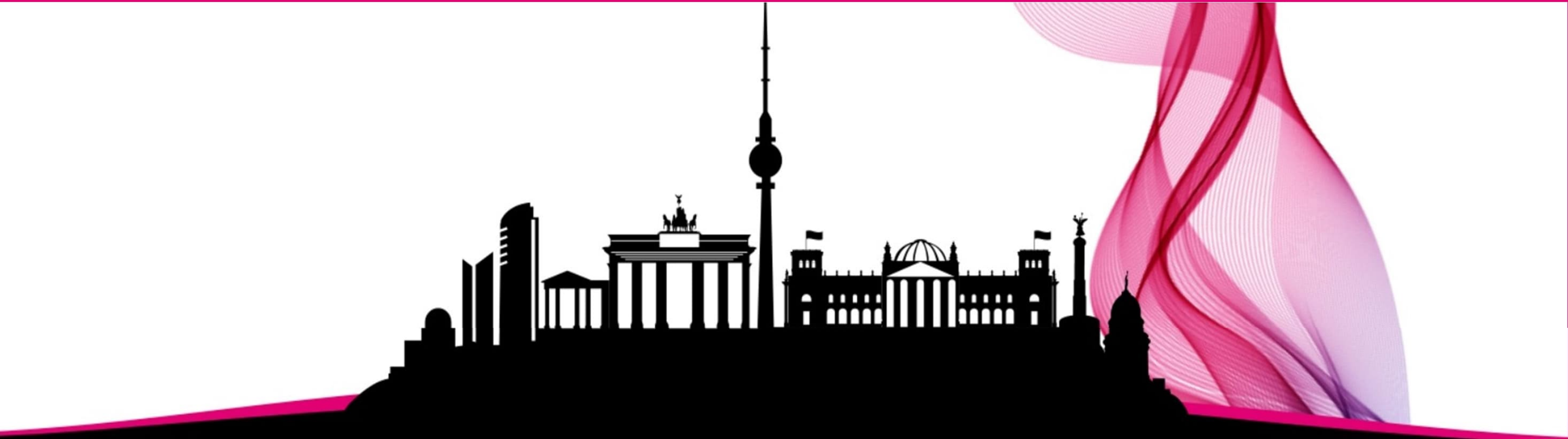
# The Road to a Quantum-Connected World:
## Insights from Deutsche Telekom’s Activities

Matheus Sena
T-Labs | Deutsche Telekom AG

Jan 2025, Geneva



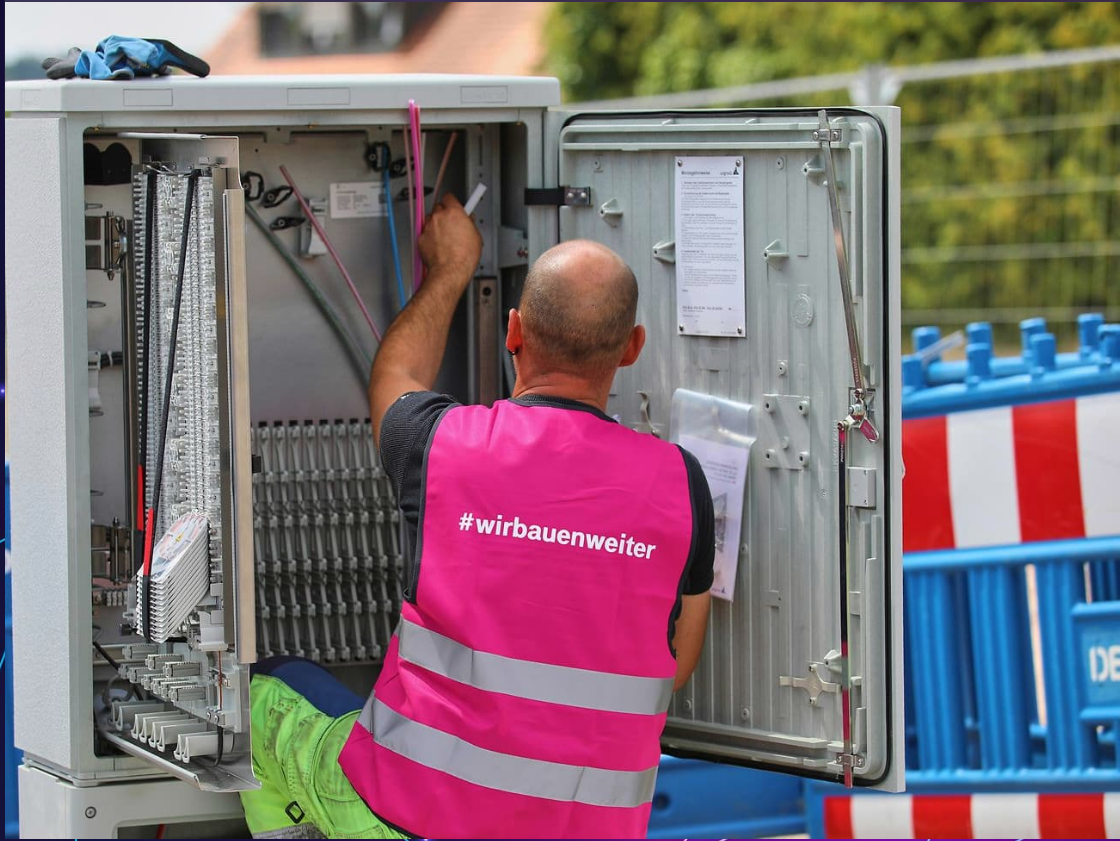
# The optical fiber infrastructure – (one of the) network operator’s biggest asset(s)

More than **8.4 million households** in Germany currently have access to Deutsche Telekom's FTTH network.

This number is **expected to grow to 10 million** households **by end of 2024**

**How to use this asset for generating new revenue streams?**

Deutsche Telekom's fiber optic network in Germany alone spans **more than 750,000 kilometers**[1]...






[1] Der Glasfaserausbau bei der Telekom

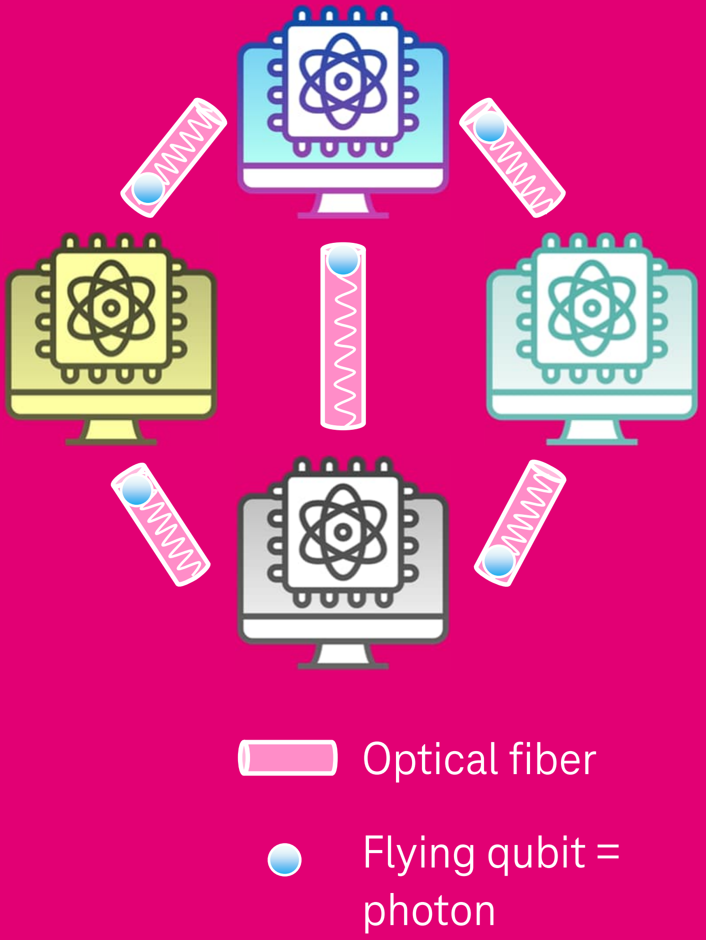
# Quantum Internet

## What?

The quantum internet is a network of quantum systems that will someday

- **send,**
- **receive,**
- and/or **compute**

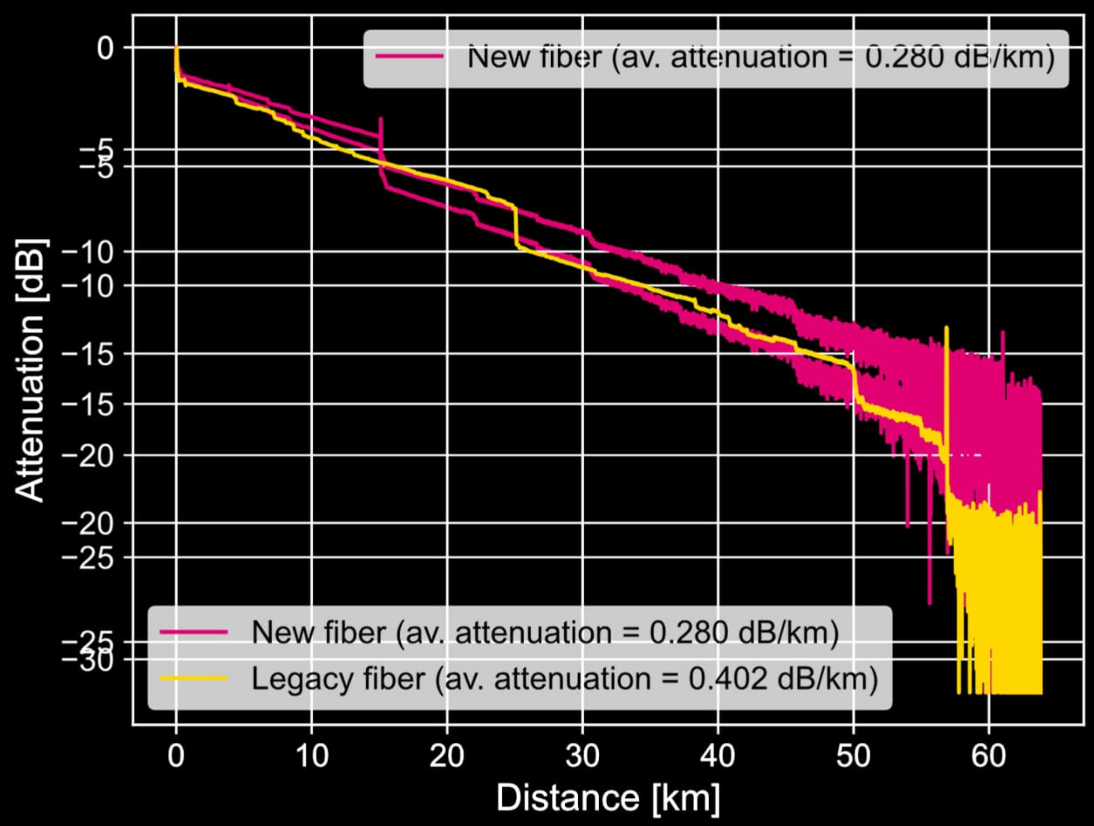
information encoded in quantum states.



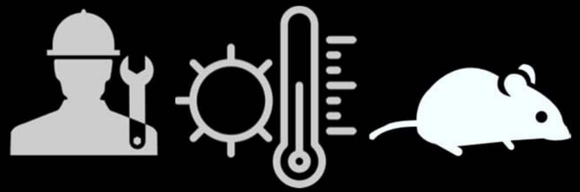

## Why?

- Security
- Distributed computing
- Improved sensing capabilities
- More accurate time synchronization

# The optical fiber infrastructure




| Characteristics | Challenges |
|---|---|
| Infrastructure evolution (from late 90's till today) | Legacy + modern networks |
| Fiber subject to external factors | Unstable qubit transmission |



A successful integration of quantum technologies into traditional communication networks requires undestanding **how to efficiently transmit/receive qubits.**

* OTDR measurements of two deployed optical fibers in Berlin

# Summary

1. Deutsche Telekom's interest in quantum technologies
    - Our team
    - Our asset
    - Sneak peek into our Q-lab
2. Quantum-safe networks
    - Quantum-key distribution – the OpenQKD project
    - The hybrid approach
3. Entanglement as a resource
    - QR.X-Project
    - Entanglement distribution
4. Quantum sensing
5. Conclusion

# Deutsche Telekom's Interest in Quantum Technology

**Deutsche Telekom Group**


### Quantum Communication

Determine the role of quantum technologies for future communication networks

T LABS Deutsche Telekom AG


### Quantum Computing

Explore use cases that may profit from exponential speed up by quantum computers

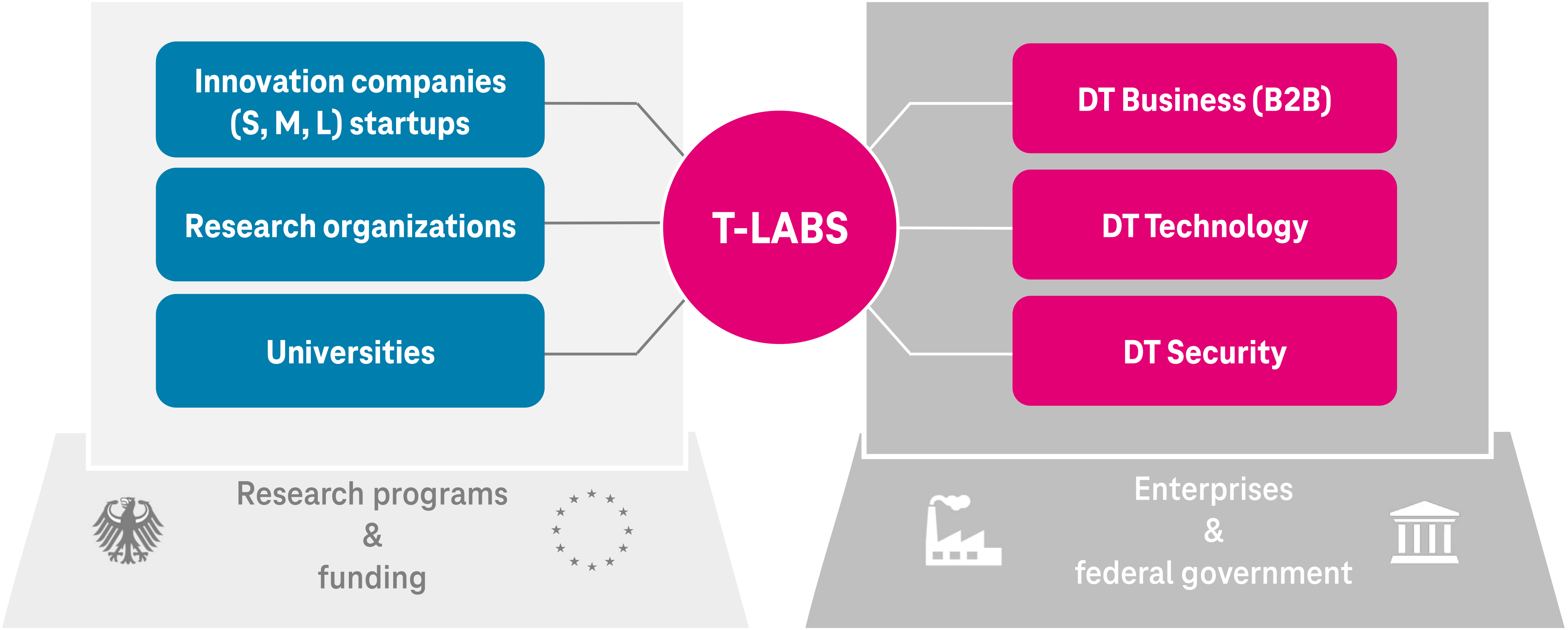
T Systems


### Quantum Key Distribution

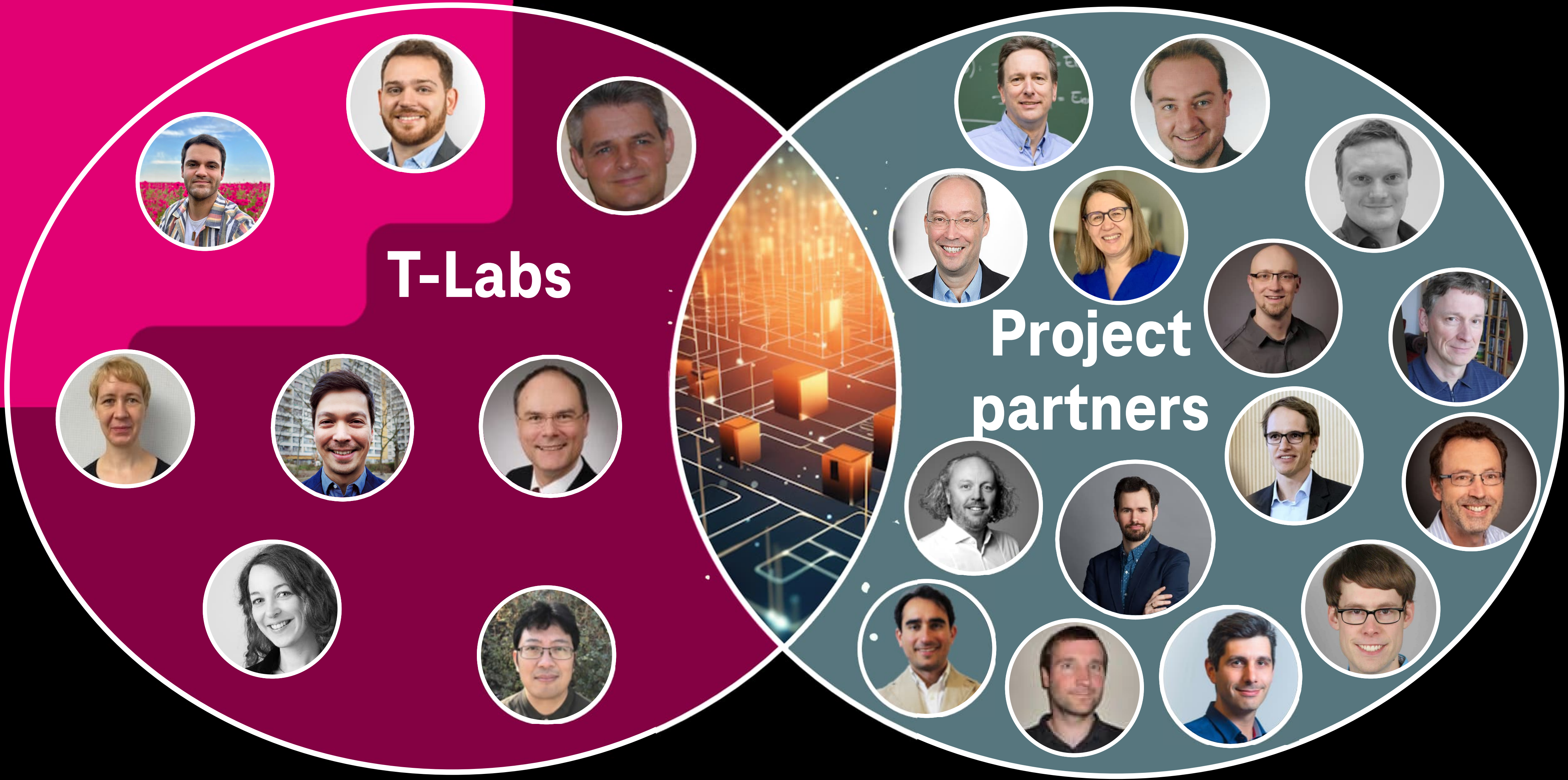
Secure future networks with quantum secure cryptography

Deutsche Telekom Technik GmbH
Deutsche Telekom Security GmbH

# Quantum @ DT and our Partner Ecosystems



# The team

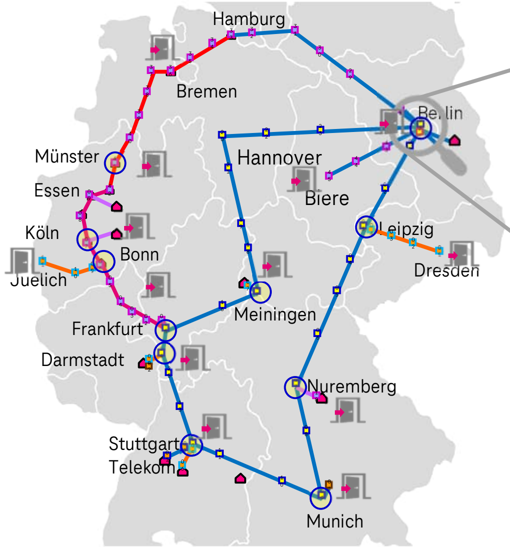


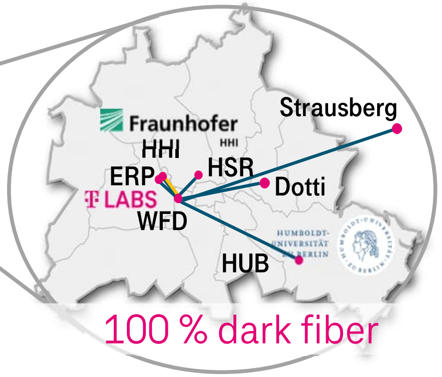
# Our asset

## The R&D TestNet

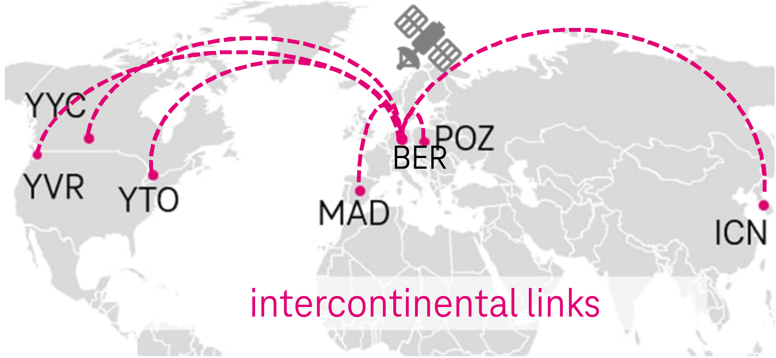
**D-Ring**
- Fiber length 2.030 km
- 27 OLAs
- 8 Access nodes ○

**NW Chain**
- Fiber length 1.375 km
- 27 OLAs
- 3 Access nodes ○



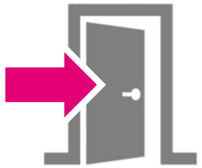




- Q-Lab in Berlin
- LoS QKD
- Entanglement distribution




- Worldwide quantum secure key exchange network based on classical cryptographic methods only (PQC)

## Quantum Lab



**Entrance to the R&D TestNet**

## Experimental Room

- Cooling
- Rackspace
- Fiber connections to the R&D TestNet
- Basic equipment
- Enough space for quantum technological components



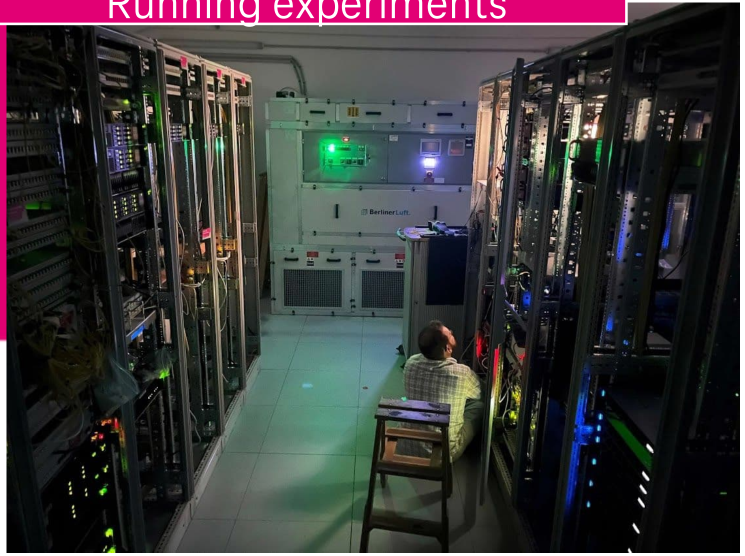

Bundesministerium für Bildung und Forschung


# Have a sneak peek into our Quantum Lab

# The Q-Lab

Lab inauguration 31.08.23


Running experiments

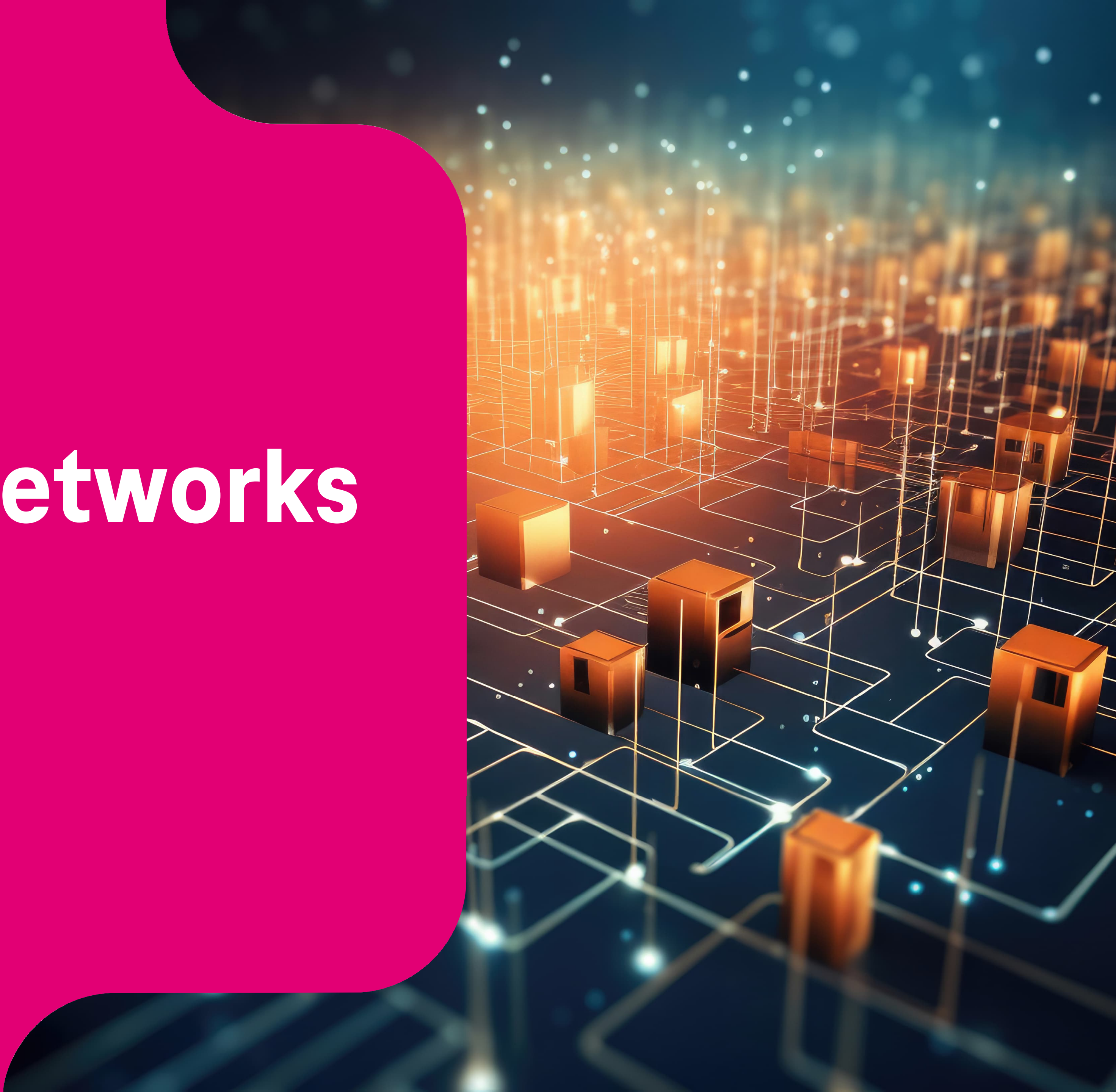


Installing new systems

Running demos

Lab tours / training

# Quantum-safe networks



GROUP
TECHNOLOGY

# OpenQKD
## Project's and DT's goals

OPEN QKD

Start: 09/2019
End: 06/2023
38 partners from 13 EU countries


**Goal of OpenQKD**

- Enable industry to integrate QKD hardware.
- Partners defined 30+ industry use cases.

## Goal of Deutsche Telekom:

- **Build a prototype for integrating QKD into an existing telecommunication network infrastructure.**

## Some of our industrial partners

TOSHIBA

VeriQloud

The testbed is supported by the Horizon 2020 research and innovation programme of the European Union under grant agreement No. 857156 (OpenQKD). Fior further details refer to: https://openqkd.eu

# Qline proof-of-concept

- **WHAT IS A QLINE[1]?**
  - New architecture for quantum communication (in) which:
    1. connects several parties using a **single fiber infrastructure;**

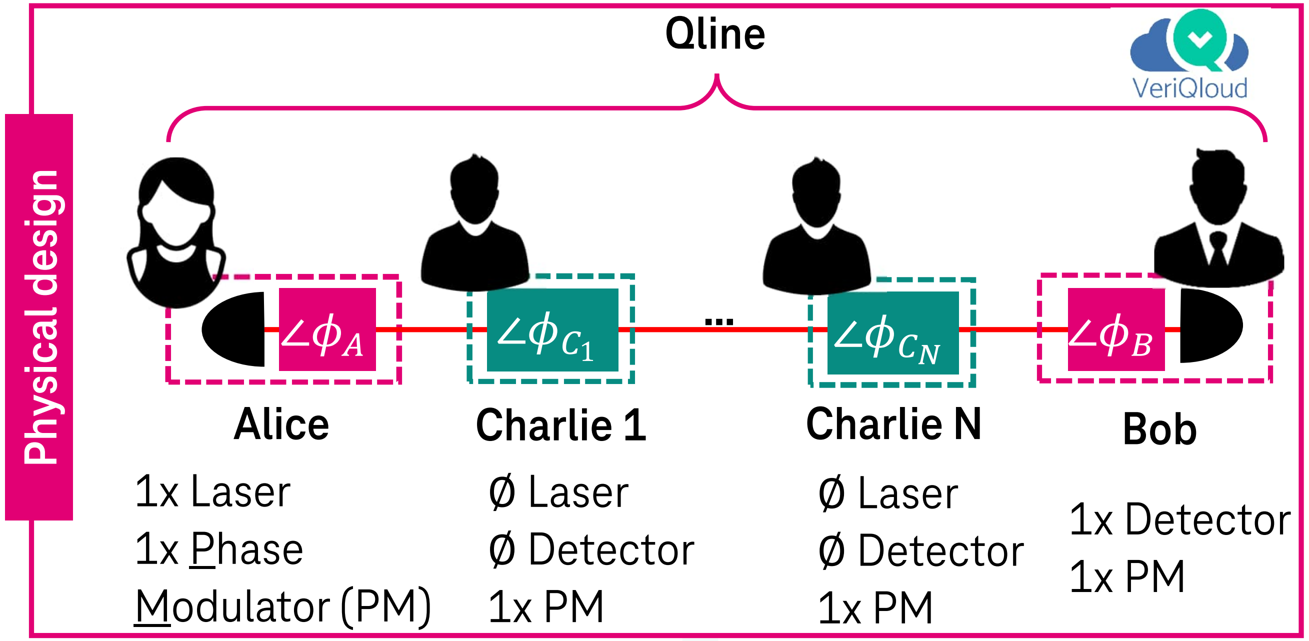

Alice: transmitter

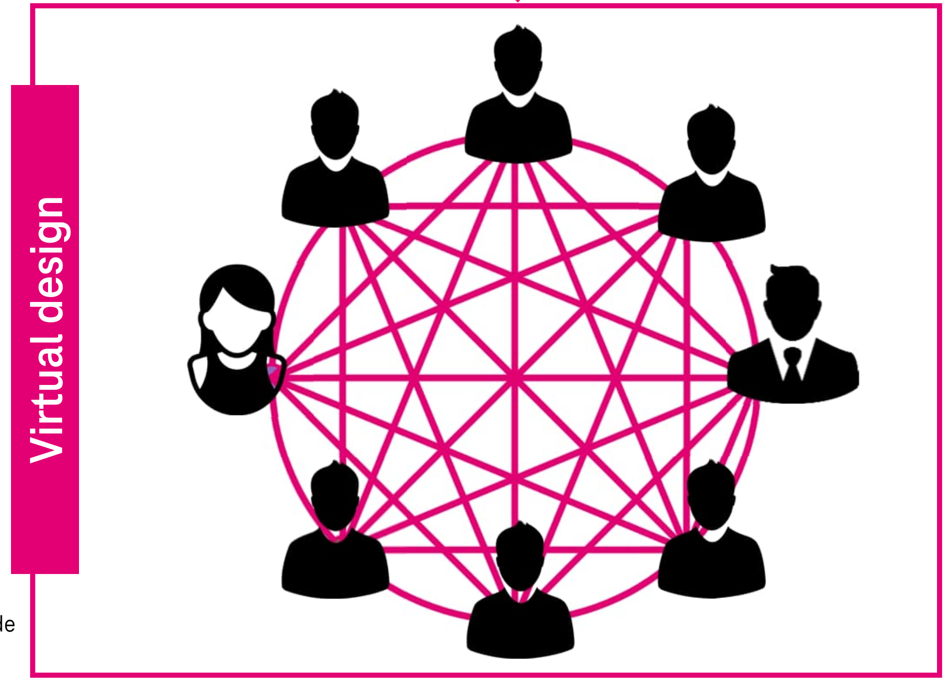
Bob: receiver


Charlie: intermediate node

    2. the qubit **generation** and **measurement** happen at the **two ends of the line**, whilst **intermediate parties** are limited to single-qubit **unitary transforms**;
    3. Laser and detector only at Alice and Bob, respectively.

- **WHY THE QLINE?**
  1. **Inexpensive design**: 1x Laser, 1x Detector, and commercial PM.
  2. **Meshed key exchange** despite linear topology.




[1]M. Doosti, L. Hanouz, A. Marin, E. Kashefi, M. Kaplan, "Establishing shared secret keys on quantum line networks: protocol and security," *arXiv preprint, 2023*.

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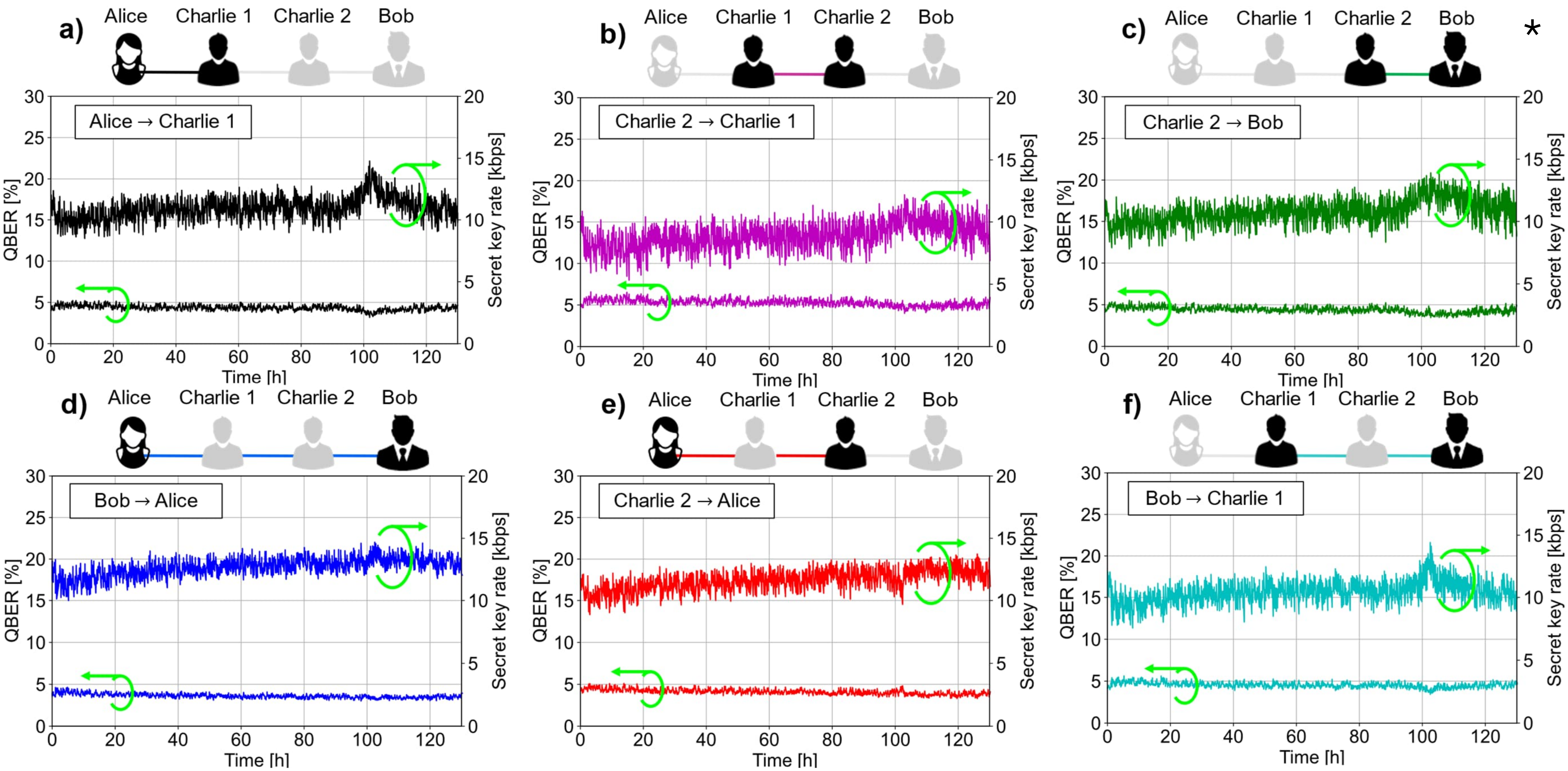
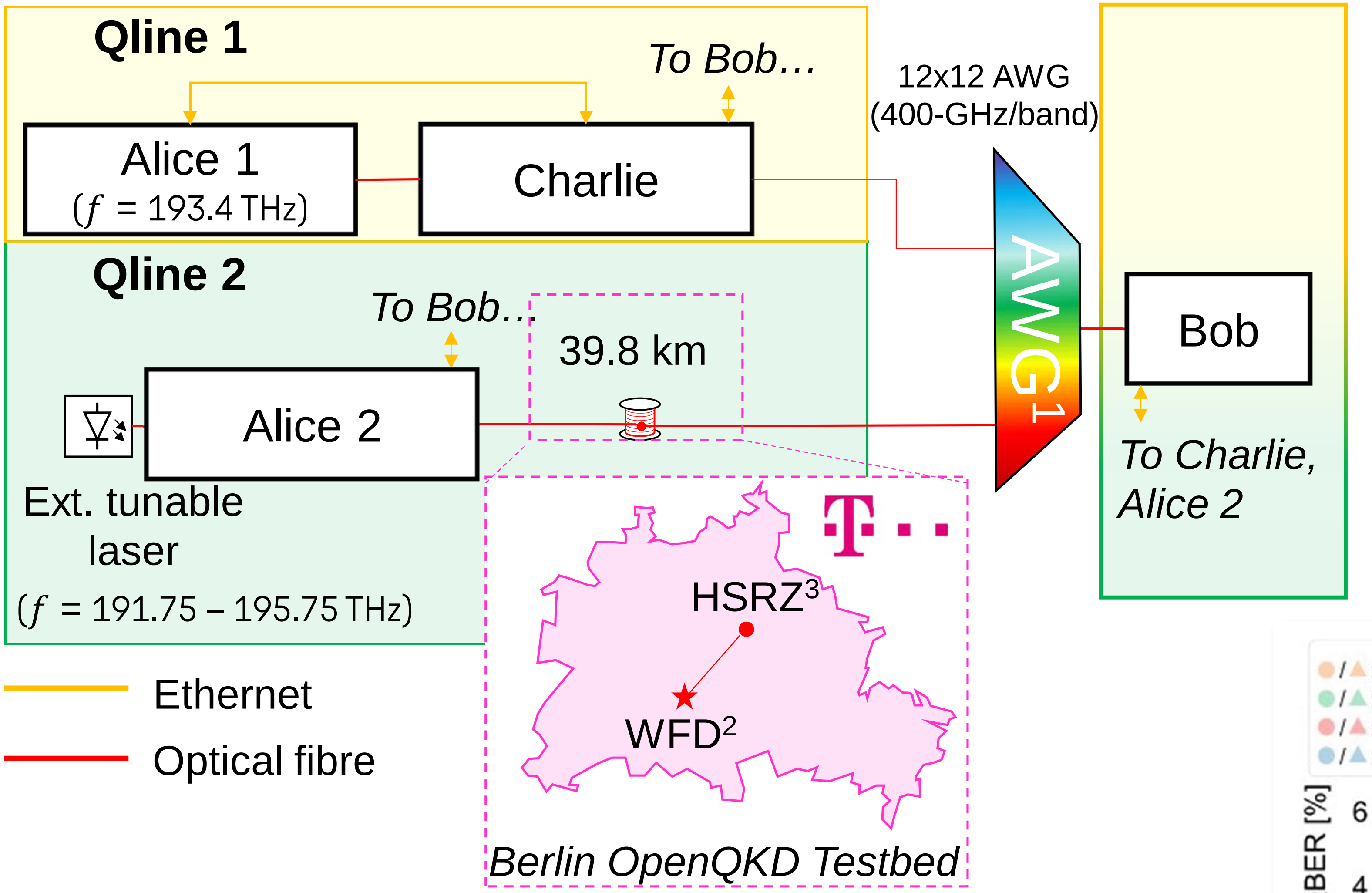
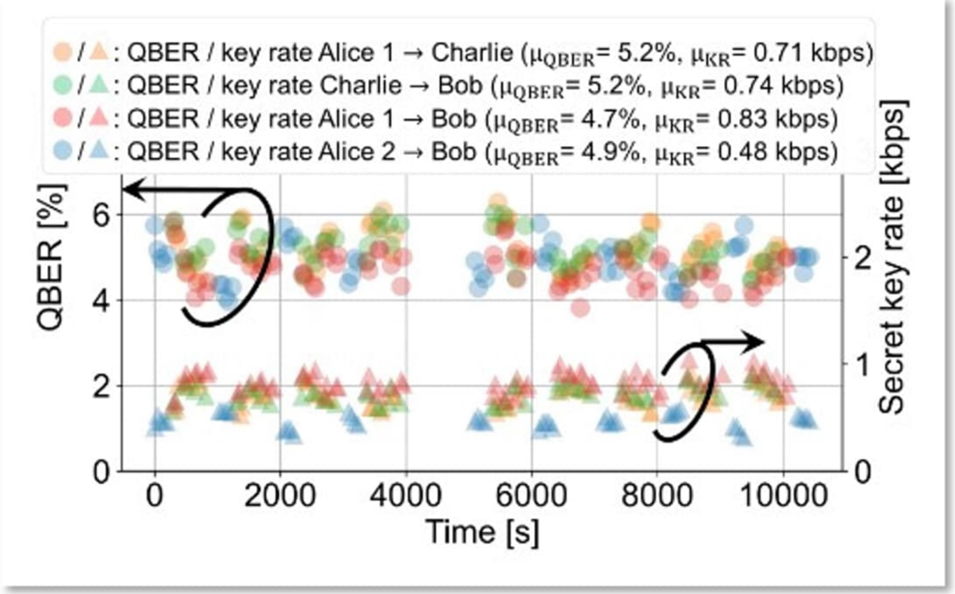





*M. Sena et al., "Deploying the Qline System for a QKD Metropolitan Network on the Berlin OpenQKD Testbed," in IEEE Photonics Journal, 2025.

[1] AWG: Arrayed waveguide grating
[3] HSRZ: Hauptstadtrepräsentanz
[2] WFD: Arrayed waveguide grating



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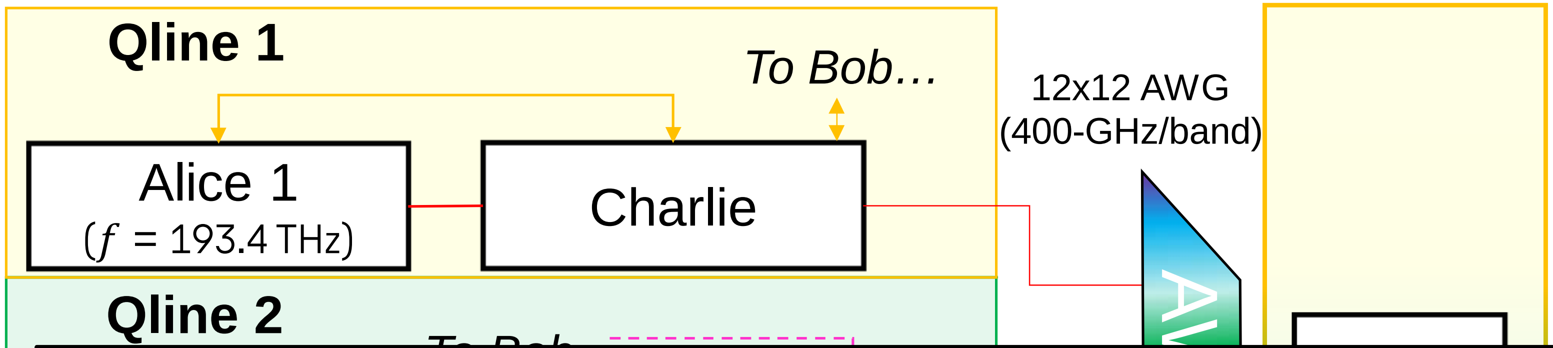
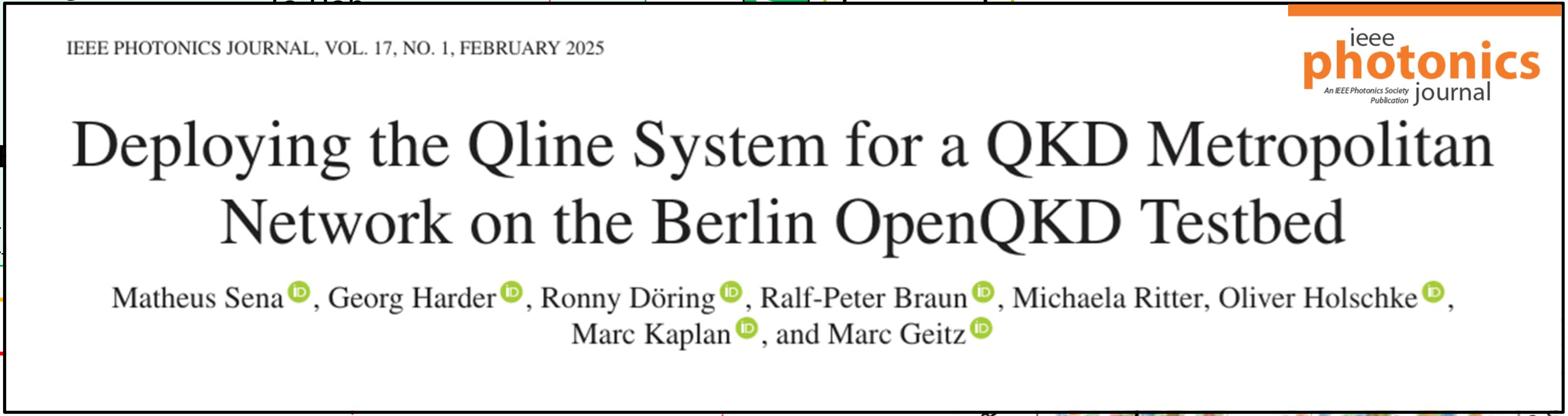
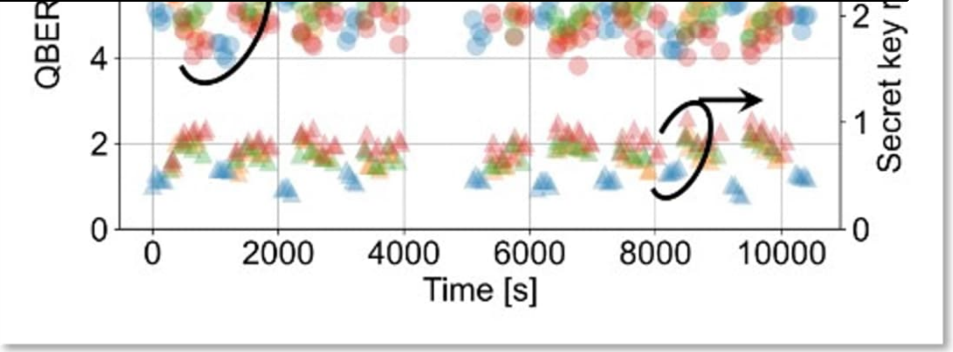




IEEE PHOTONICS JOURNAL, VOL. 17, NO. 1, FEBRUARY 2025

ieee photonics journal
An IEEE Photonics Society Publication

# Deploying the Qline System for a QKD Metropolitan Network on the Berlin OpenQKD Testbed

Matheus Sena, Georg Harder, Ronny Döring, Ralf-Peter Braun, Michaela Ritter, Oliver Holschke, Marc Kaplan, and Marc Geitz




M. Sena *et al.*, "Deploying the Qline System for a QKD Metropolitan Network on the Berlin OpenQKD Testbed," in *IEEE Photonics Journal*, 2025.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# What do the security agencies say?

NIST

Bundesamt
für Sicherheit in der
Informationstechnik

AGENCE NATIONALE DE LA SÉCURITÉ DES SYSTÈMES D'INFORMATION
ANSSI

National Cyber
Security Centre


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WHITEPAPER

# Quantum security technologies

## NCSC Position

Given the specialised hardware requirements of QKD over classical cryptographic key agreement mechanisms and the requirement for authentication in all use cases, the **NCSC does not endorse the use of QKD for any government or military applications**, and cautions against sole reliance on QKD for business-critical networks, especially in Critical National Infrastructure sectors.
In addition, we advise that any other organisations considering the use of QKD as a key agreement mechanism ensure that robust quantum-safe cryptographic mechanisms for authentication are implemented alongside them.
**NCSC advice is that the best mitigation against the threat of quantum computers is quantum-safe cryptography**. Our white paper on quantum-safe cryptography is available on the NCSC website.

https://www.ncsc.gov.uk/whitepaper/quantum-security-technologies

# SHOULD QUANTUM KEY DISTRIBUTION BE USED FOR SECURE COMMUNICATIONS?

Quantum Key Distribution (QKD) presents itself as a technology functionally equivalent to asymmetric key agreement schemes that are used in nearly all secure communication protocols over the Internet or in private networks. The defining characteristic of QKD is its alleged superior secrecy guarantee that would justify its use for high security applications. However, deployment constraints specific to QKD hinder large-scale deployments with high practical security. Furthermore, new threats on existing cryptography, and in particular the emergence of universal quantum computers, are taken into account by upcoming standardized "post-quantum" algorithms.

QKD may find some use in a few niche applications, for instance as a defense-in-depth measure on point-to-point links. However, the use of state-of-the art classical cryptography including post-quantum algorithms is by far the preferred way to ensure long-term protection of data, as it is the only technology choice that offers the functional properties needed in modern communication systems.
In any case, the cost incurred by the use of QKD should not jeopardize the fight against current threats to information systems which overwhelmingly do not exploit cryptographic weaknesses.

For another point of view on this topic with similar arguments and conclusions, the reader may consult the white paper of the National Cyber Security Centre (UK) [1], or the position of the NSA (USA) [2].

https://www.ssi.gouv.fr/publication/should-quantum-key-distribution-be-used-for-secure-communications/

# Quantum Key Distribution (QKD) and Quantum Cryptography (QC)



**Technical limitations**

1.Quantum key distribution is only a partial solution.

2.Quantum key distribution requires special purpose equipment.

3.Quantum key distribution increases infrastructure costs and insider threat risks.

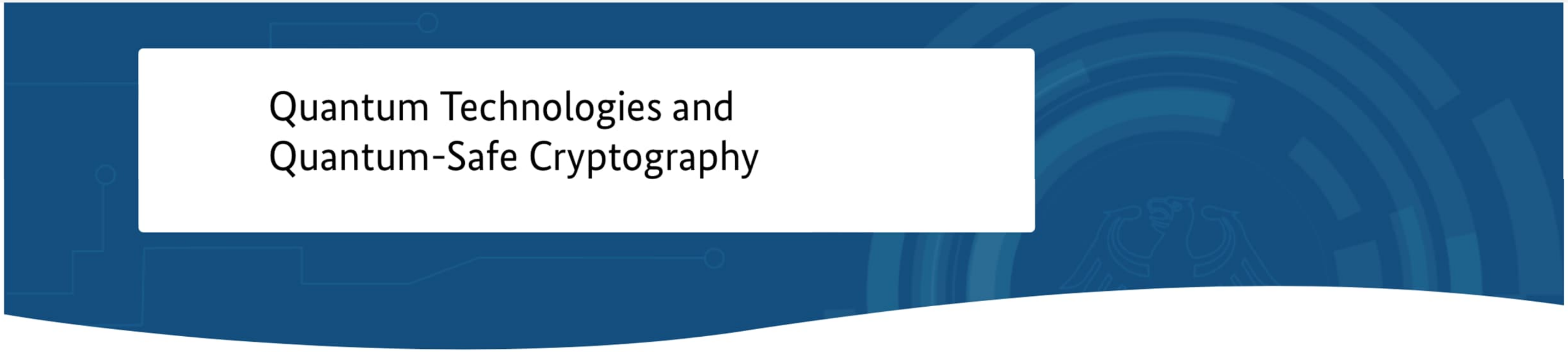
4.Securing and validating quantum key distribution is a significant challenge.

5.Quantum key distribution increases the risk of denial of service.

**Conclusion**

In summary, NSA views quantum-resistant (or post-quantum) cryptography as a more cost effective and easily maintained solution than quantum key distribution. **For all of these reasons, NSA does not support the usage of QKD or QC to protect communications in National Security Systems, and does not anticipate certifying or approving any QKD or QC security products for usage by NSS customers unless these limitations are overcome.**

https://www.nsa.gov/Cybersecurity/Quantum-Key-Distribution-QKD-and-Quantum-Cryptography-QC/

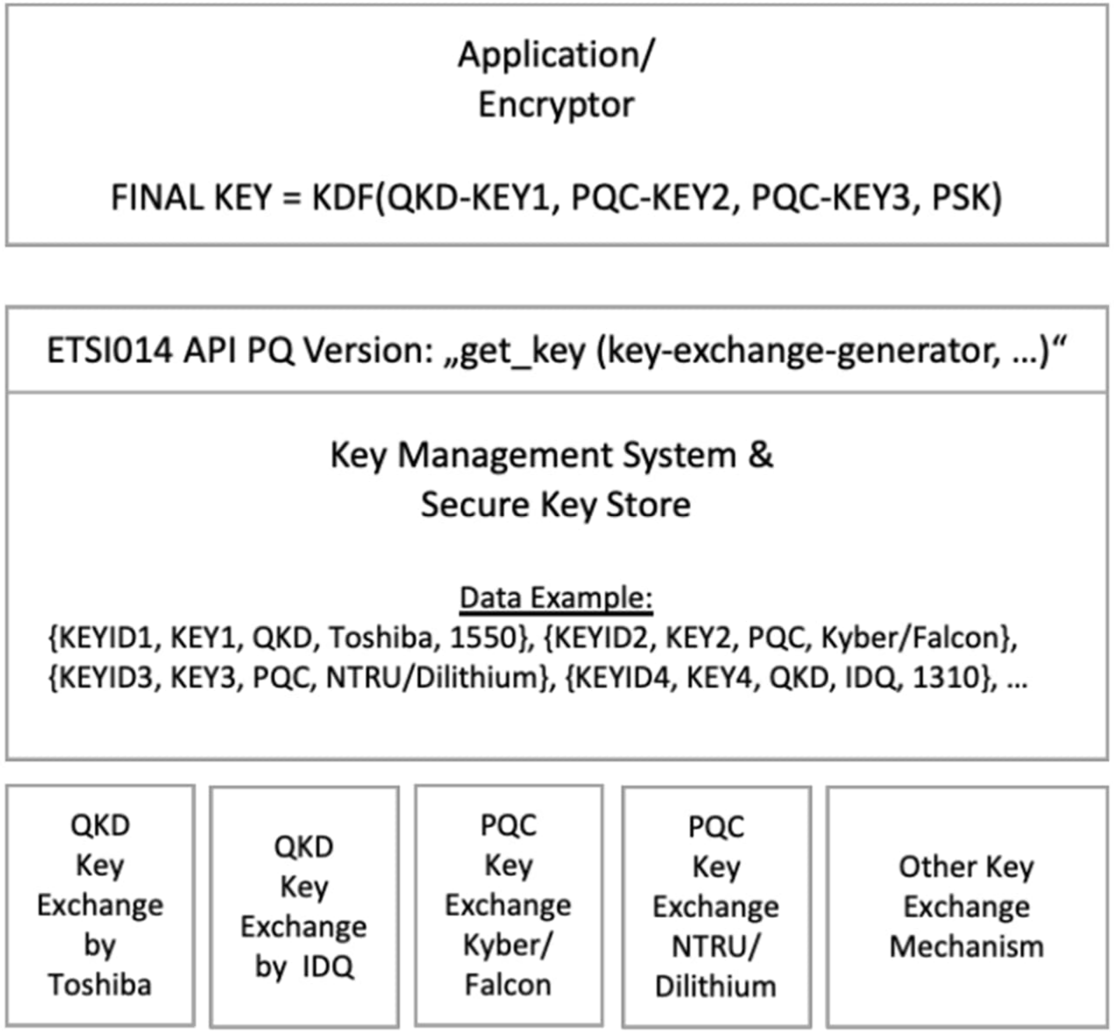



Core Messages:

- From the BSI's perspective, it is no longer a question of 'if' or 'when' there will be quantum computers
- Post-quantum cryptography will become the standard in the long term.
- Post-quantum methods should only be used in combination with classic methods (read: in a hybrid format) whenever possible. A hybrid approach (with two or more post-quantum procedures) will be a possible solution even after cryptographically relevant quantum computers are developed.
- Quantum cryptography is a complement to post-quantum cryptography … not yet ready for widespread use.

https://www.bsi.bund.de/EN/Themen/Unternehmen-und-Organisationen/Informationen-und-Empfehlungen/Quantentechnologien-und-Post-Quanten-Kryptografie/quantentechnologien-und-post-quanten-kryptografie_node.html

# How do we envision a hybrid approach (QKD+PQC)?



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- **Improvement through multiple encryption keys**: The hybrid key exchange method can be enhanced by robustly **combining more than two encryption schemes**.
- **Enhanced security with more keys**: Combining more keys improves the final encryption keys' security, as their robustness relies on multiple factors such as **quantum physics** and various **post-quantum cryptography (PQC) algorithms**.
- **Disjoint network paths for key exchange**: If QKD and PQC key exchanges **occur along different, disjoint network paths**, the overall security will further increase.
- **Adversary challenge**: An adversary would need to attack the network at multiple, geographically distinct locations simultaneously, making an attack significantly more complex.

*M. Geitz, R. Döring and R. -P. Braun, "Hybrid QKD & PQC Protocols implemented in the Berlin OpenQKD testbed," *2023 8th International Conference on Frontiers of Signal Processing (ICFSP)* 2023.


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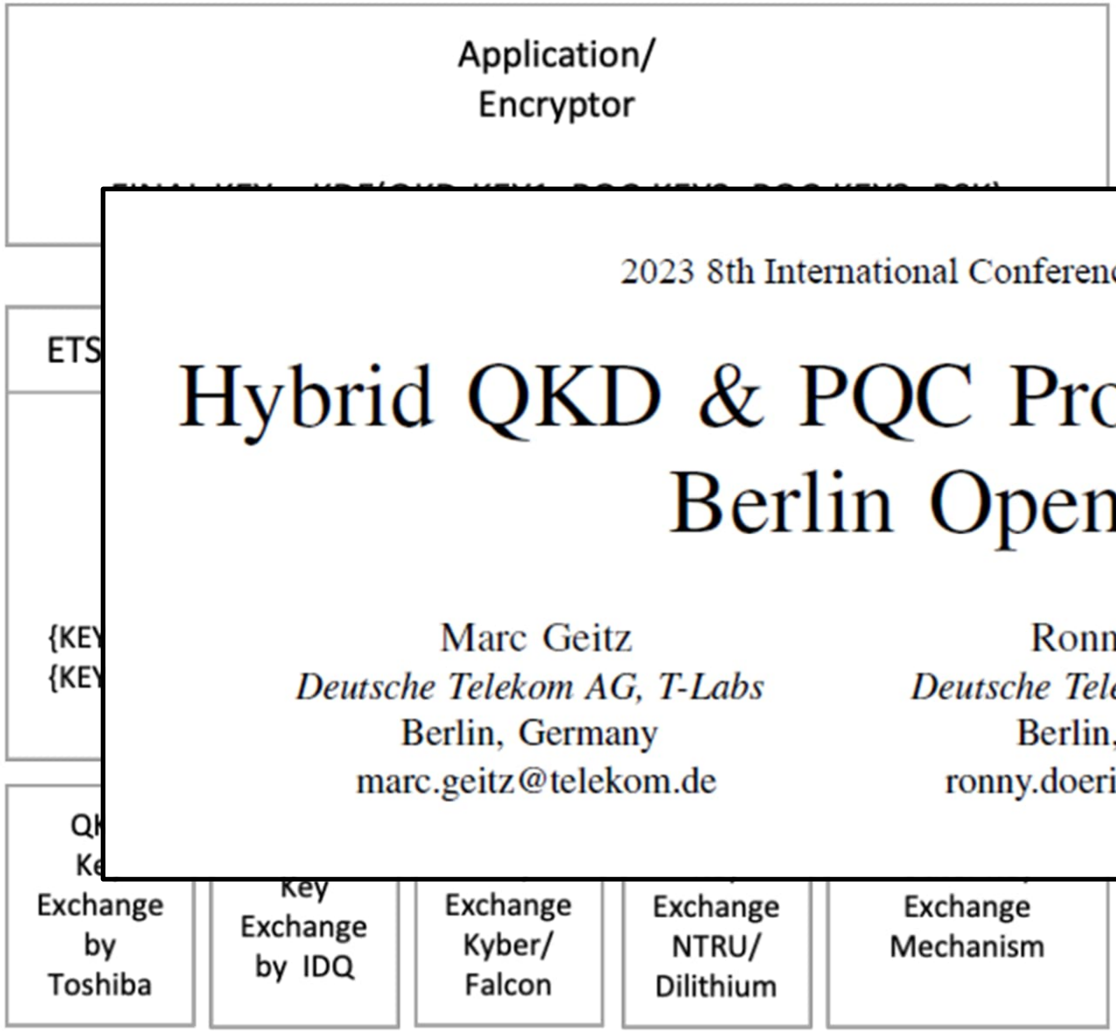
# How do we envision a hybrid approach (QKD+PQC)?

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2023 8th International Conference on Frontiers of Signal Processing

# Hybrid QKD & PQC Protocols implemented in the Berlin OpenQKD testbed


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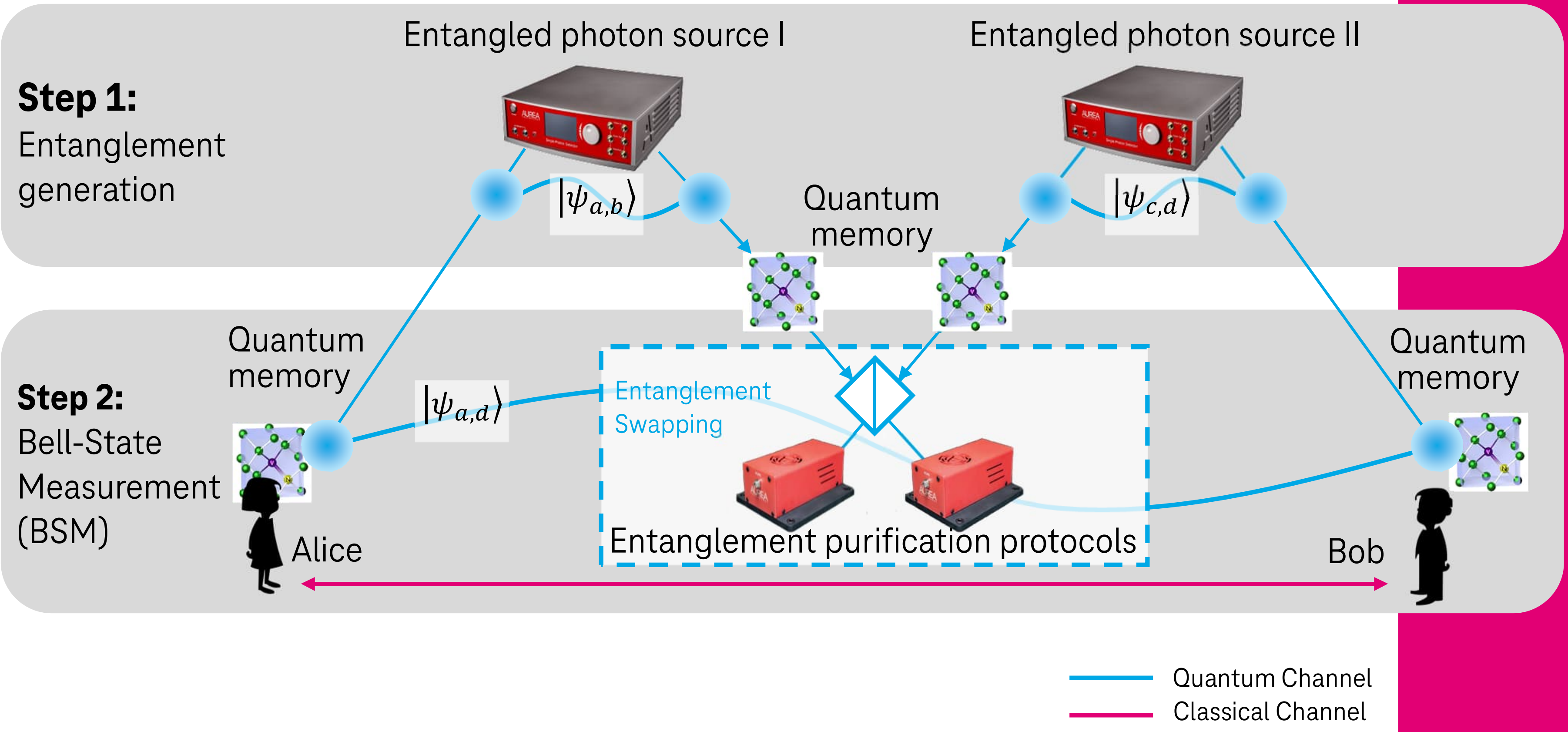
# Entanglement as a resource

GROUP TECHNOLOGY

# Entanglement swapping for the quantum repeater

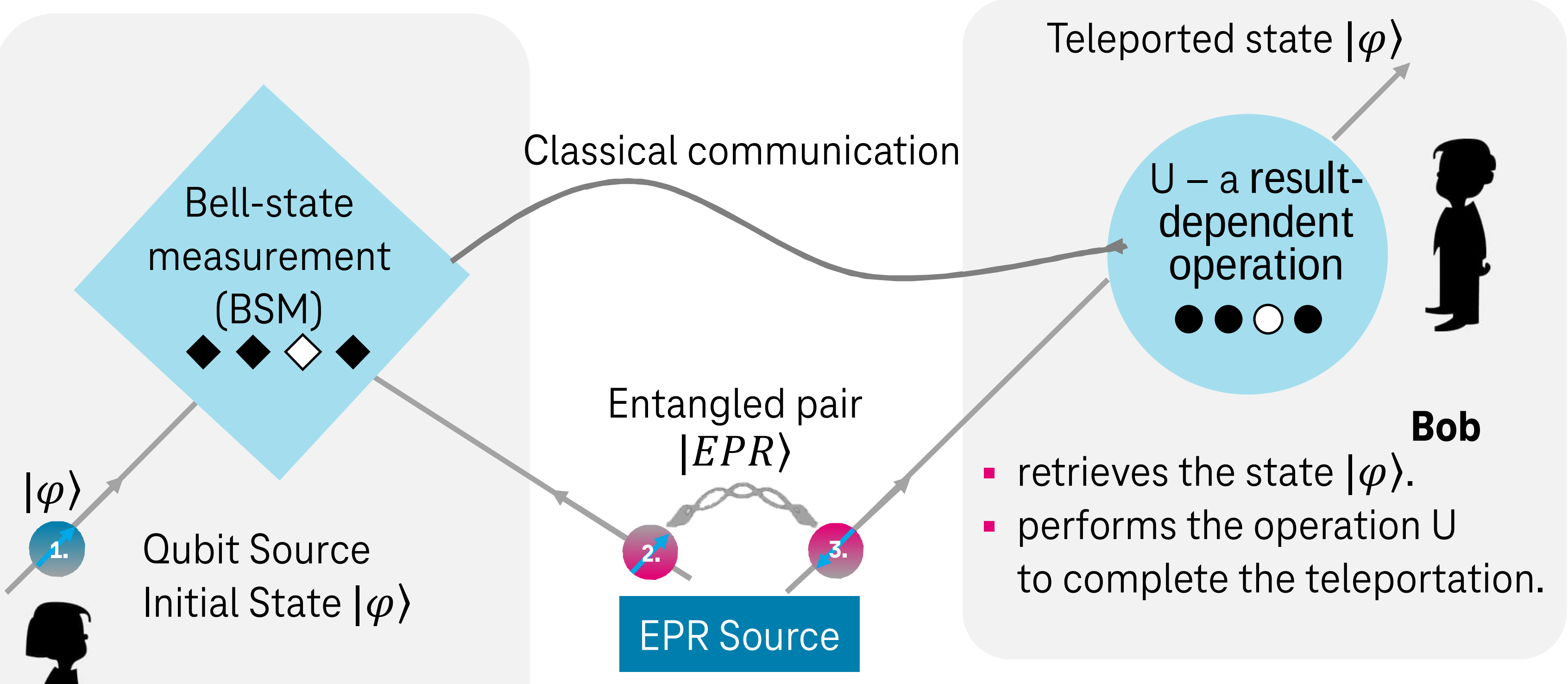
**Extends quantum communication range by linking entangled particles, overcoming signal loss.**




Entanglement swapping protocol

# Quantum Teleportation

"Move the quantum state from one qubit to another"




**Bob**

- retrieves the state $|\varphi\rangle$.
- performs the operation U to complete the teleportation.

**Alice**

- performs a BSM (a joint measurement) on the unknown qubit $|\varphi\rangle$ and one $|EPR\rangle$ photon.
- the result keeps $|\varphi\rangle$ unknown
- Alice sends a command via a classical channel for a unitary operation U on the second $|EPR\rangle$ photon

EPR: Einstein–Podolsky–Rosen (EPR) pair of qubits -> entangled photon pair
BSM: Bell state measurement
U: Unitary operator


GROUP TECHNOLOGY

# QRx planned activities
## Experiments with Fraunhofer HHI

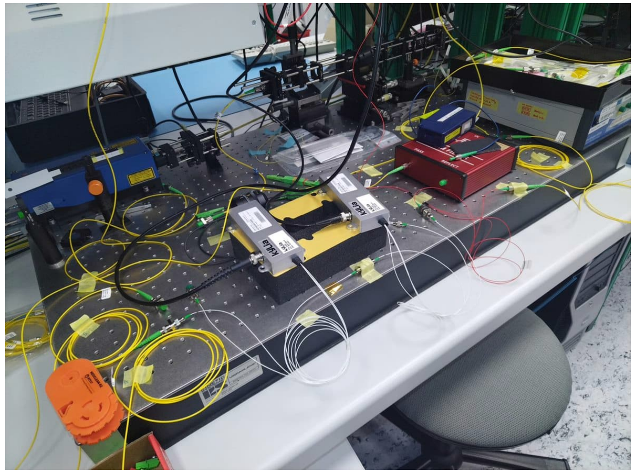
### Planned Experiments in the Berlin fiber optic network

1. Entanglement transfer over the direct open air optical link between the HHI & DT (LoS) and fiber optical network
2. QKD with entangled photons
3. Entanglement swapping
4. Execution of quantum teleportation
   (if the time frame still fits & the technical requirements are met)

### Prerequisite for carrying out the experiments

1. Setup of the LoS
   a. Equipment of a separate room @DT in WFD with a fiber optic connection to the Berlin DT research test network (dark fiber)
   b. Internet access has yet to be switched on
2. Connection of the HU Berlin to the fiber optic network
   - Six connections of dark fiber are patched until Adlershof/Erwin Schrödinger Zentrum
   - Measurements to evaluate the Attenuation done with OTDR :
     Length: ~ 25 km; Fiber Loss dB/km: ~ 0,3dB
3. DT AG Procurement of the laboratory equipment, compatible with that of the HHI
4. Jointly characterization of the DT quantum photon source and detectors (September)

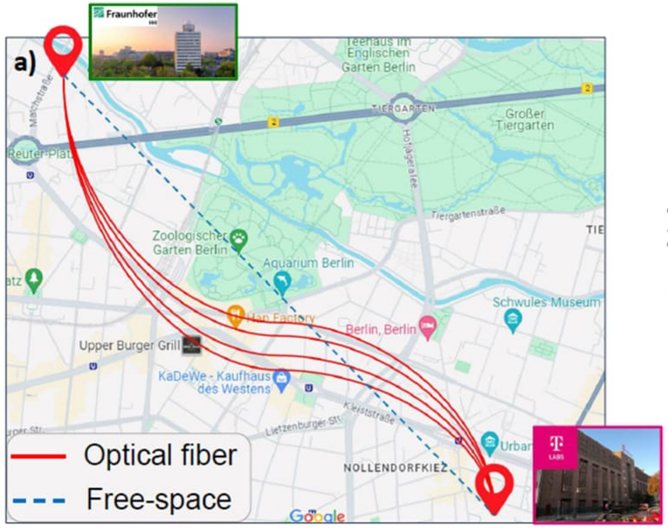
Joint experiments by **HHI** & **DT** in

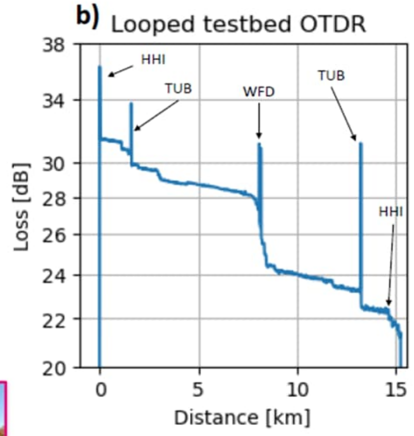


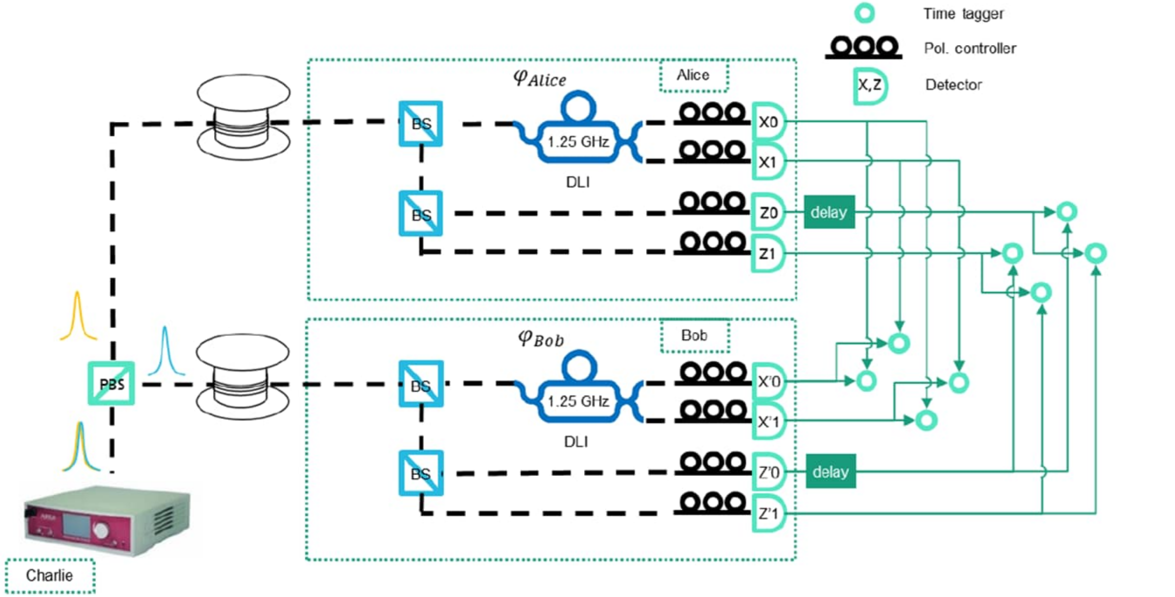

Characterization of DT`s quantum photon source and Single-Photon detectors

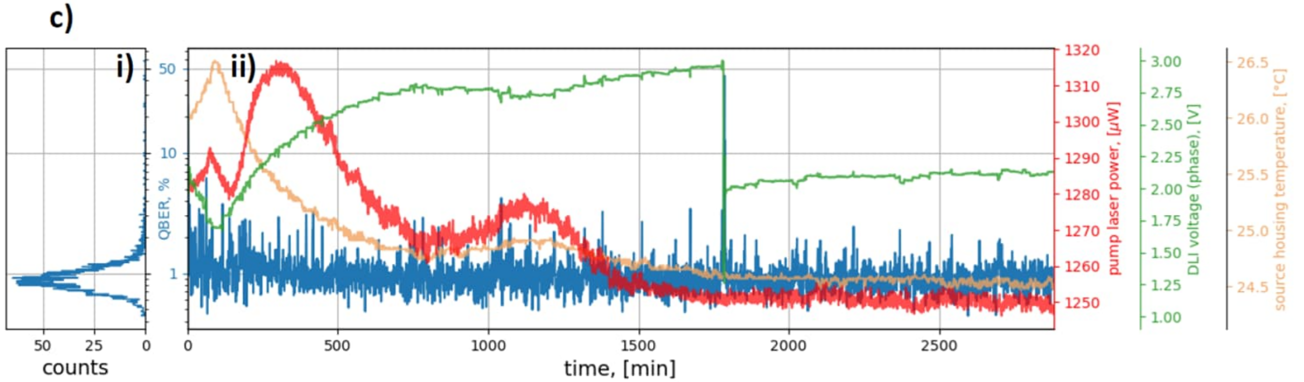
# QRx planned activities

## Experiments with Fraunhofer HHI



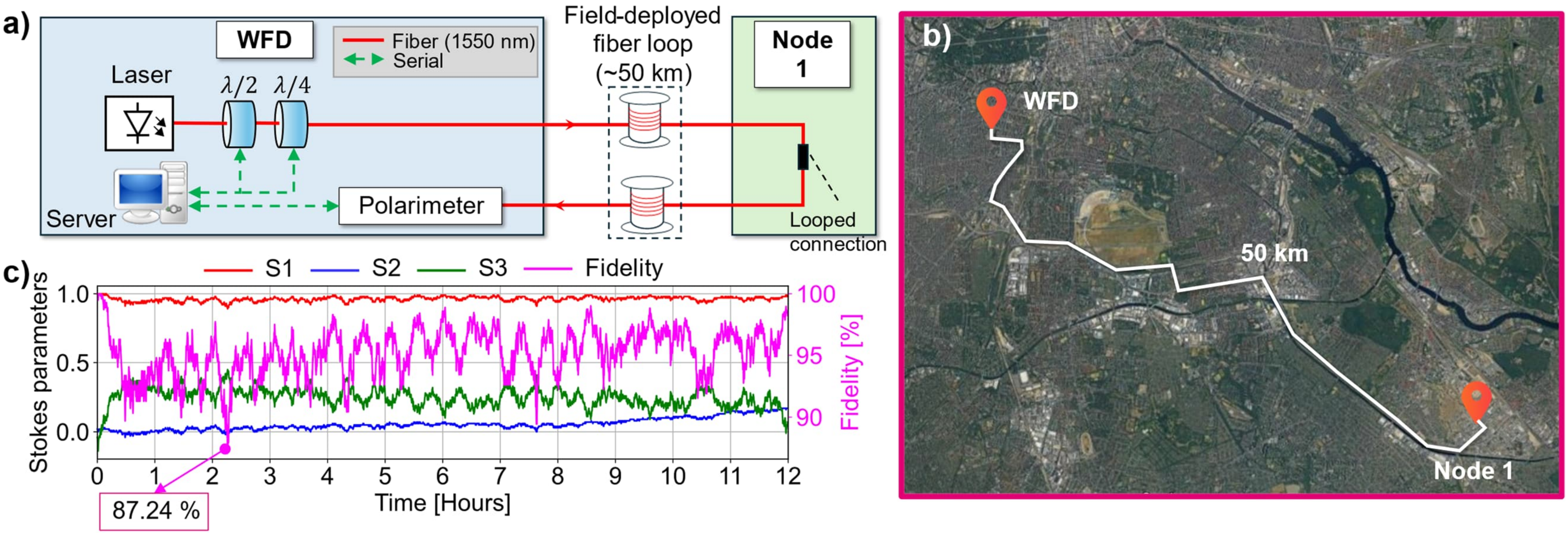

- For the results reported in this study, a total of 4 fiber connections between T-Labs and the Fraunhofer HHI have been used.
- Each fiber connection spans a distance of 6.9 km.

# Entanglement distribution
## Some of our activities with Qunnect

Qunnect

**Polarization drifts turn qubit transmission very unstable**

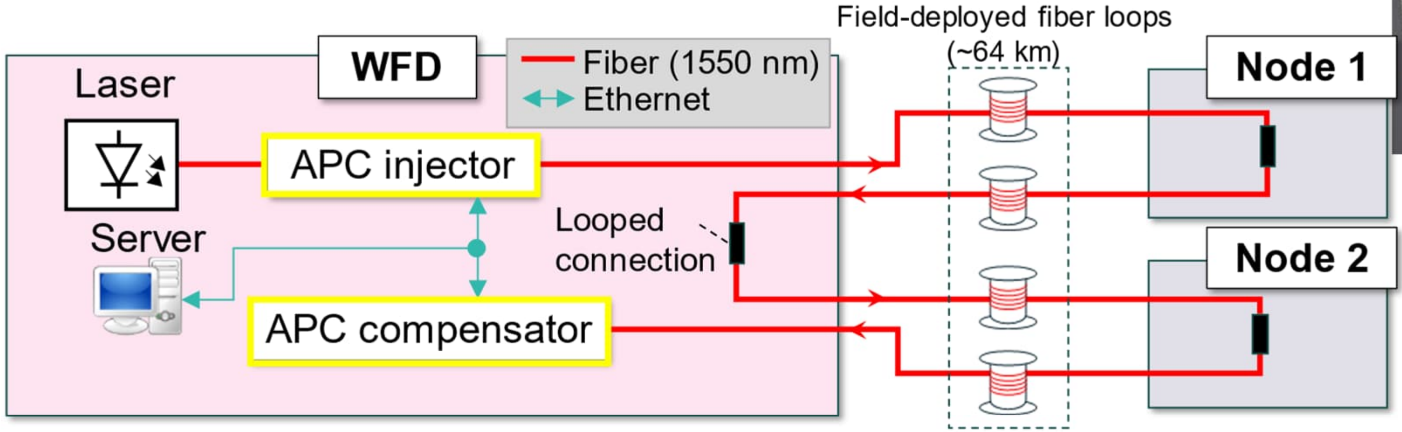
- Temporal behaviors of the Stokes parameters and Fidelity when classical light is transmitted over 50 km of field-deployed fiber

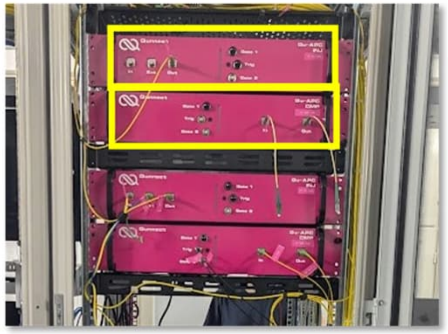


# Entanglement distribution
## Some of our activities with Qunnect

**Automatic polarization control**

- Key feature for ensuring stable qubit transmission over field-deployed optical fibers.

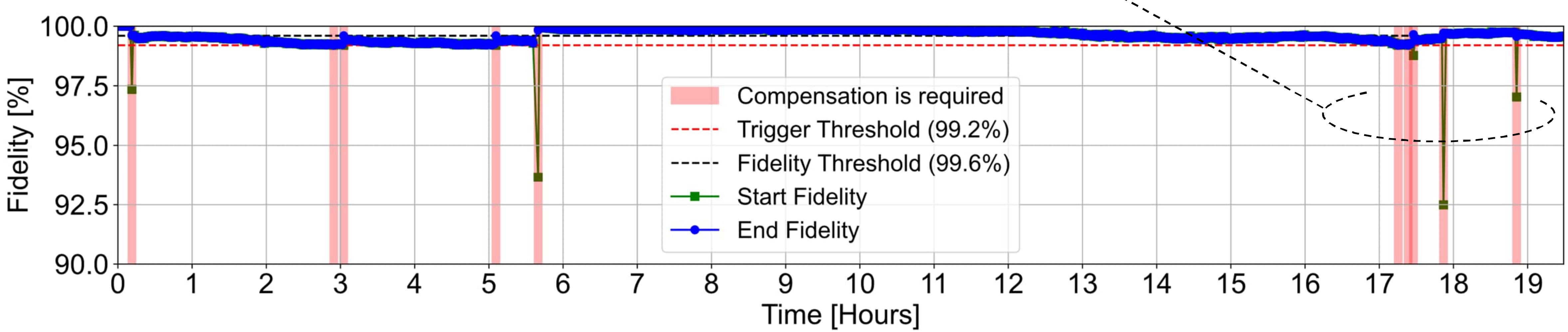


# Entanglement distribution

## Some of our activities with Qunnect

Instabilities caused by Deutsche Telekom technicians performing fiber maintenaince in front of the building.

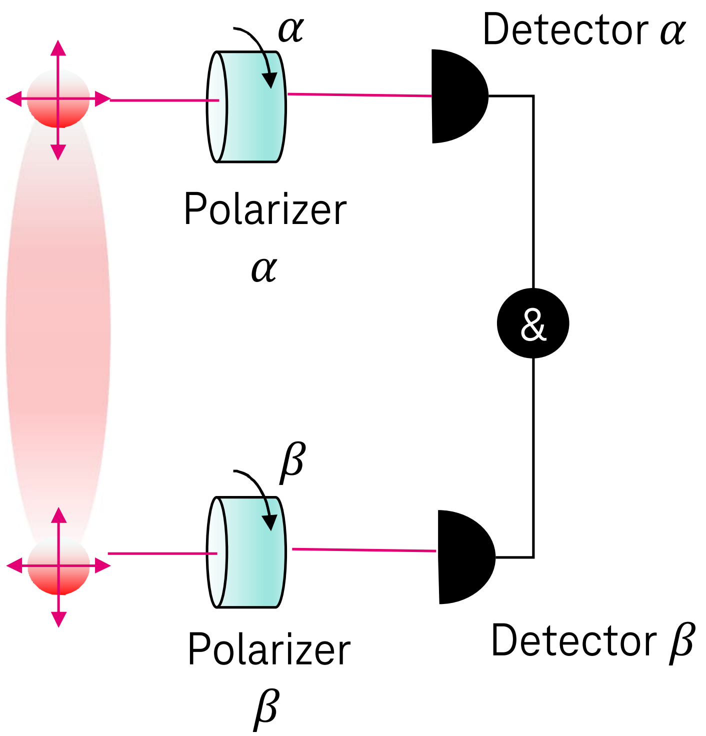


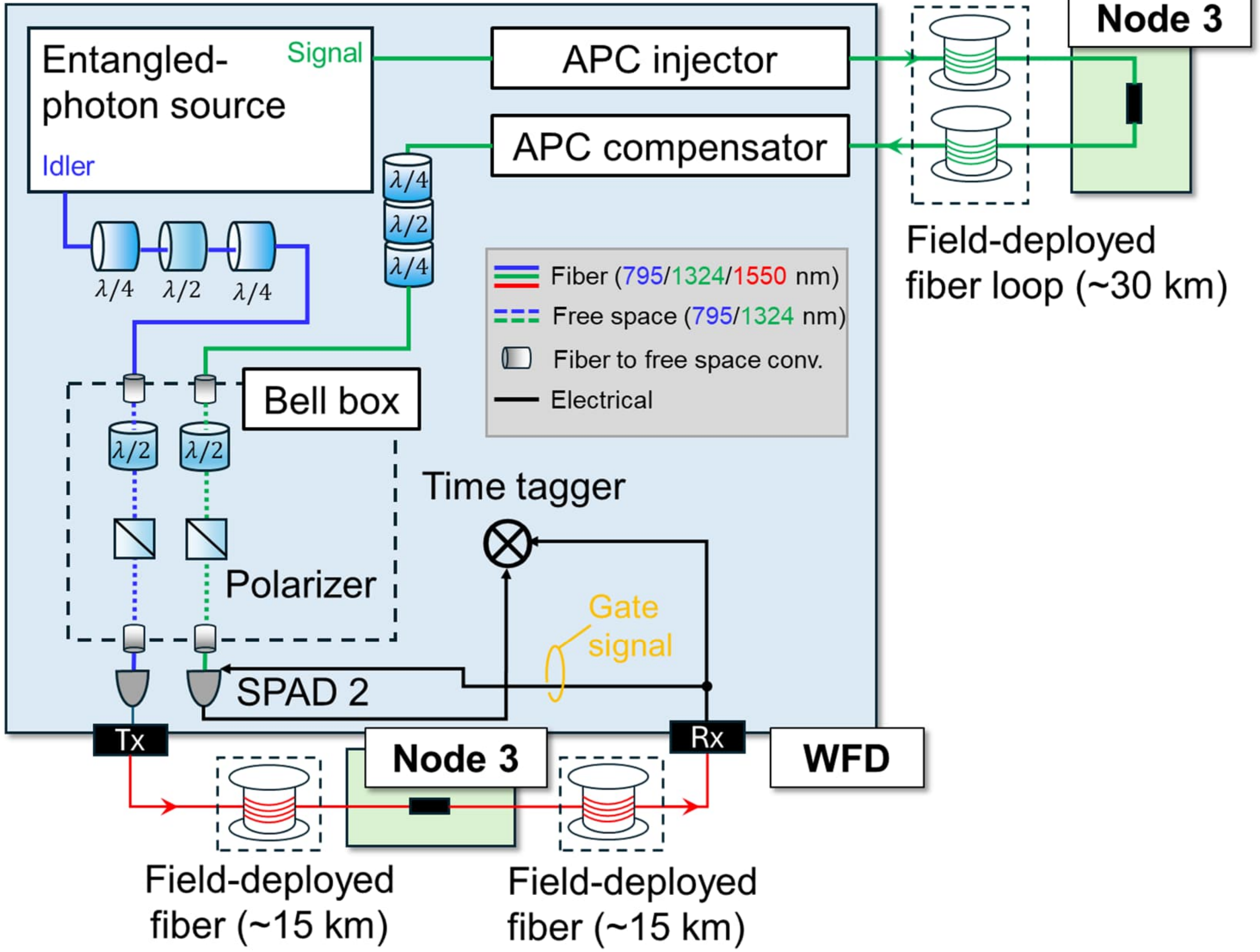

- Mean fidelity: 99.60%
- Uptime: 99.57%

# Entanglement Distribution

## CHSH (Clauser, Horne, Shimony, Holt) test

- Way of performing a check on the quality (Bell parameter) of the entanglement.
- $2 \leq$ Bell parameter $(S) \leq 2\sqrt{2}$



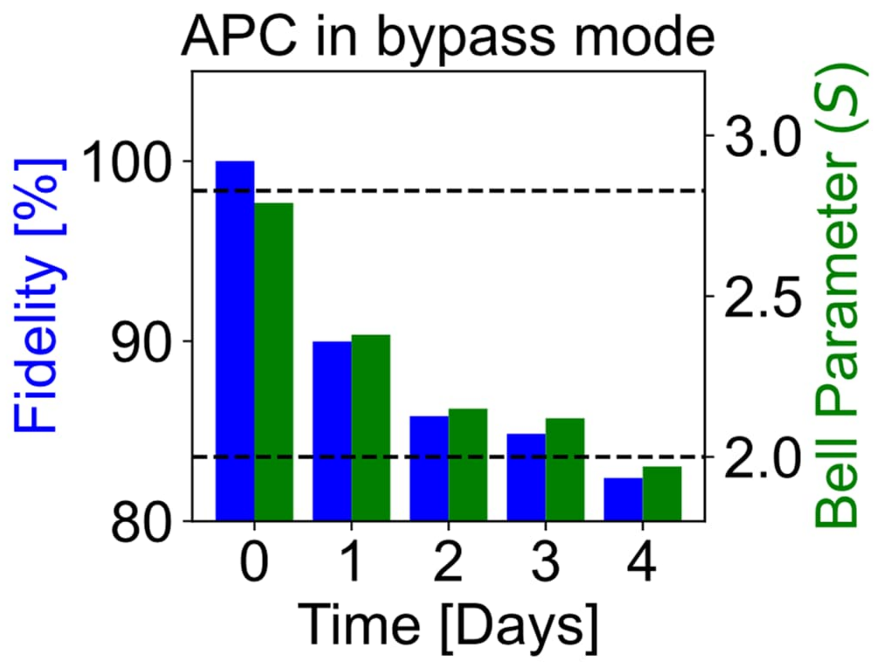

Qunnect

# Entanglement Distribution

## Berlin Fiber Testbed

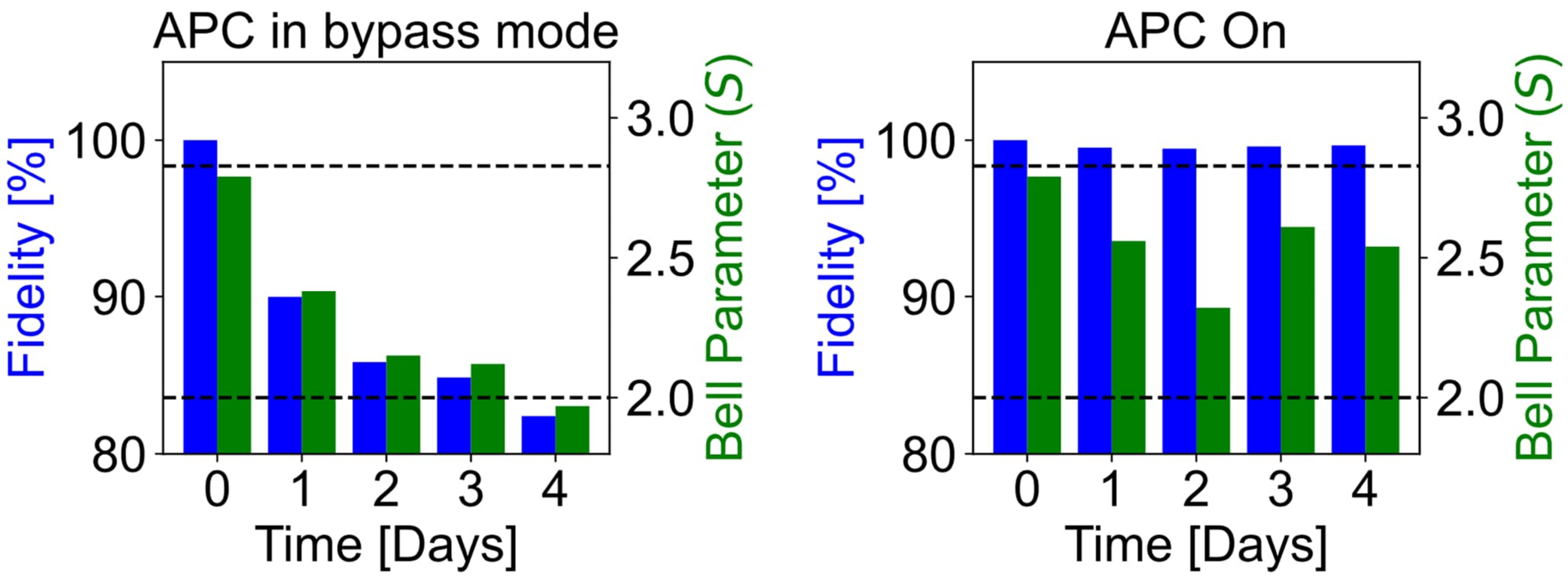

WFD: Winterfeldtstraße

# Entanglement Distribution



# Entanglement Distribution

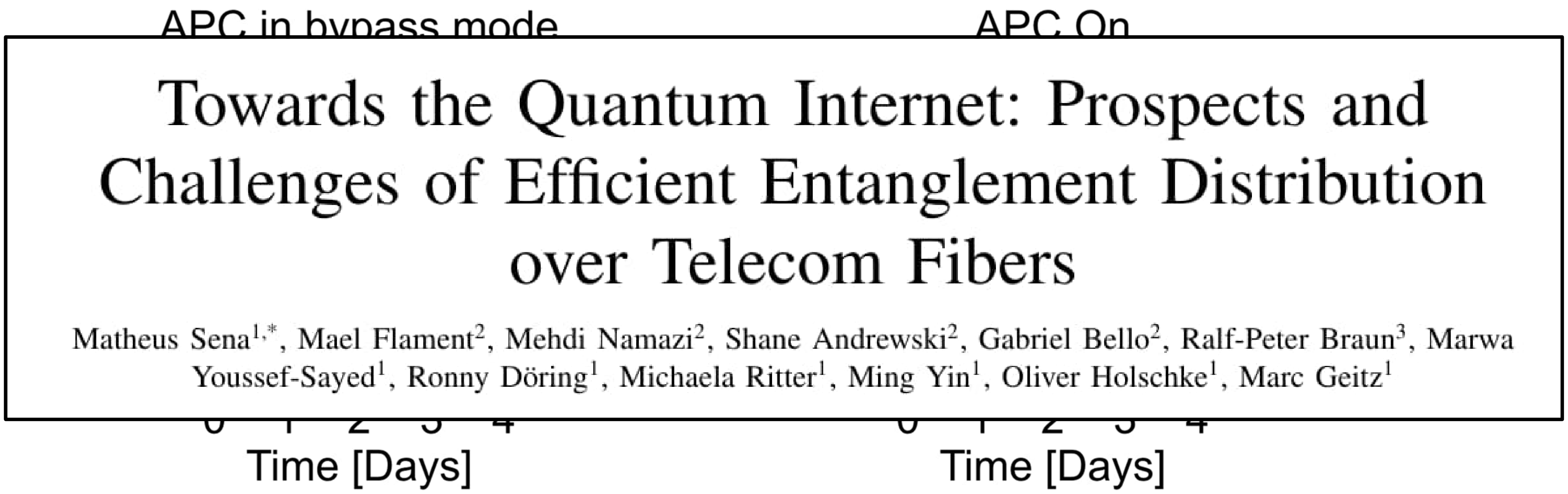
Qunnect




- Mean fidelity: 99.60%
- Mean Bell parameter: 2.52

# Entanglement Distribution

Qunnect




## Towards the Quantum Internet: Prospects and Challenges of Efficient Entanglement Distribution over Telecom Fibers

Matheus Sena[1,*], Mael Flament[2], Mehdi Namazi[2], Shane Andrewski[2], Gabriel Bello[2], Ralf-Peter Braun[3], Marwa Youssef-Sayed[1], Ronny Döring[1], Michaela Ritter[1], Ming Yin[1], Oliver Holschke[1], Marc Geitz[1]

- Mean fidelity: 99.60%
- Mean Bell parameter: 2.52

M. Sena *et al*., "Towards the Quantum Internet: Prospects and Challenges of Efficient Entanglement Distribution Over Telecom Fibers," *2024 Asia Communications and Photonics Conference (ACP),* 2024,

# Entanglement Distribution

Qunnect

OFC 50
Celebrating 50 Years of Optical Networking and Communications

## High-Fidelity Entanglement Distribution Through Berlin Using an Operator's Fiber Infrastructure

Matheus Sena[1,*], Mael Flament[2], Mehdi Namazi[2], Shane Andrewski[2], Gabriel Portmann[2], Ralf-Peter Braun[3], Marwa Youssef-Sayed[1], Ronny Döring[1], Michaela Ritter[1], Oliver Holschke[1], Marc Geitz[1]

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**Abstract:** We successfully integrated an automated system for distributing entangled photons across a 30-km field-deployed fiber in Berlin. Over a 17-day continuous operation, it achieved >99% fidelity, underscoring its potential for scalable, city-wide quantum networks. 

# Quantum sensing

GROUP
TECHNOLOGY

# 3. Sensing/metrology



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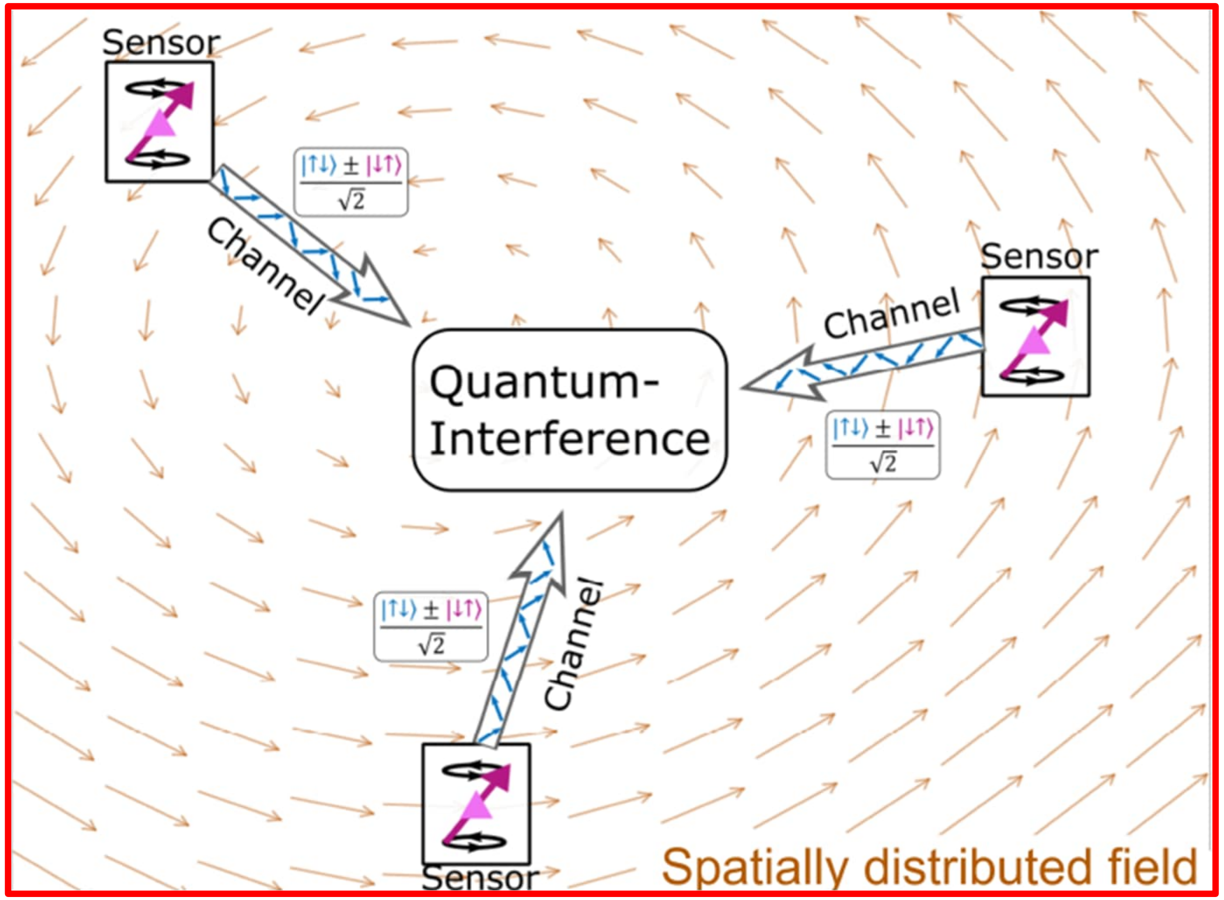
## Concept of spatially distributed quantum metrology as a quantum-IoT[1]





1. The optically addressable spin qubits are used as sensors, which carry quantum information in the form of photons that are consequently superimposed on a central server.

2. The server performs multi-sensor quantum projection and detection to generate a highly sensitive and time-dependent signal of environmental field fluctuations using the interference signal.

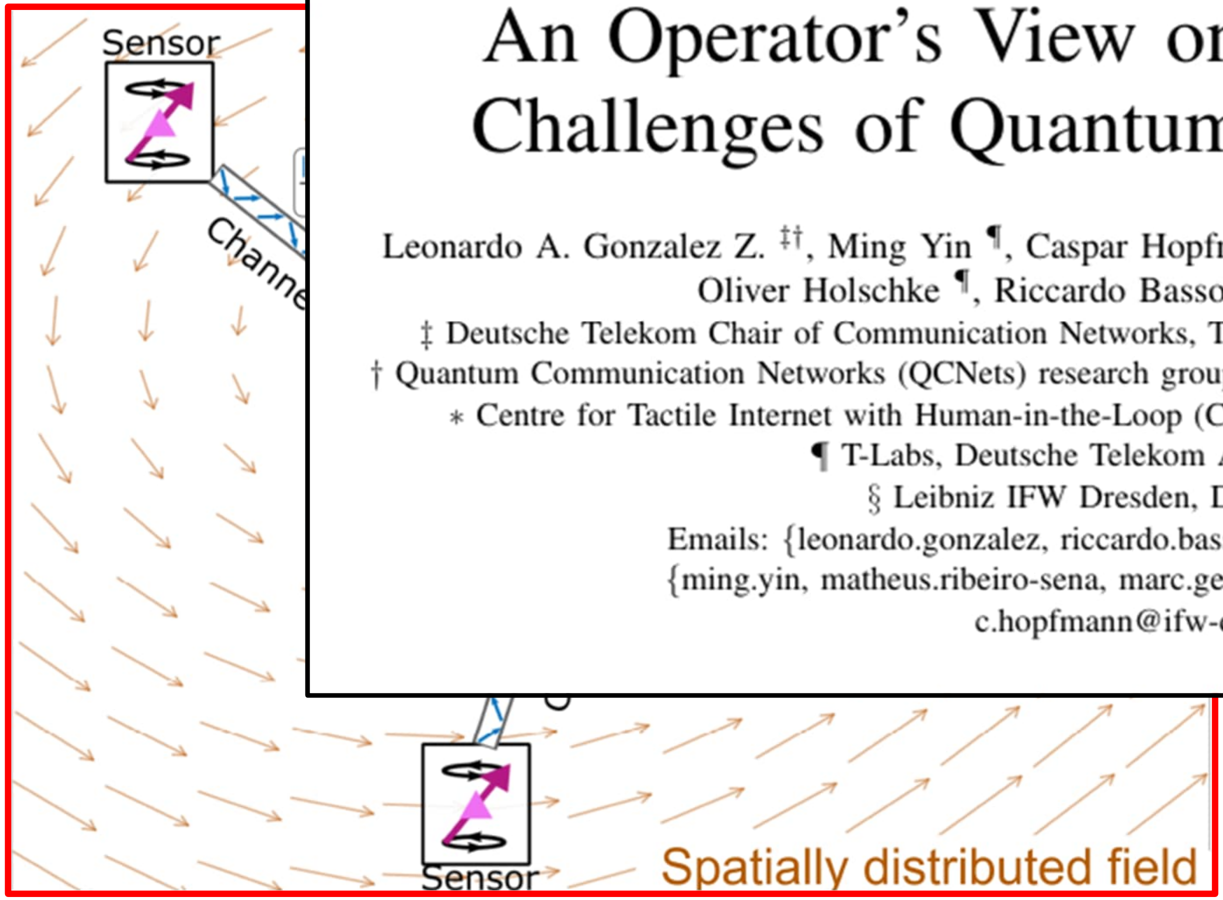
[1]L. A. Gonzalez Z. *et al.*, "An Operator's View on Opportunities and Challenges of Quantum Internet of Things," *2023 IEEE 9th World Forum on Internet of Things (WF-IoT)*, 2023.

# 3. Sensing/metrology

QUIET

Bundesministerium für Bildung und Forschung

## Concept of spatially distributed quantum




# An Operator's View on Opportunities and Challenges of Quantum Internet of Things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# 4. Other applications

## Quantum random number generation

- Entangled pairs produce randomness that can't be replicated by classical algorithms, ensuring unpredictability[1].

## Distributed quantum computing

- Together, the quantum repeater and quantum teleportation create a stable quantum network, allowing multiple quantum computers to operate as a single distributed system[2].

## Entanglement-based time synchronization

- Entangled photons can be used to perform the synchronization of low-Earth-orbit (LEO) satellites[3].

[1]J.E. Jacak *et al.*, "Quantum random number generators with entanglement for public randomness testing," *Sci Rep* 10, 164, 2020.
[2]Z. Davarzani et al. "A hierarchical approach for building distributed quantum systems," *Sci Rep* 12, 15421, 2022.
[3]R. Gosalia et al. "LEO Clock Synchronization with Entangled Light," *IEEE Global Communications Conference*, 2023.

# Conclusion

## Why does DT have interest in quantum technologies?

- We believe that quantum has a potential beyond QKD for the telecommunication's business.
- New revenue streams that can be explored by using DT's widespread optical fiber networks.

## Challenges?

- Understand, propose and verify new quantum-related and real-world use-cases.
- Building stable quantum networks.

## What lies ahead?

- How far can we push the entangled photons over fiber?
- Show the usability of these photons in teleportation, quantum repeater protocols.
- Explore other use-cases beyond QKD:
  - Entanglement-based time synchronization?

# Thank you!

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