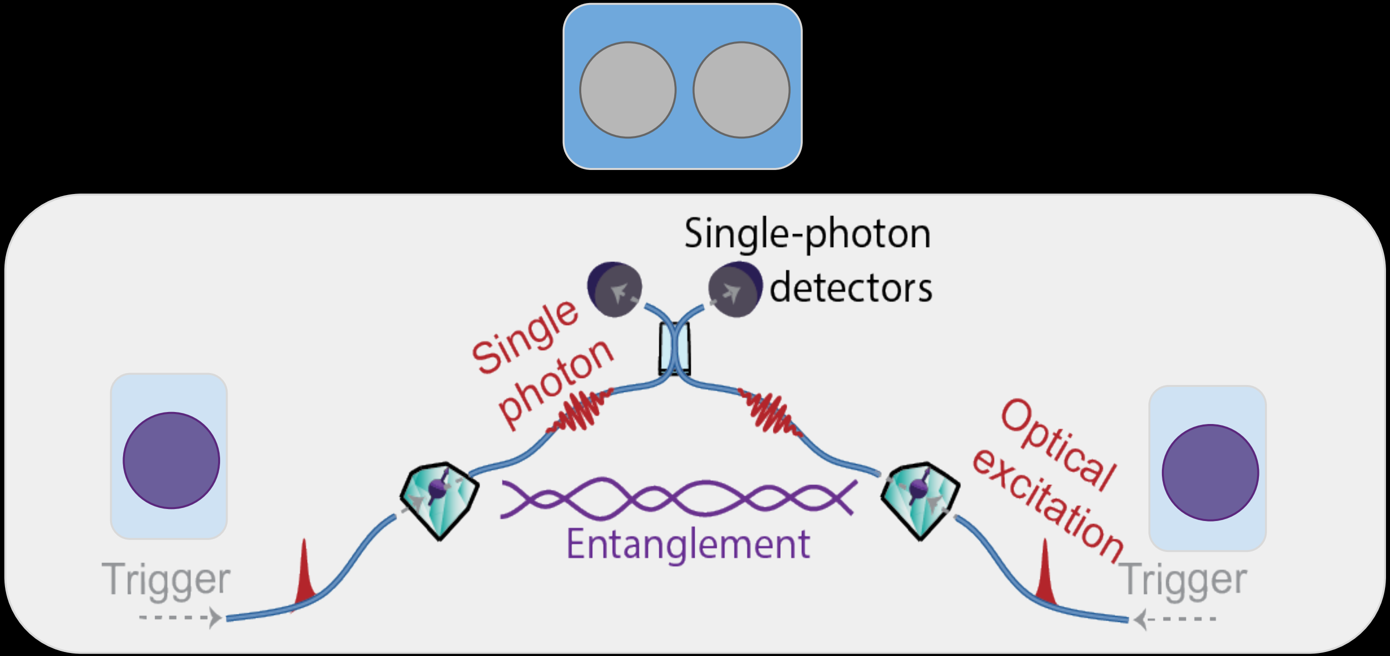
Example of Quantum Hardware





- Nitrogen vacancy in diamond
- Communication qubit
- Storage qubits
- Entanglement at 1.3 km

Physical Entanglement Generation



How Entanglement is Produced

Can I work with this without physics? ☺

Yes! Network Stack: Quantum Link Layer (ACM SIGCOMM 2019)

Stephanie Wehner

Axel Dahlberg

Matthew Skrzypcyzk

Leon Wubben

Filip Rozpedek

Rob Knegjens

Julio de Oliveira Filho

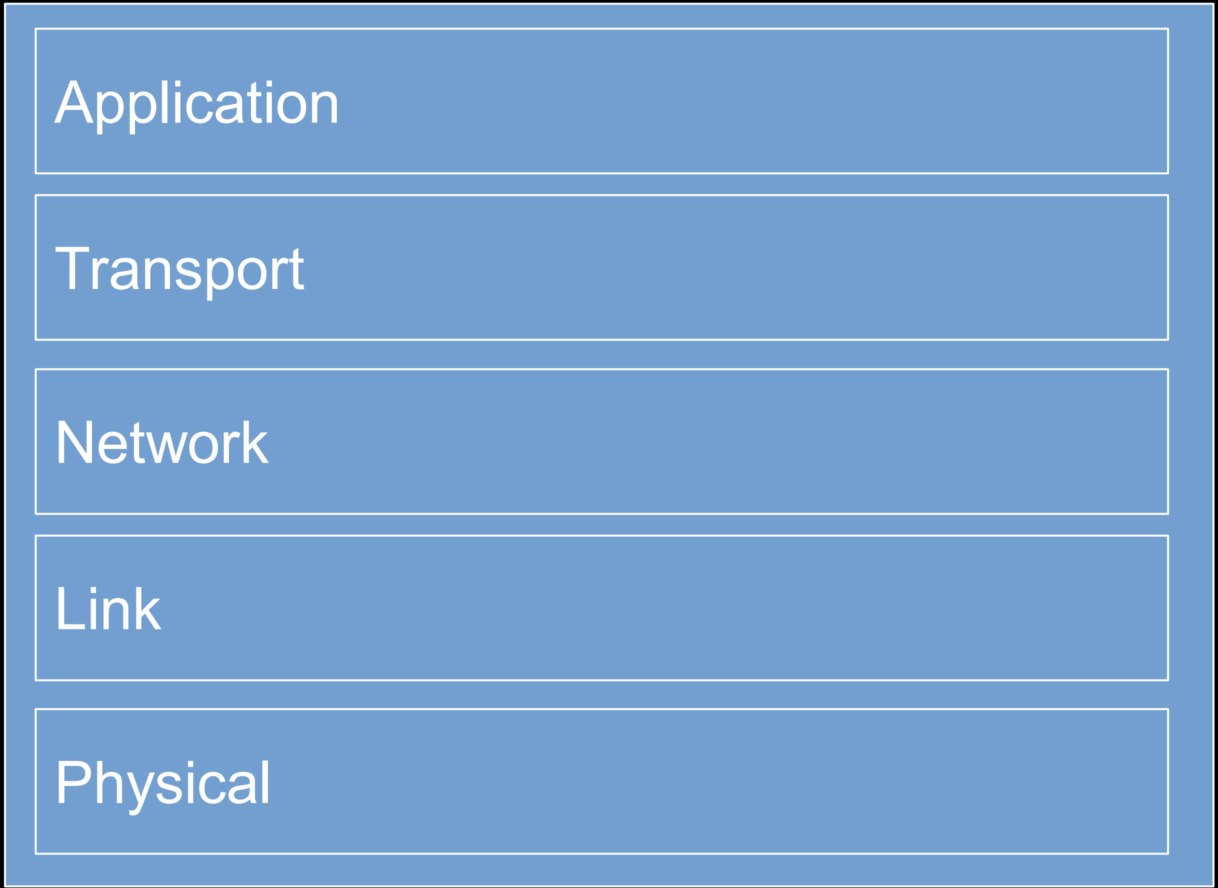
Przemek Pawelczak

Matteo Pompili

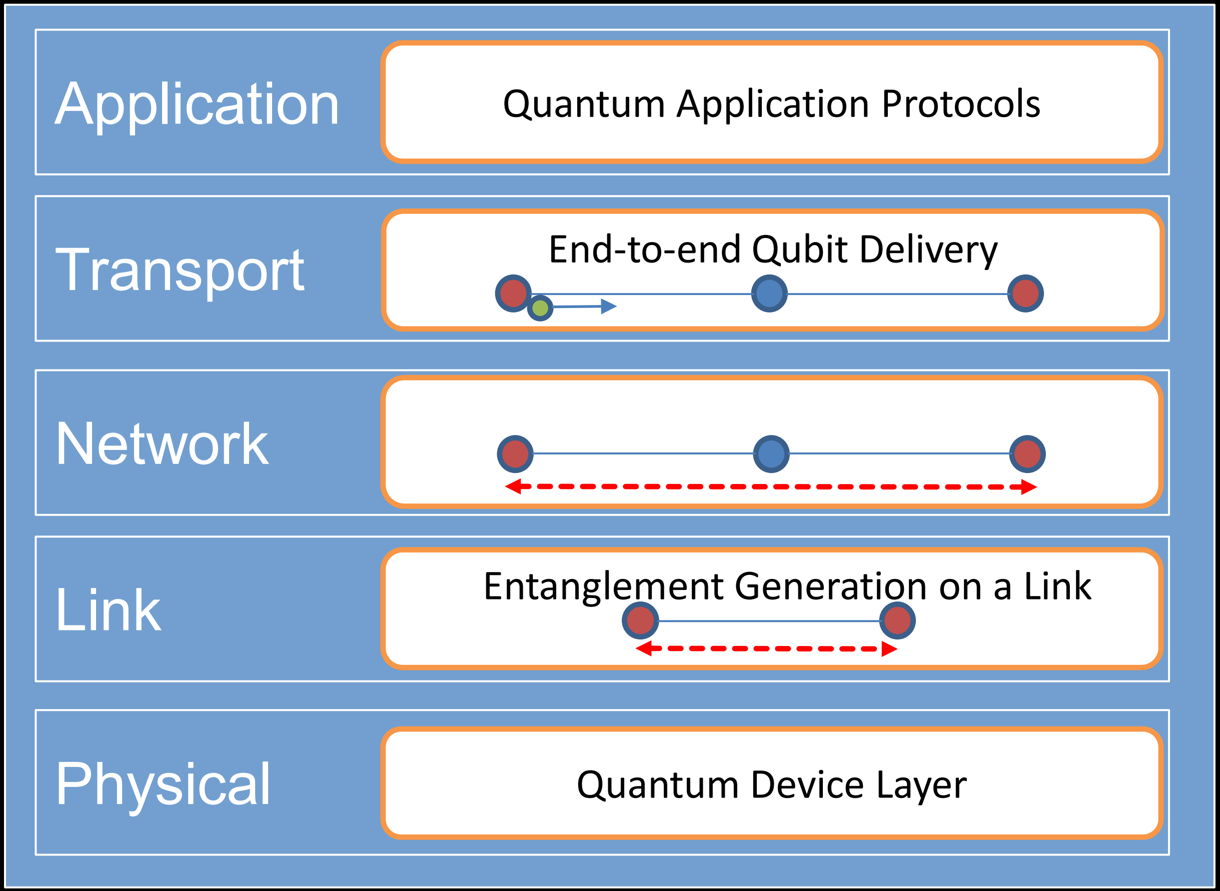
Arjan Stolk

Ronald Hanson

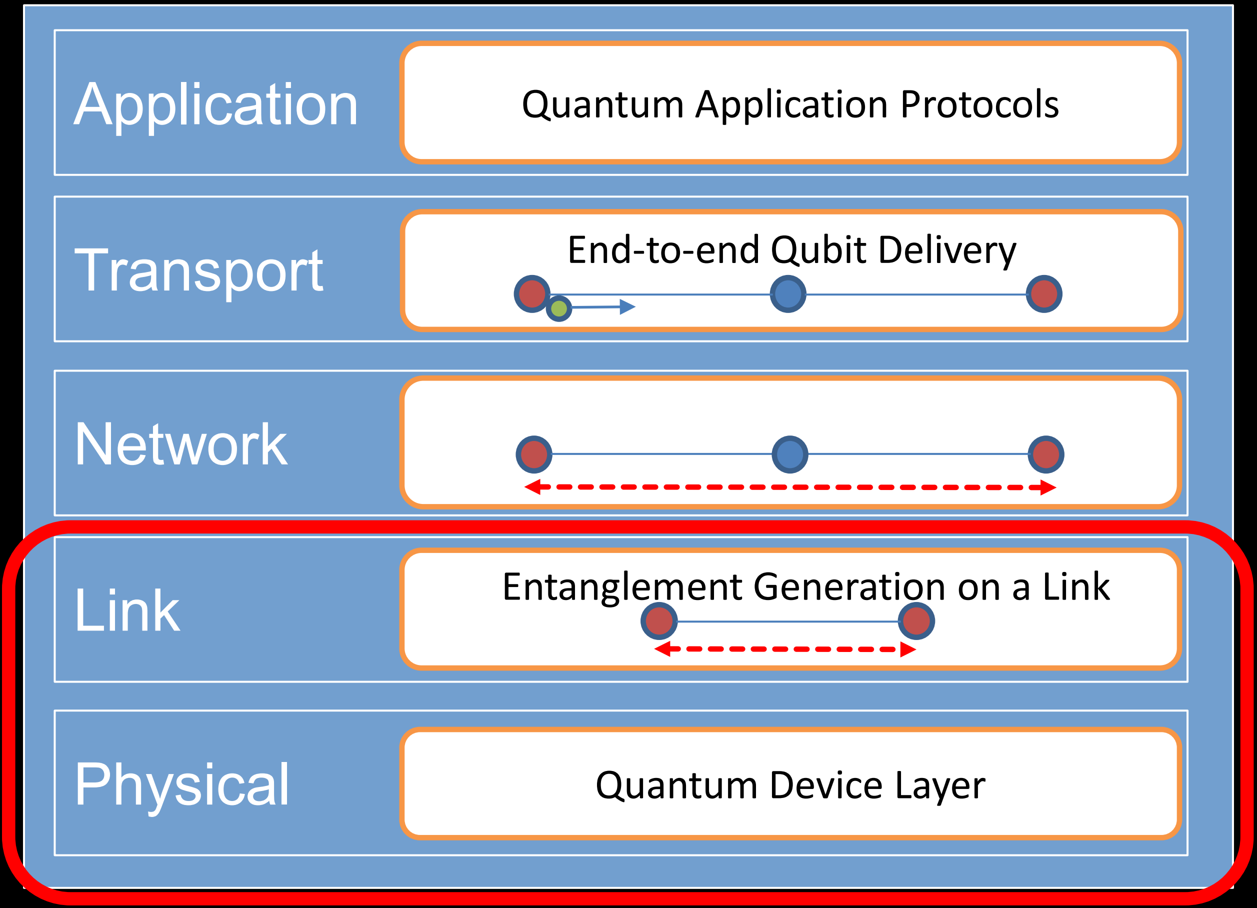
Quantum Network Stack



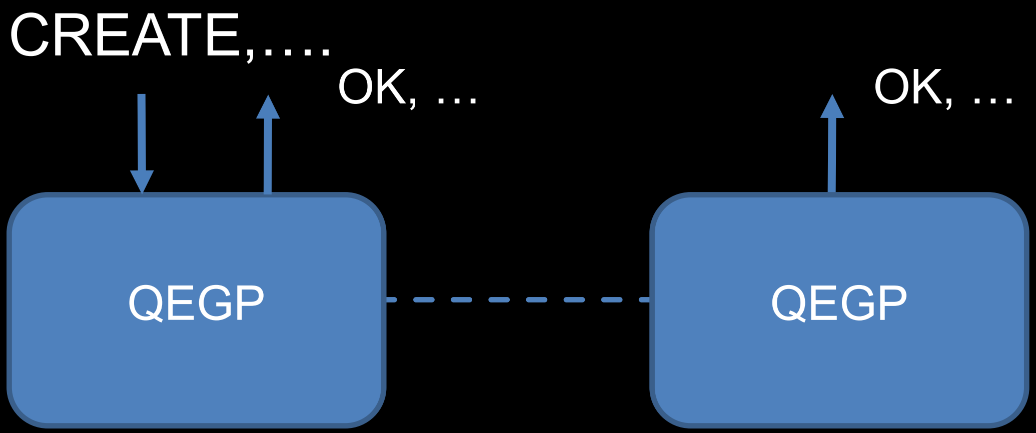
Quantum Network Stack



Quantum Network Stack



Link Layer: Entanglement Generation Service



QEGP – Quantum Entanglement Generation Protocol

Performance Metrics

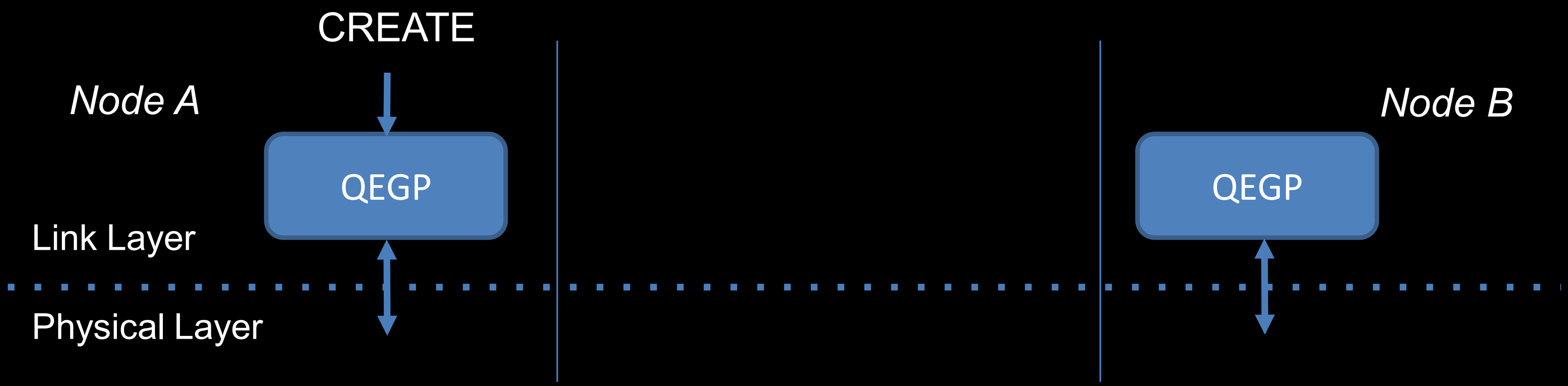
Quantum Metrics

- *Fidelity*: quality of entanglement, rate of success trade-off

Standard Metrics

- *Latency*: issuing request to getting a pair
- *Throughput*: pairs/s
- *Fairness*: difference in performance metrics between nodes

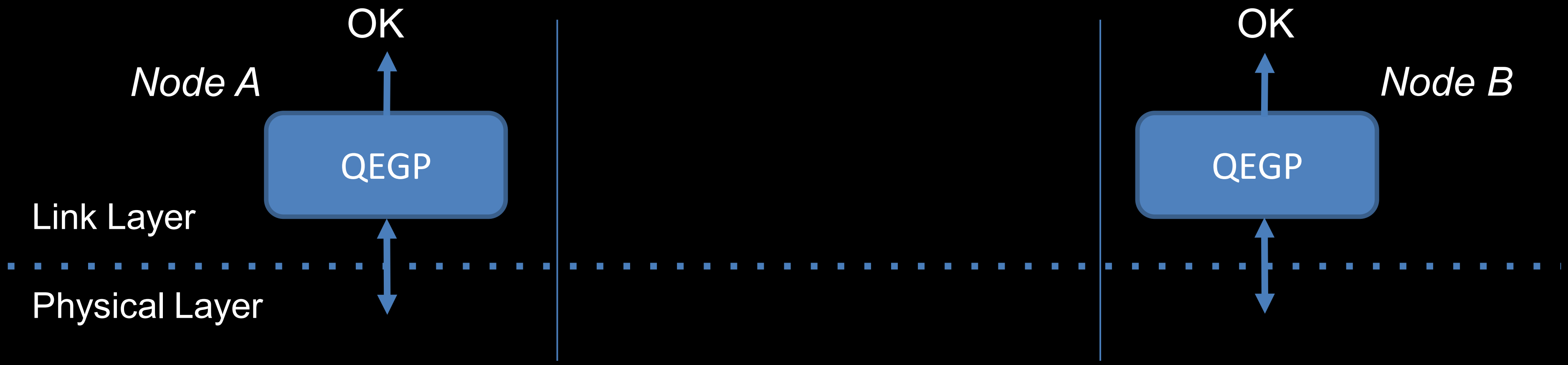
CREATE



Higher layer to QEGP

- # pairs, minimum fidelity, max waiting time, ..

OK: Expected Service



QEGP to higher layer

- Entanglement ID, qubit ID, fidelity estimate, ...

Use Cases

Application Use Cases

- *Measure directly*: many pairs measured immediately
- *Create and keep*: few pair(s) stored for processing

Network Layer Use Case

- *Create and keep*: entanglement swapping with two pairs

Design Considerations

Noise due to attempts

- Producing entanglement induces noise on storage qubits

(Kalb et al, *Phys. Rev. A*, 97. 2018)

  - Avoid triggering unless both nodes agree

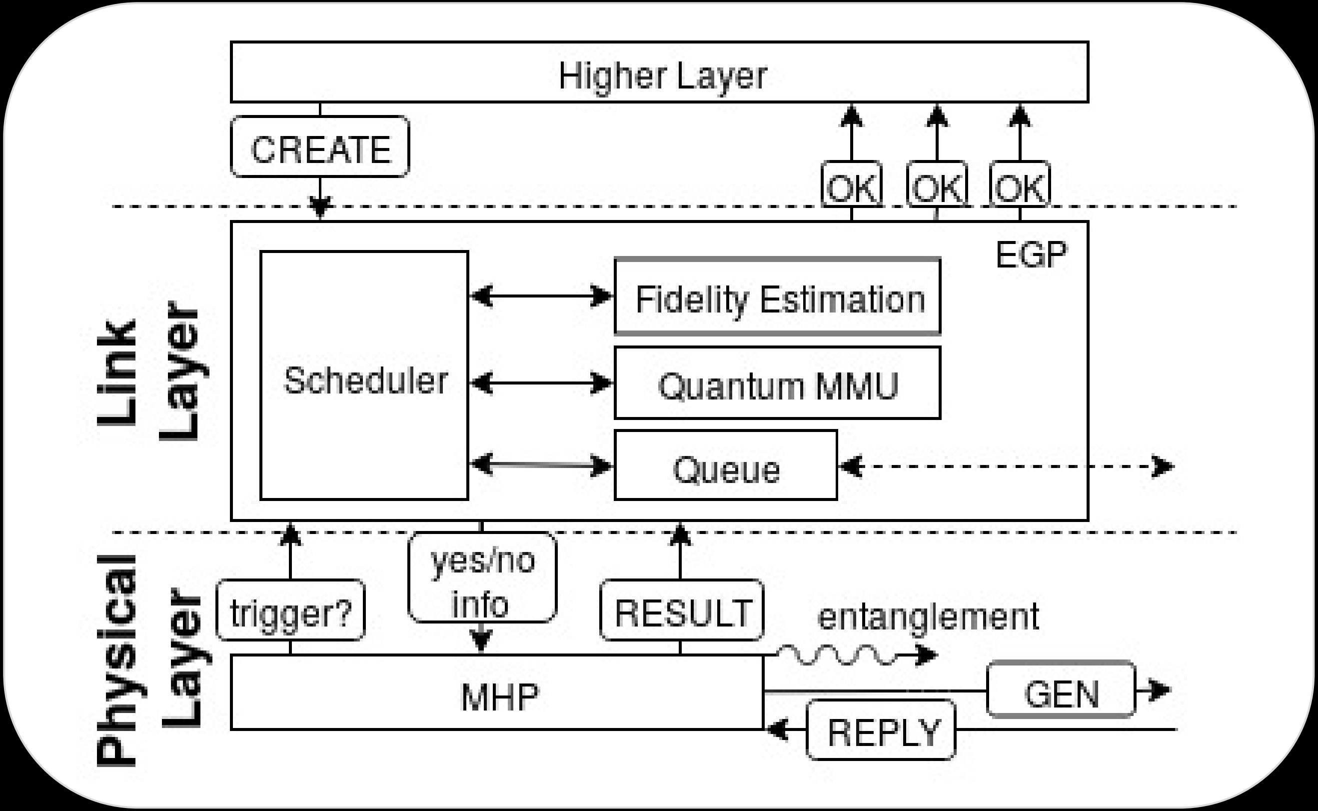
Noise is time dependent

- Avoid waiting once entanglement made
  - Prior discussion preferred

Quantum CRC for error detection difficult

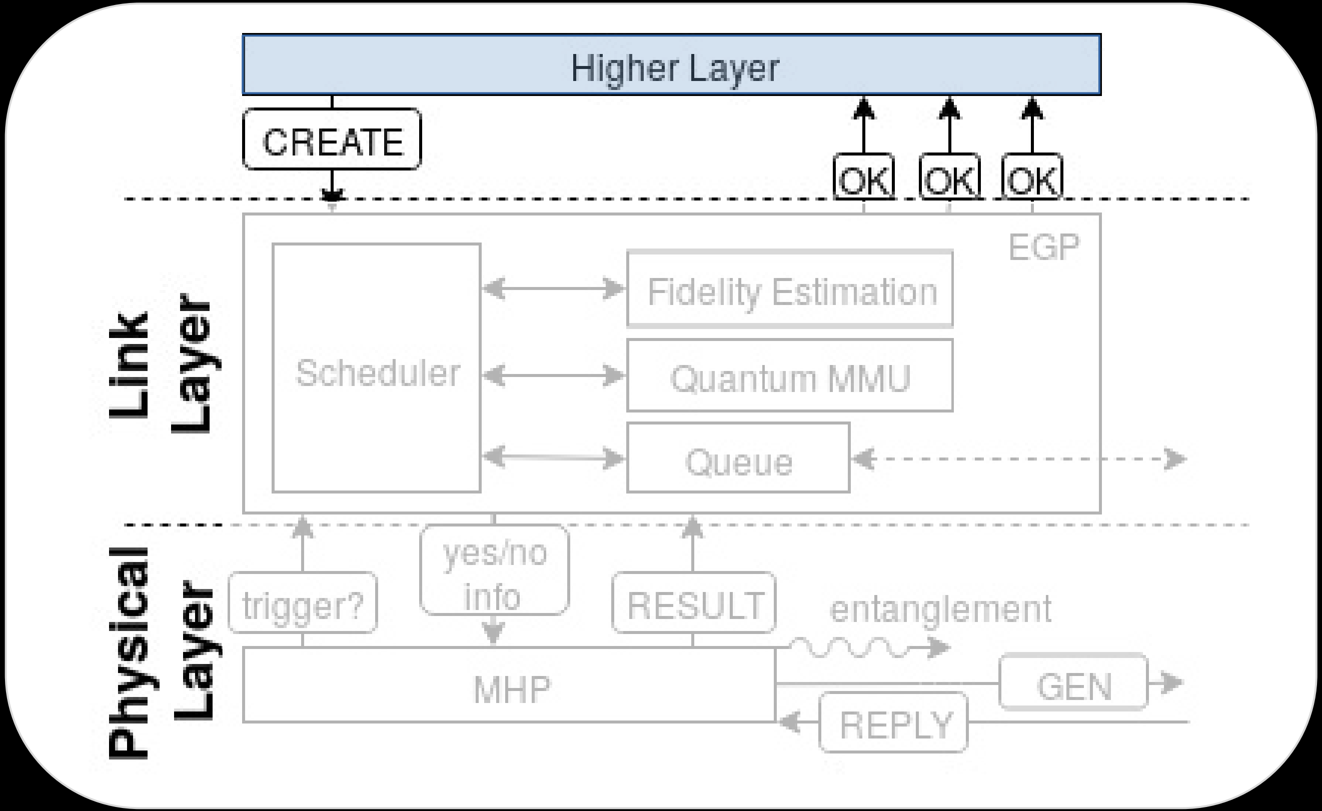
- Applications do not require perfect entanglement
  - Reduce complexity by interspersing test round
  - Theorem (summary): also works for correlated noise

A Link Layer Protocol and Evaluation

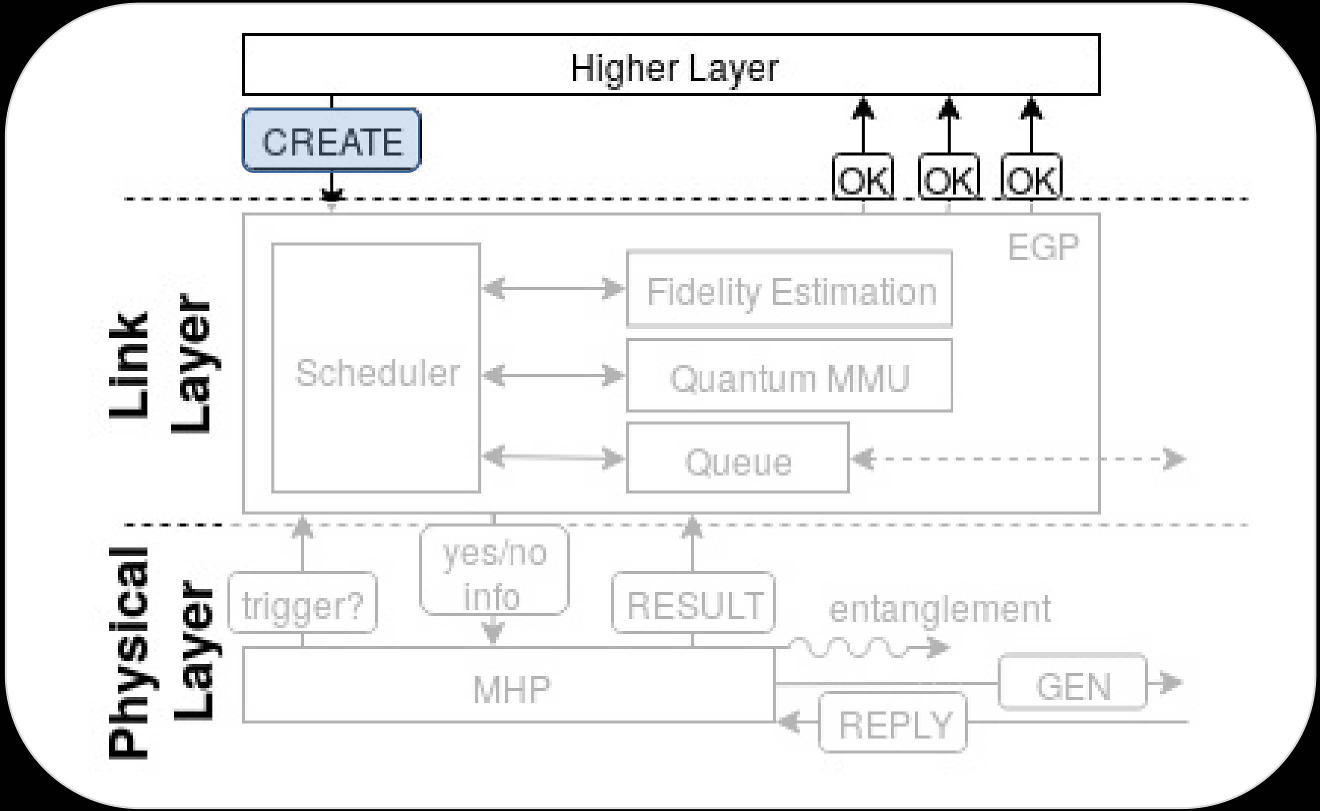


More details?
See paper ACM SIGCOMM 2019

A Link Layer Protocol



A Link Layer Protocol



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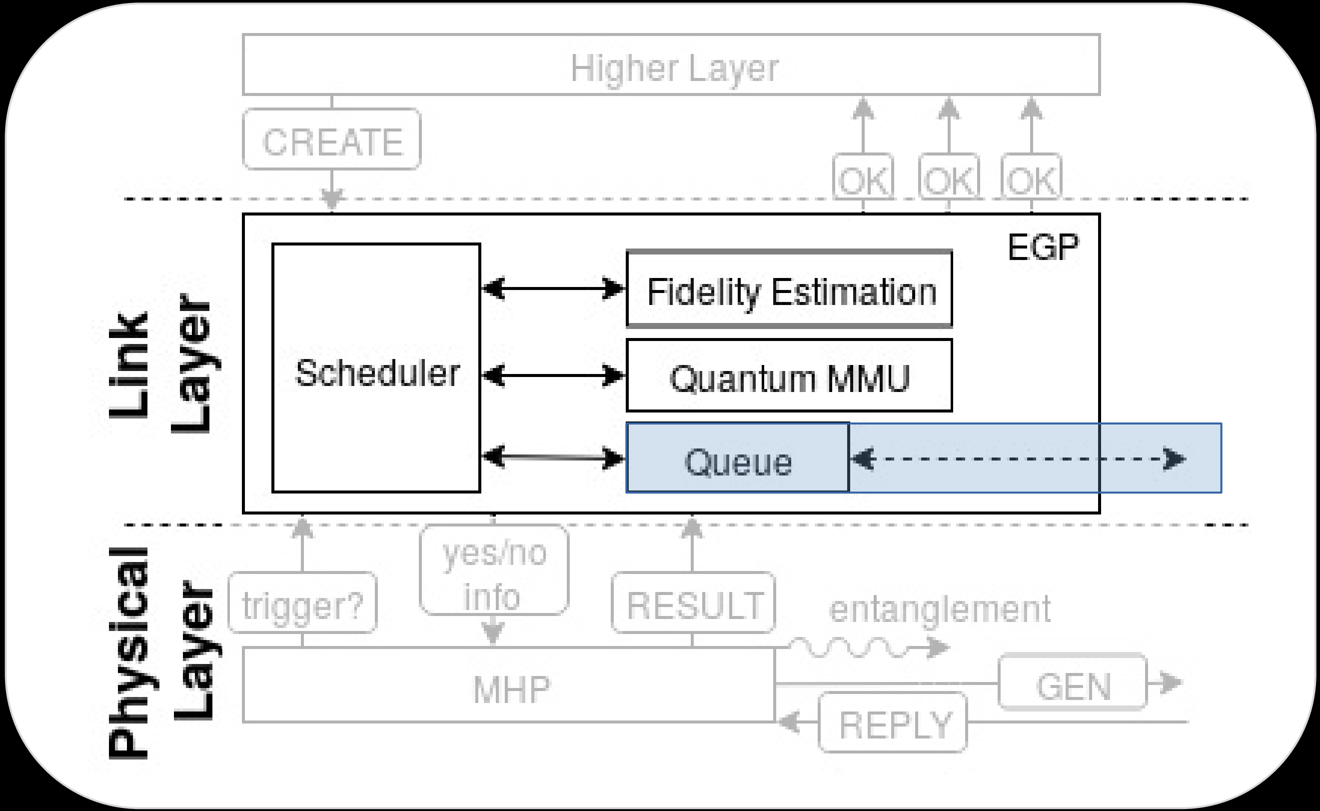

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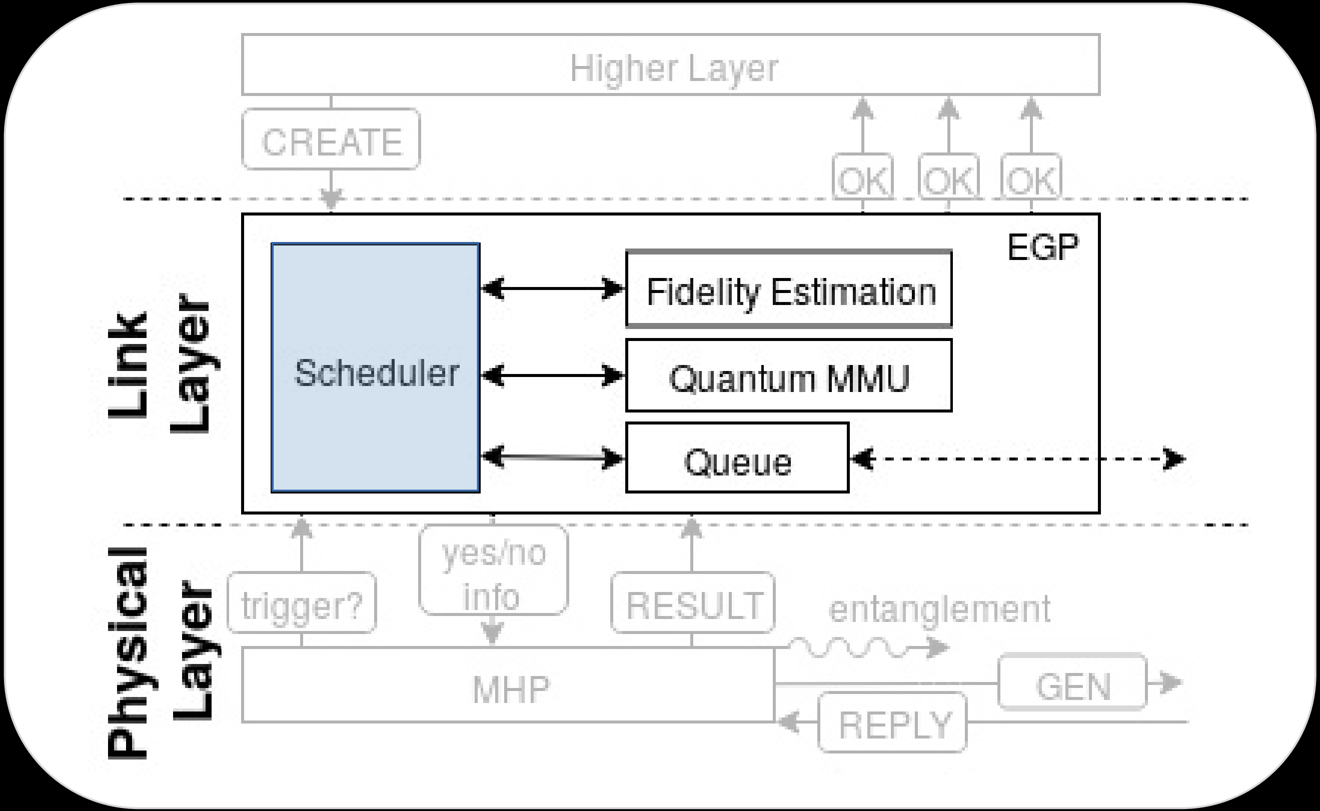

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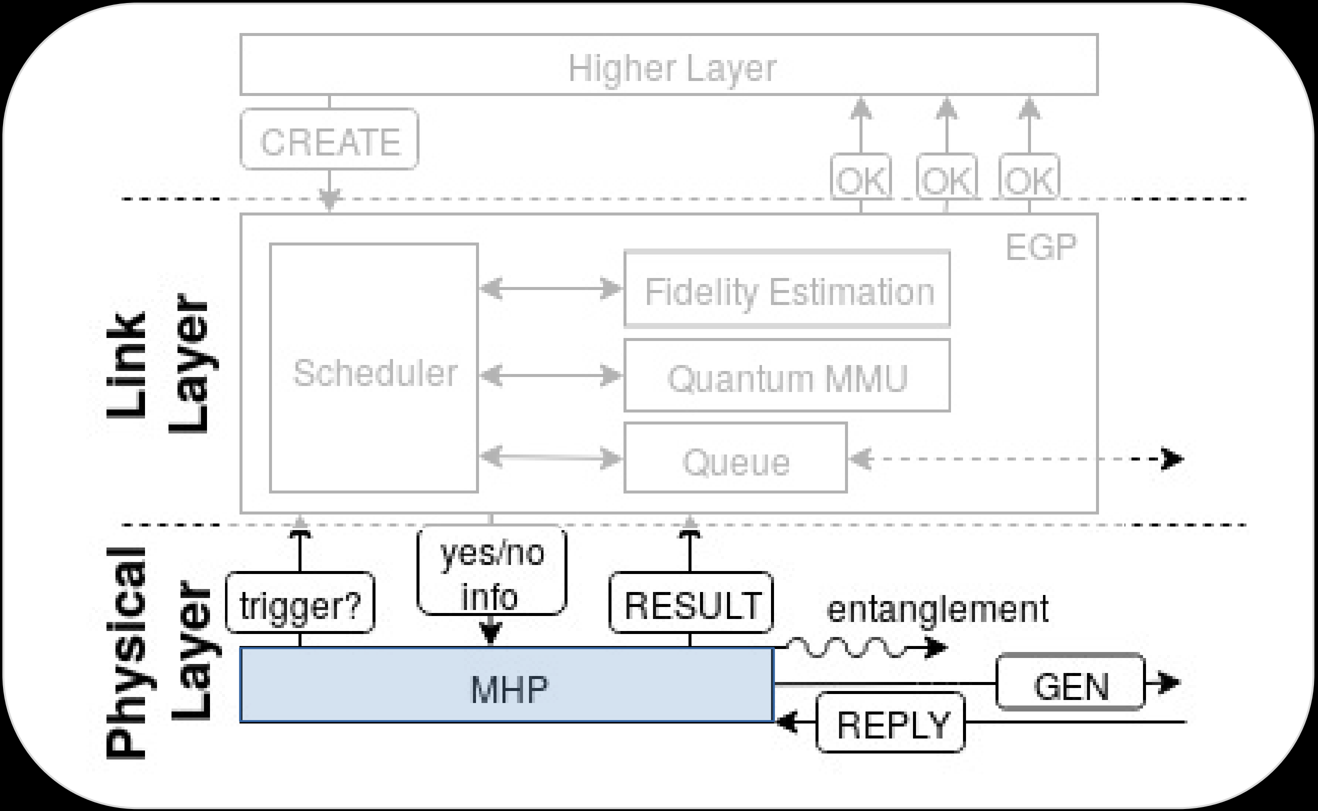

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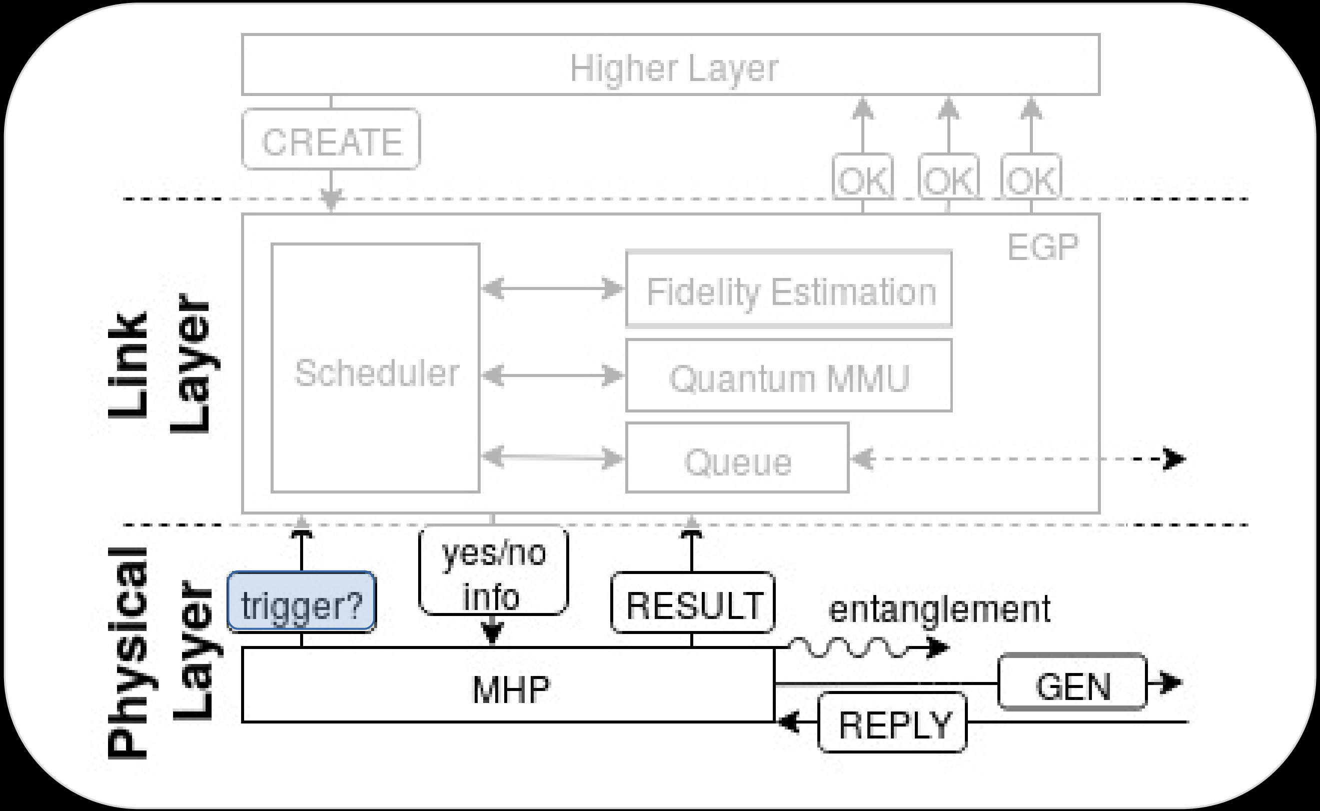

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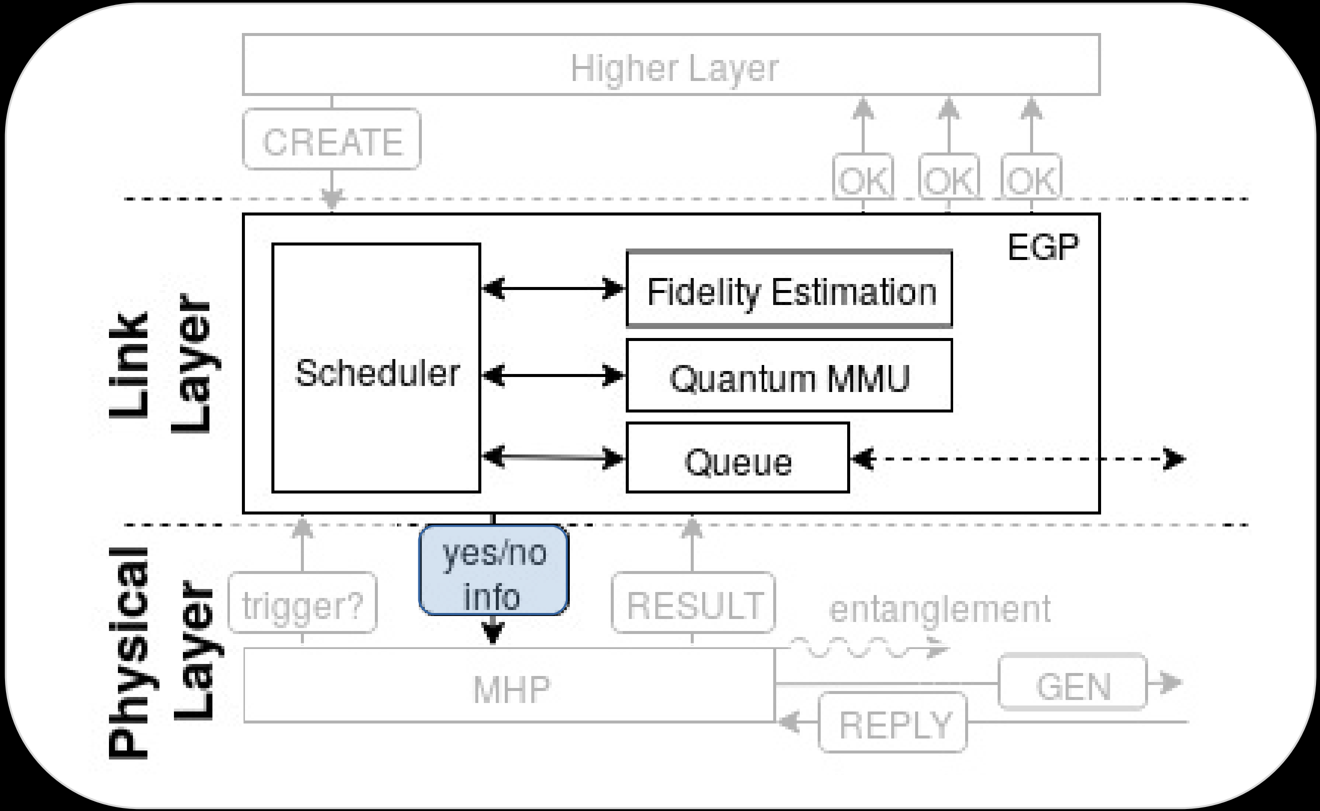
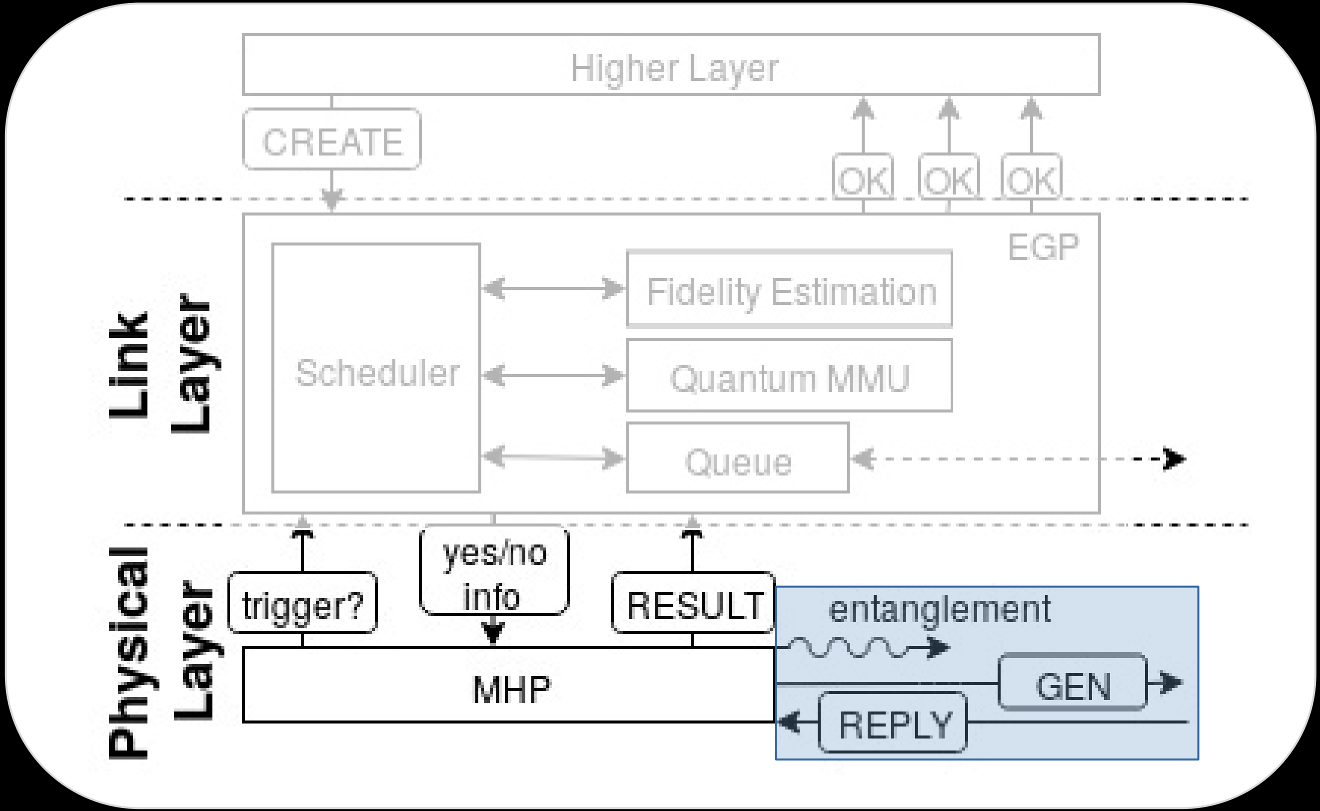


A Link Layer Protocol



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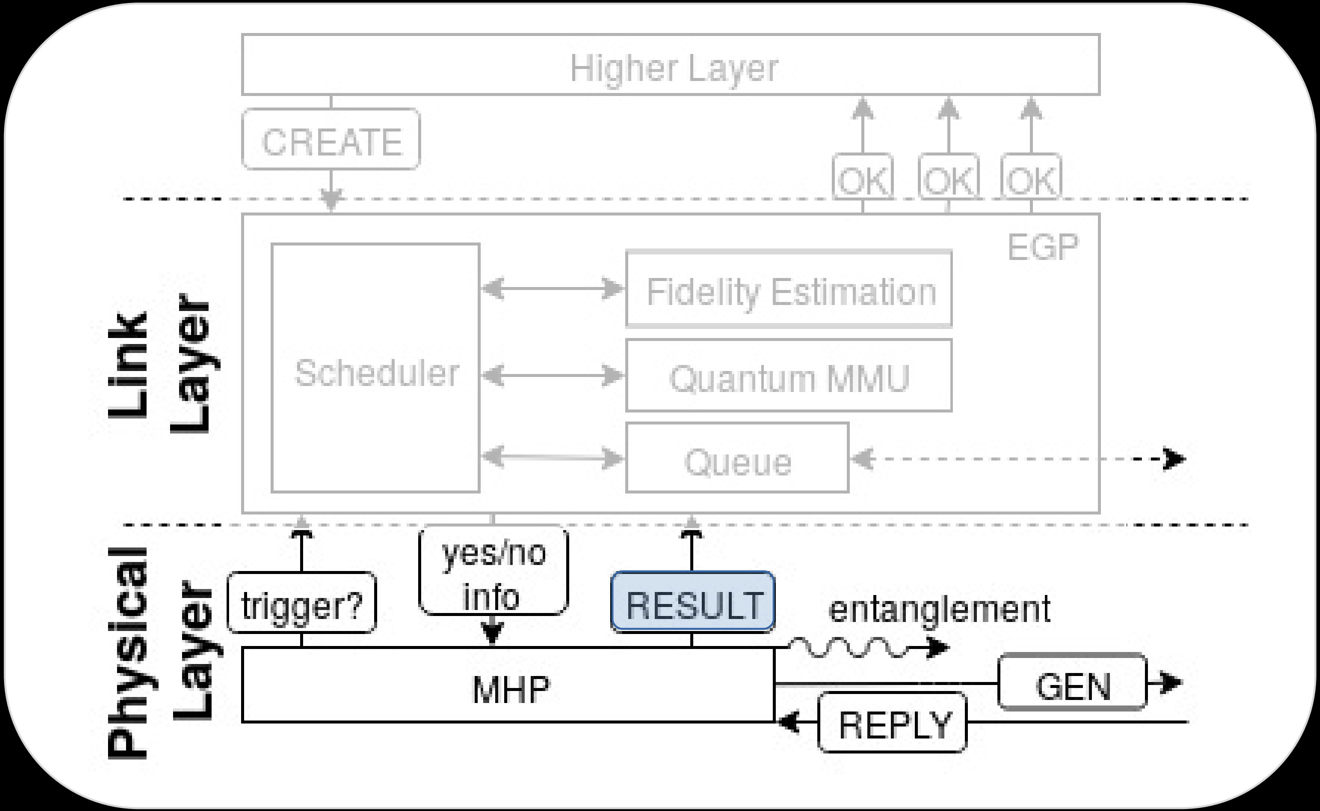

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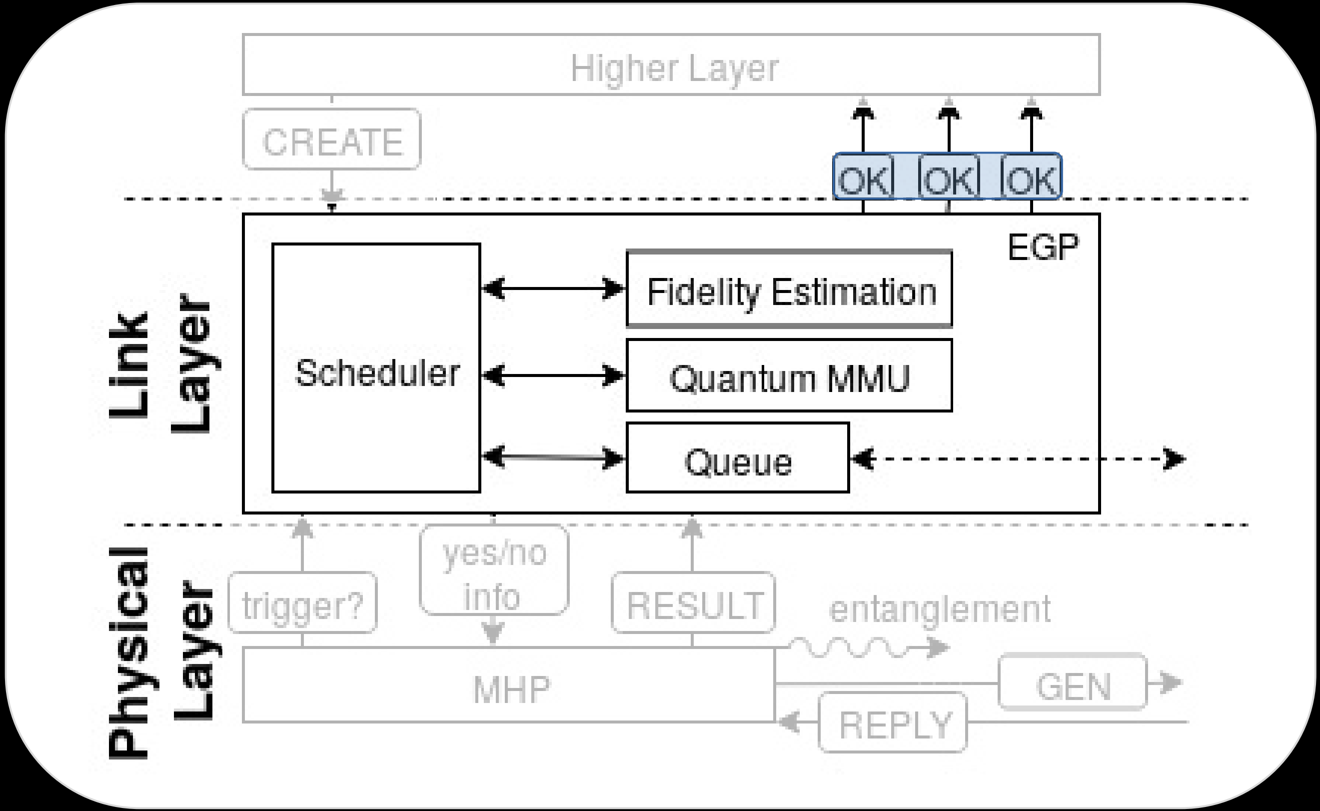

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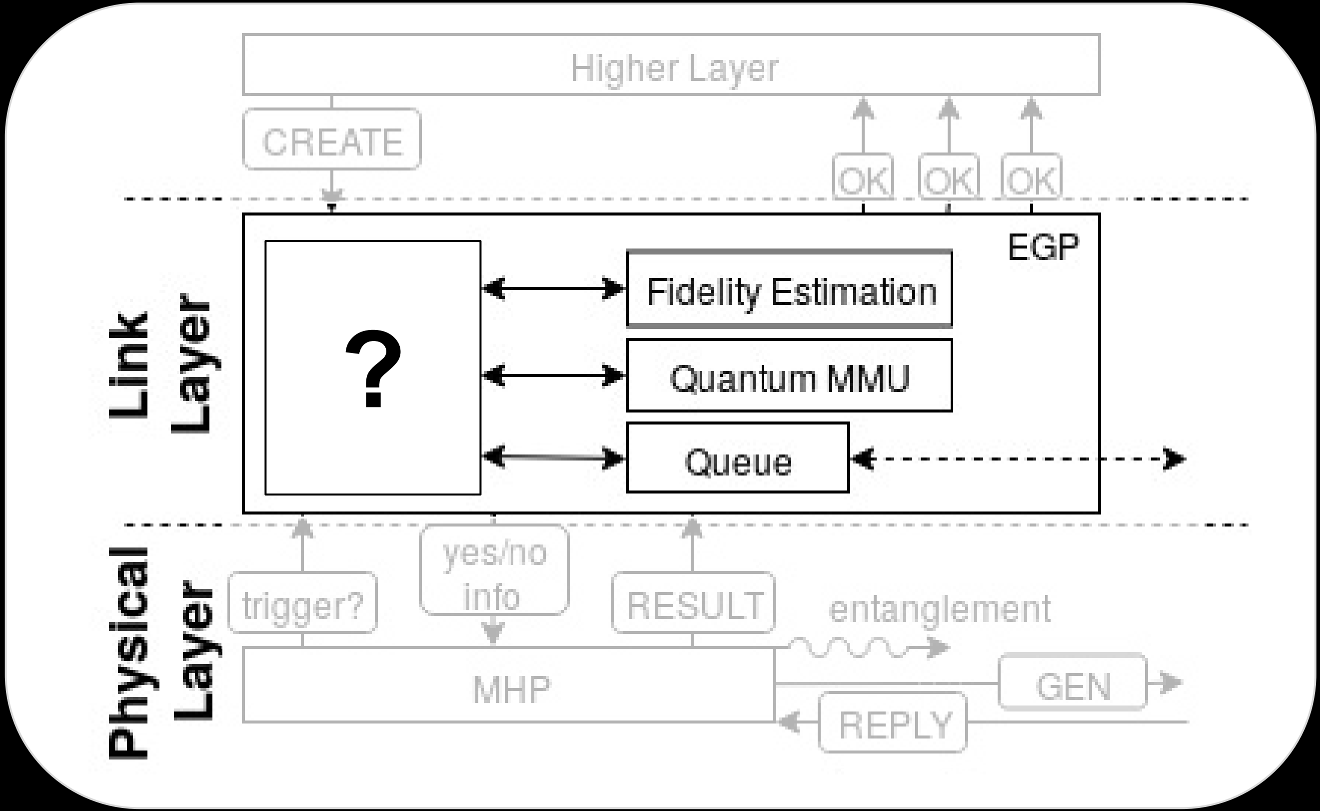


Investigating Scheduling using Simulation Tool: NetSQUID

- Discrete event simulator
- Model and validate simulated quantum hardware
- Model physical components e.g. fibers, nodes, and midpoint

Simulation Environment: SurfSARA

- **Long runs**
  - *Protocol robustness*: recovery mechanisms
- **Short runs**
  - *Performance trade-offs*: latency, throughput and fidelity
  - *Metric fluctuations*: different scheduling strategies

Simulations	Core hours	Simulated time	Scenarios
2578	94244	707 hours	173

SURF SARA

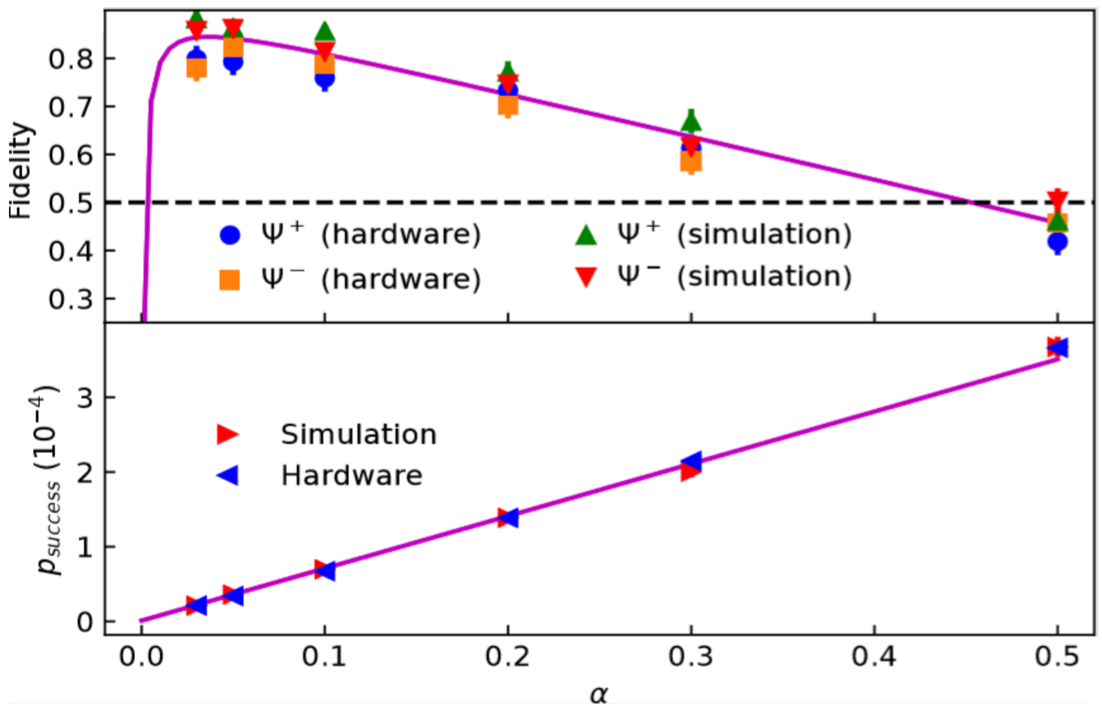
Simulation Example: QL2020

KPN PBX
detector location

Assumed loss
0.1 dB/splice
0.3 dB/km

Evaluation: Quantum Hardware Model

- Simulate experiments
- Fidelity vs rate of success
- Qubit memory lifetimes



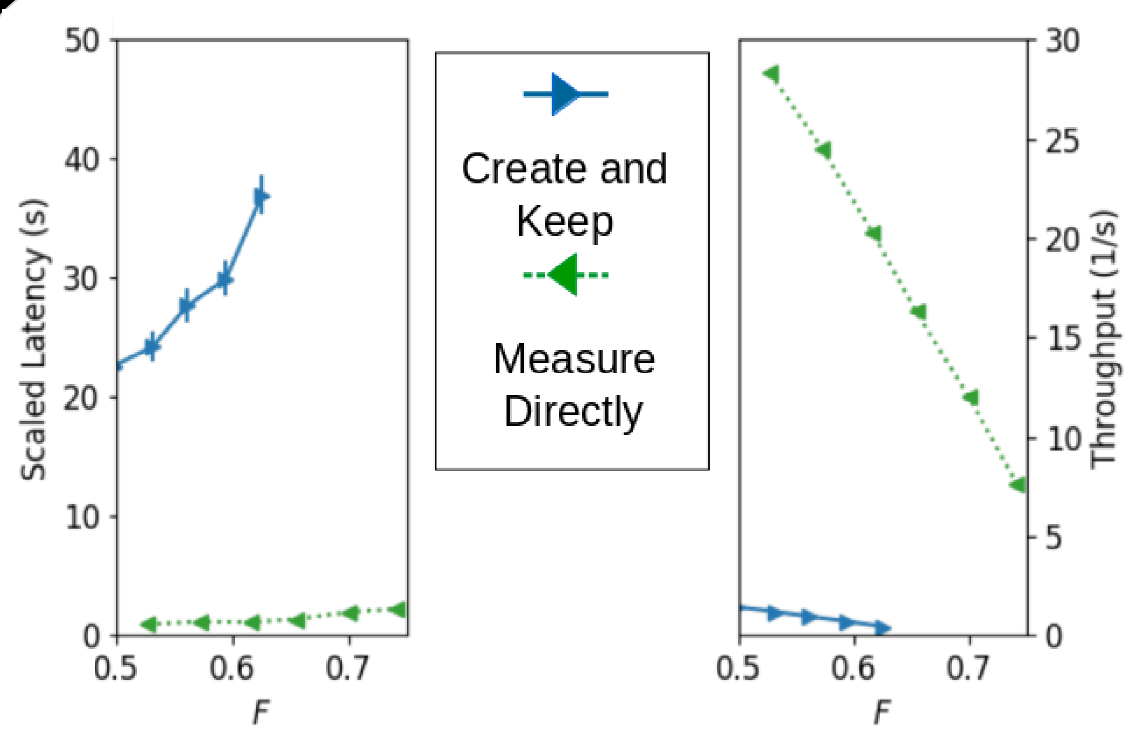
Evaluation: Single Request Types

Parameters

Fidelity	>0.5
Control message loss probability	Up to 10^-4

Takeaways

- Robust against extreme channel loss
- Fidelity primarily impacts latency and throughput



Our Contribution

- Functional allocation of quantum network stack
- Systematic study of design considerations and use cases
- First physical and link layer protocols
- Performance evaluation and scheduling investigation

Where to go from here?

Many computer science challenges

- Fast and reactive control plane for generating entanglement
- ….. In a multi-user network ☺ in a multi-user network

- Efficient routing of entanglement in the network

- Development of quantum programming paradigms for networked applications

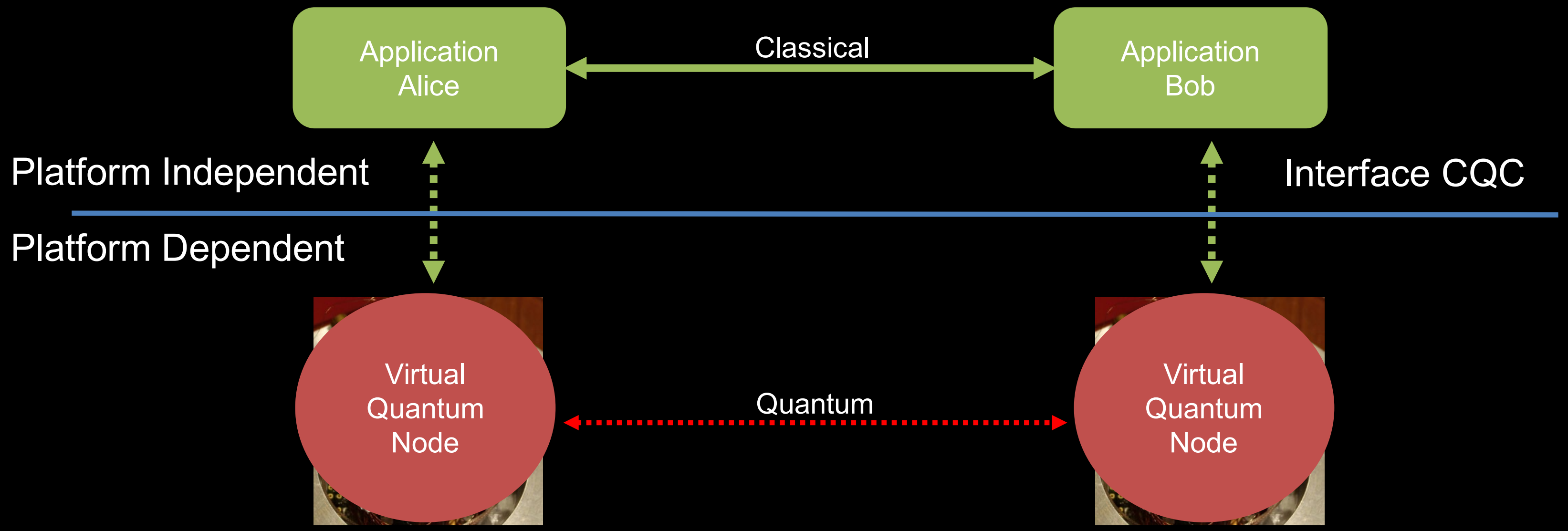
- Compile optimizations for networked quantum processors

- Scheduling and arbitration of local quantum operations and entanglement generation on a local quantum processor

- Understanding application requirements
- ….

Want to learn more?

Don’t have your own hardware but want to explore applications? ☺



Application level simulator - SimulaQron
Download at http://www.simulaqron.org

Don’t have your own hardware but want to explore quantum networking? ☺

NetSquid: Network Simulator for Quantum Information using Discrete events.

Uses at all levels of the stack include:
- More accurate study of possible repeater designs
- Determine importance hardware parameters to attain them
- Parameter optimization
- Determine and validate network designs (e.g. repeater placements)

- Analyze control stack
- Determine application protocol performance
- ……

Download at http://www.netsquid.org

Learn Quantum Cryptography!

edX QuCryptoX

Want to read more?

- Link Layer
- A. Dahlberg, M. Skrypzcyk et al., A link layer protocol for quantum networks, ACM SIGCOMM, 2019

- Introduction to Quantum
  - Nielsen & Chuang, Quantum Computation and Quantum Information, 10th edition, 2011, Cambridge University Press

- Overview Articles
  - H J. Kimble. 2008. The quantum internet. Nature 453, 7198 (2008), 1023.
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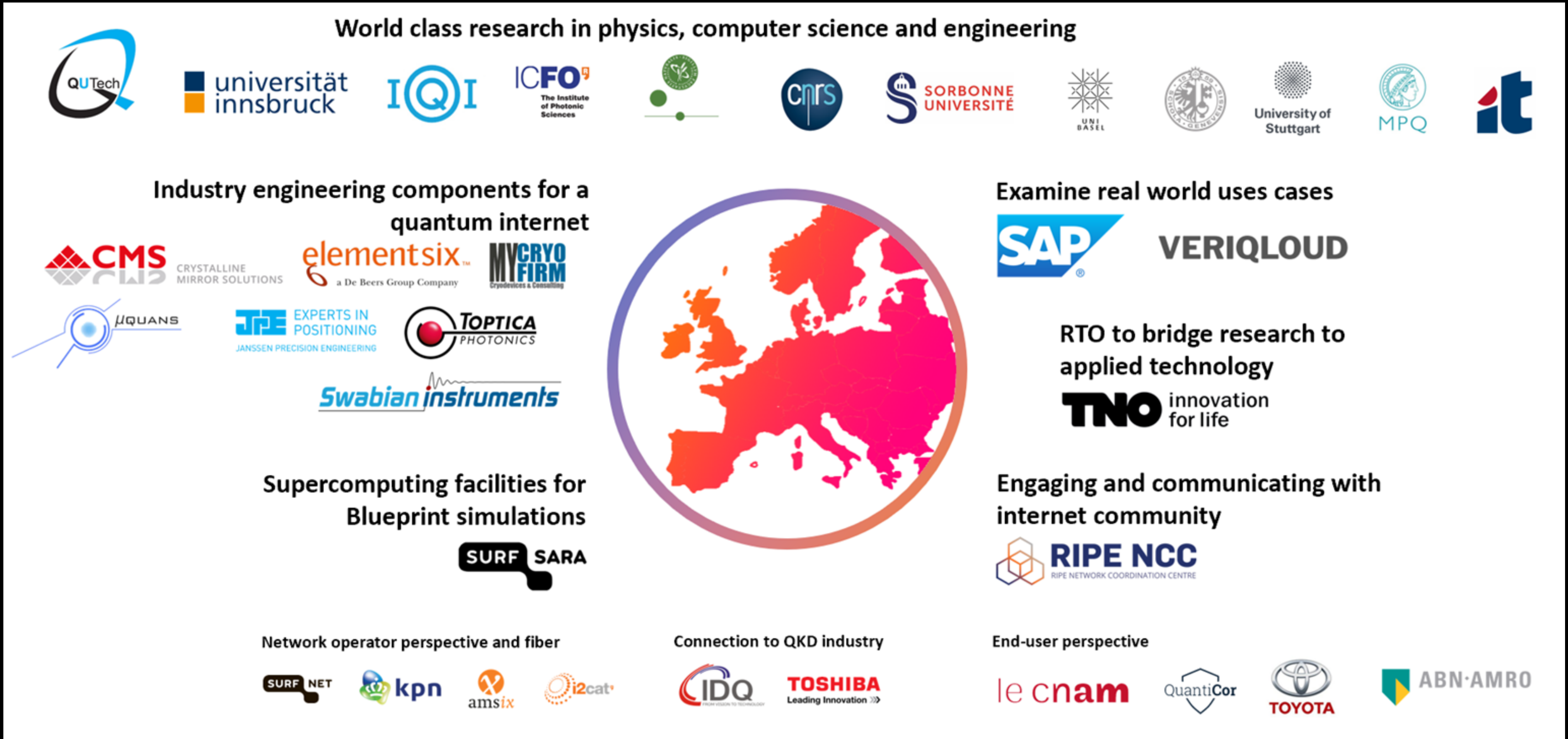

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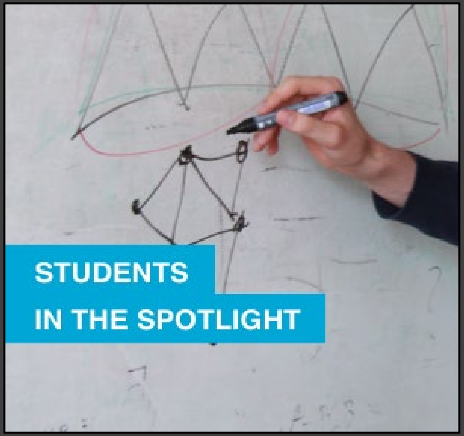

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