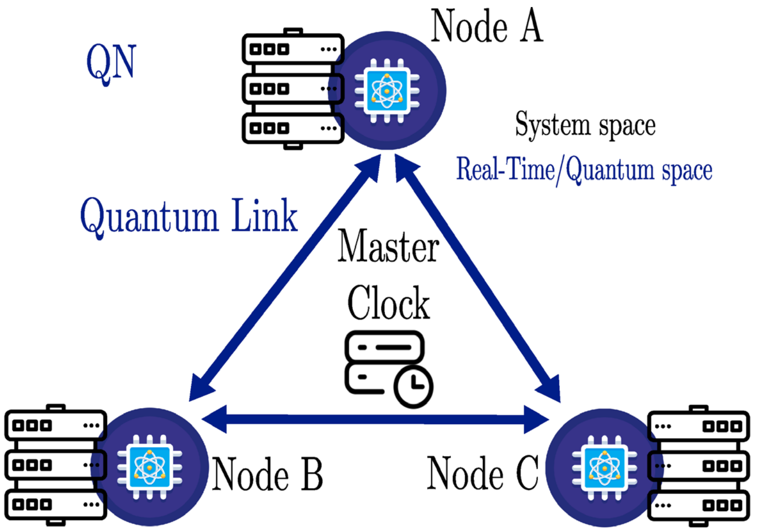
Multiplane Sub-Nanosecond Timing via SyncE/PTP Enabling Synchronous Quantum Networks



M. Jofre, A. Agustí-Torra and D. Rincón-Rivera – BAMPLA, Network Engineering Dept.

Motivation – The need for Time Synchronization

Time **synchronization in the ns-μs range** in Telecom networks ensures that all devices and equipment operate in unison, maintaining data integrity, quality of service, and security protocols

Complementary, Quantum Networks require distributed **ps-ns range synchronization** for:

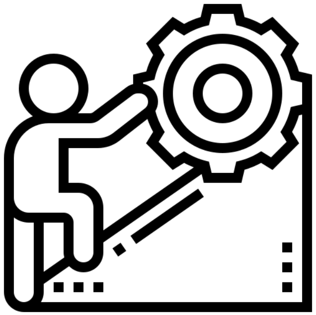
- Qubit **timestamped** single-photon arrival times.
- **Verify Entanglement**/Bell-state measurements across nodes (changing bases accordingly).
- **Temporal alignment** in future qubit buffer queues for advanced quantum operations.
- **Avoid interference** with collocation of other traffic.
- …

Therefore, there is a need for time synchronization **without requiring excessive bandwidth consumption, post-computation**, and **being scalable** for N nodes!!!

This work is mainly centered in Discrete Variables Quantum Communications

Time Synchronization Challenges

In particular, when shifting **from Point-to-Point** quantum communications **to Quantum Networks** (multi-nodes) – implement logics among nodes



Precision Requirements

- Timetagging: < 1 ns detector synch.
- Entanglement Distribution: < 100 ps for Bell-state measurements.
- Quantum Repeaters: < 10 ps for memory read/write sync.

Some only hardware synchronization techniques:

- GPS: Accuracy ~10-100 ns (Urban/indoor multipath adds ~50 ns uncertainty).
- Fiber-Based Sync: <100 ps but delay Fluctuations: 1 ps/m/°C (requires active compensation).
- Optical Clock Networks: Accuracy: <10 ps over 1000 km (also require active compensation).
- Quantum Sync: Entangled photon pairs enable <1 ps transfer (theoretical) but require some classical synchronization framework.

Good for Real-time/Quantum Plane, **but what about the Processing System - Control Plane**!!!

Main Results of this work

Quantum Networks benefit from a **Control plane** (aside of the real-time/quantum plane) for implementing the **logical operation** among **multiple nodes**

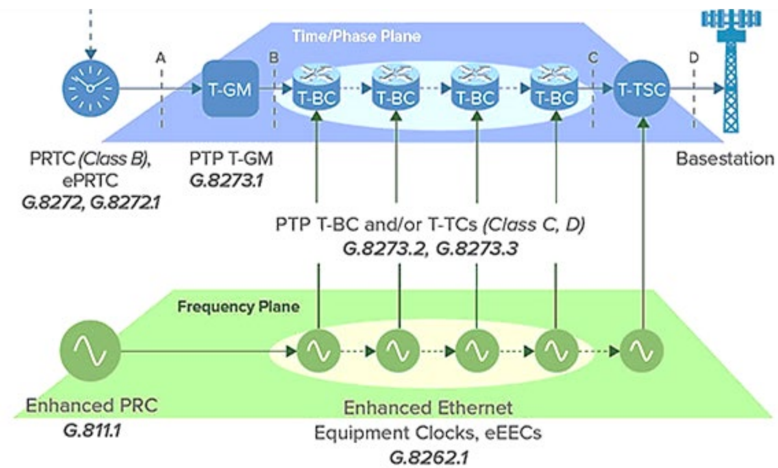
- Implemented **PTP slaves** time **synchronized** to a **Master PTP** clock server.
- **Synchronization** among **many nodes** with ns accuracy and temporal jitter.
  - Improved to **hundreds of ps** with SyncE+PTP.
- **Bridging** the Real-time/**Quantum plane** with the **Control logical plane**:
  - **Synchronous transmission** (slotted) using triggered sources.
  - **Mechanism** to continuously **fine-adjust** the **qubits** time **synchronization**.
- **Characterization** of the synchronization performance with respect:
  - **Qubit** detection.
  - **Coincidence** detection.

M Jofre, "Qubit rate modulation-based time synchronization mechanism for multi-node quantum networks", IEEE Transactions on Quantum Engineering, 2025.

Synchronization vs. Planes

Each **plane** is **responsible** for specific **functions** in Quantum Networks

Control plane

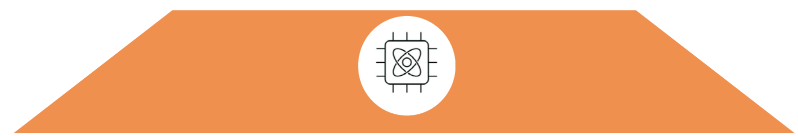


Qubit – Photonics/Others:

- Encoding/Decoding
- Transmission/Detection

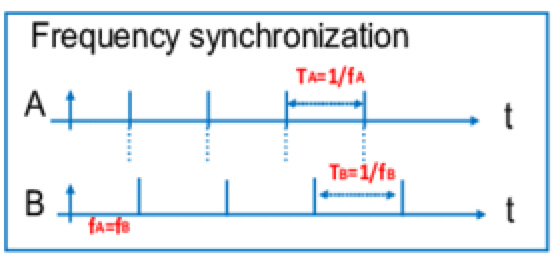
Electronics – Real Time Units/FPGA:

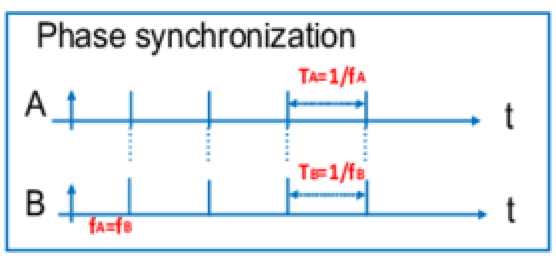
- Timetagging
- Transfer data

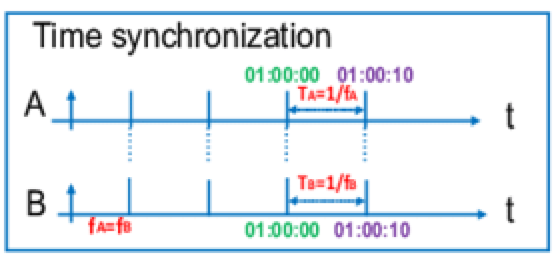


Real-time/Quantum plane

Both **planes inter-synchronized** with different capabilities!!!







Time synchronization **- Absolute reference** timestamping of qubits

Hardware clocks performance

Practical clocks (rubidium and crystal oscillators) have a limited **frequency accuracy** (instead of clocking at 10 MHz they might clock at 10.01 MHz) and a limited **stability** (is the variation over time of the output frequency).

The detection time t', given the transmitter time t, is connected via

$$t' = (t + \Delta T) \cdot (1 + \Delta u),$$

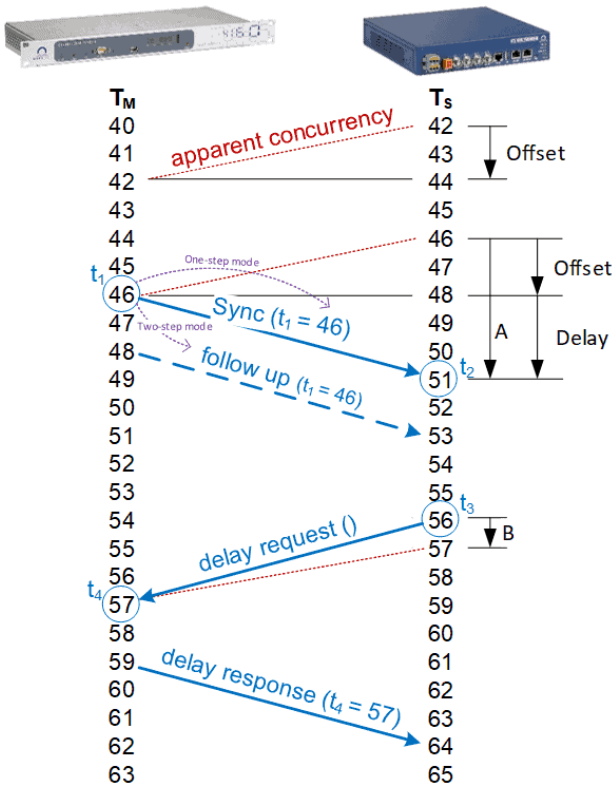
where ΔT is a **time offset** (which can change over time) and Δu is **the relative frequency difference** between the two clocks.

These values can be characterized (in average) with Allan variance curves, but other strategies are required for fast and continuous corrections.

Hardware clocks need continuous corrections

Precision Time Protocol

IEEE 1588 standard, with current version PTPv2 and different profiles (configurations depending on the application)



Offset and delay calculations

Theory:

$$A = t_2 - t_1 = Delay + Offset$$
$$B = t_4 - t_3 = Delay - Offset$$

$$Delay = \frac{A + B}{2}$$

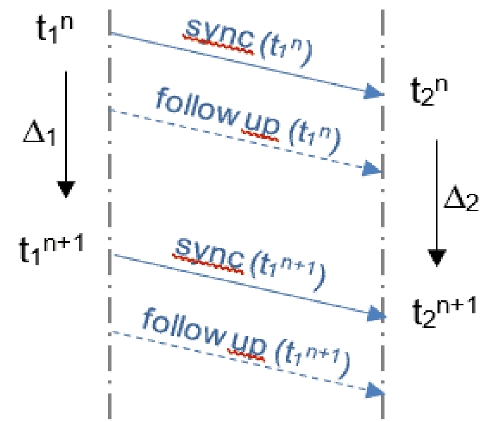
$$\boldsymbol{Offset} = \frac{A - B}{2}$$

Example:

$$A = 51 - 46 = 5$$
$$B = 57 - 56 = 1$$

$$Delay = \frac{5 + 1}{2} = 3$$

$$\boldsymbol{Offset} = \frac{5 - 1}{2} = \boldsymbol{2}$$



$$Send\ interval\ Master\ \Delta_1 = t_1^{n+1} - t_1^n$$

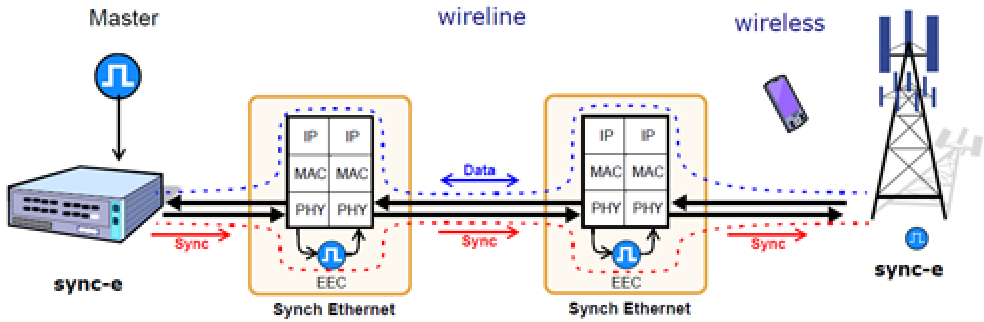
$$Receive\ interval\ Slave\ \Delta_2 = t_2^{n+1} - t_2^n$$

$$\boldsymbol{Drift\ of\ the\ slave} = \frac{\boldsymbol{\Delta_2 - \Delta_1}}{\boldsymbol{\Delta_2}}$$

Network messaging capable of achieving **hundreds ns time synchronization** in the **Control logical plane** (operating system)

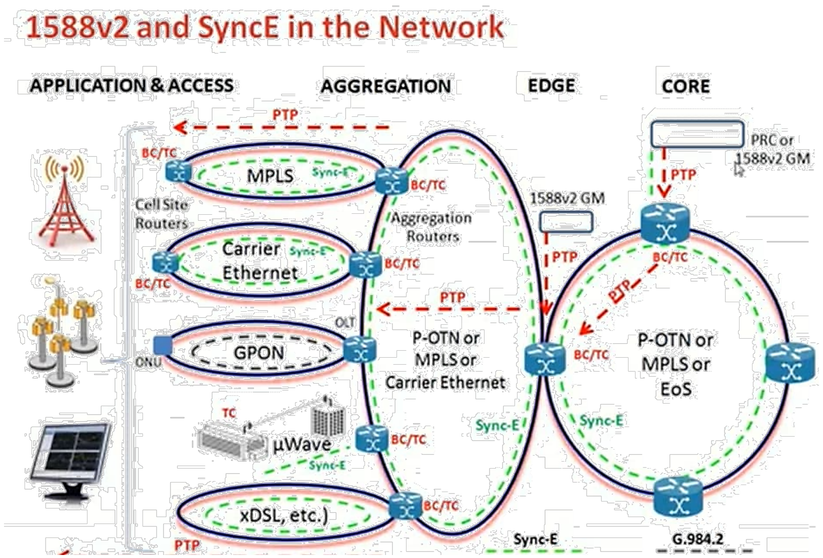
Useful for **Control plane –** provides continuous correction efficiently

Expansion to Hardware clock – SyncE+PTP



SyncE

Retrieves a clock **frequency** reference with a PLL (and can hold reference for short empty intervals)



SyncE+PTP

Achieves hundreds of **picosecond frequency** synchronization in the **Real-time** plane, and hundreds of **nanosecond time** synchronization in the logical **Control** plane.

Useful for both Real-Time/Quantum and Control plane – provides continuous correction efficiently – **but** the **quantum plane still** needs continuous **correction** from interchanged **qubits**

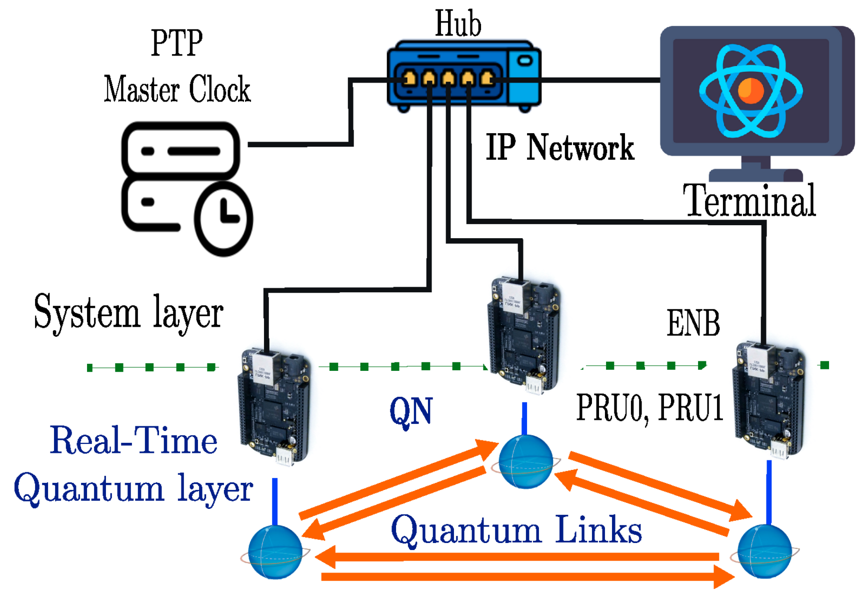
Quantum Network scheme

- **Three quantum nodes** (Node A, Node B, and Node C), each equipped with an Electronic Network Board (ENB).

- Connected through an **Ethernet hub** to support PTP (or SyncE+PTP).

- Each node is configured to participate in a **master-slave time synchronization** hierarchy, with a **PTP (or SyncE+PTP) master clock**.

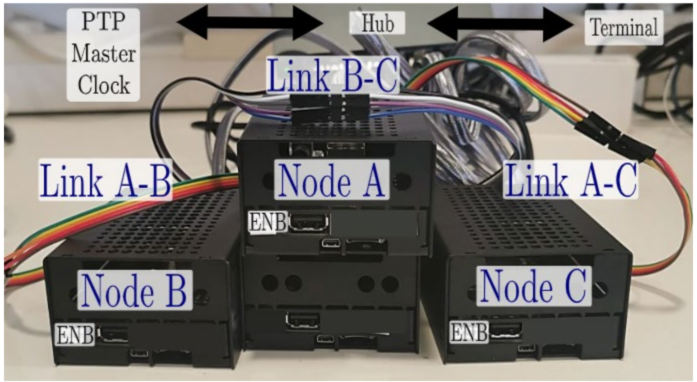
- Six half-duplex **physical link** connections are implemented between specific ENB pins to transmit signal representing **qubits**:



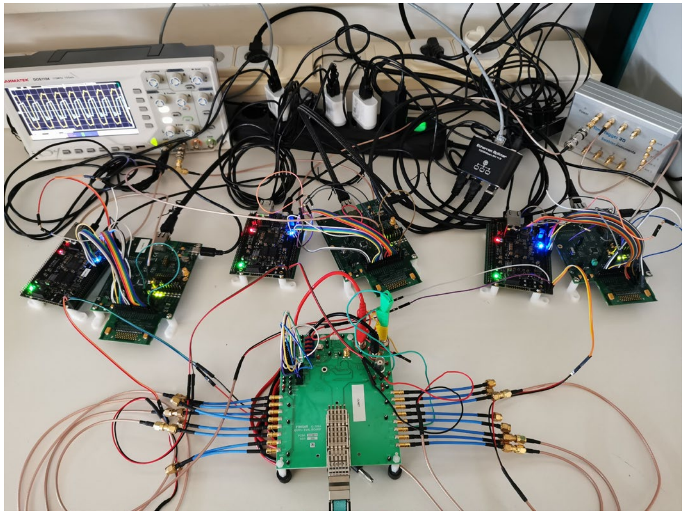
  - In particular, the **physical links** are each provided with **four effective connections** to send equivalent specific states, i.e., **quantum state encoding/decoding**.

Laboratory setup

First generation PTP slaves + real-time units



Second generation SyncE+PTP slaves + FPGA

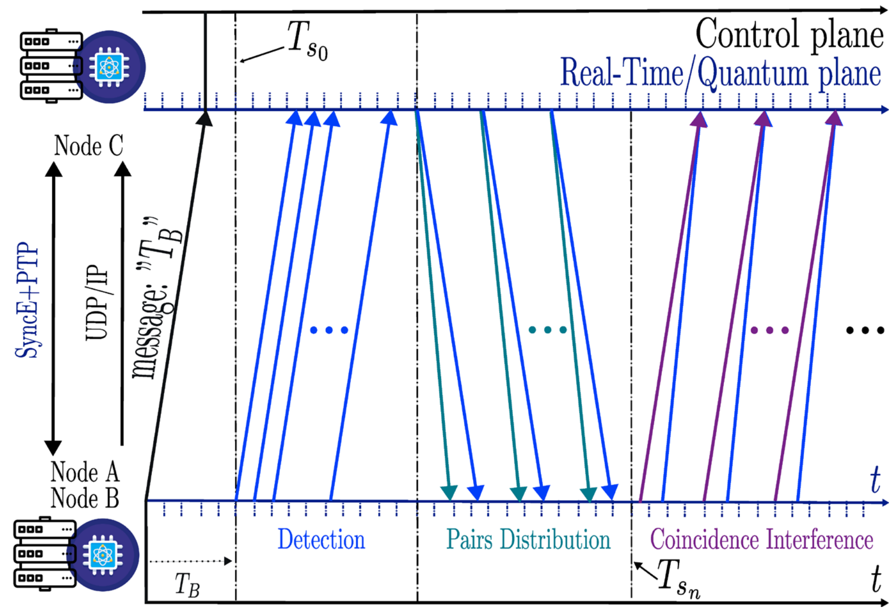


Grand Master Clock Server Networking

Synchronous transmission

Synchronous transmission: triggered source at specific times (fine grained time slots)

- Relies on **frame-based transmission** with precise **slotting**.
- Synchronous slots ensure predictable latency for real-time protocols.
- Guard intervals prevent overlap, minimizing retransmissions.



Current **frame time window 20 µs** - can be reduced with multi-core systems.

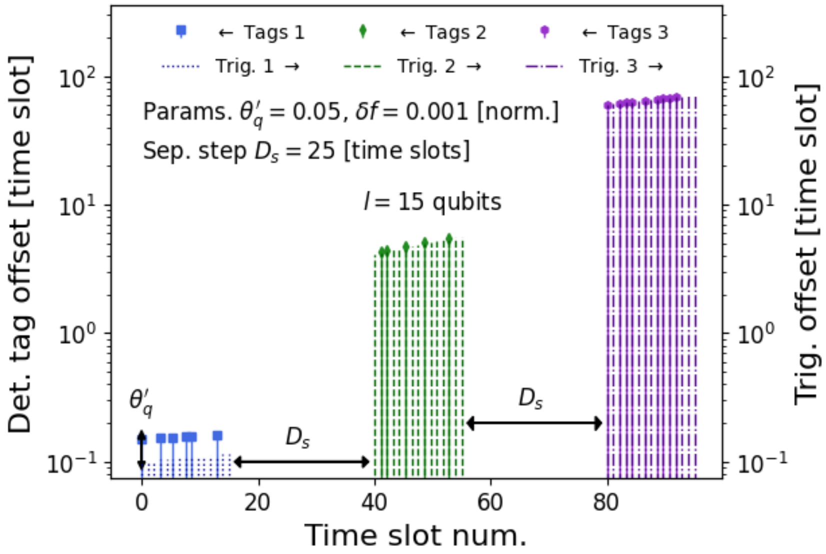
Current **time slots 5 ns** (limited by current electronics resolution) – can be reduced with FPGA systems.

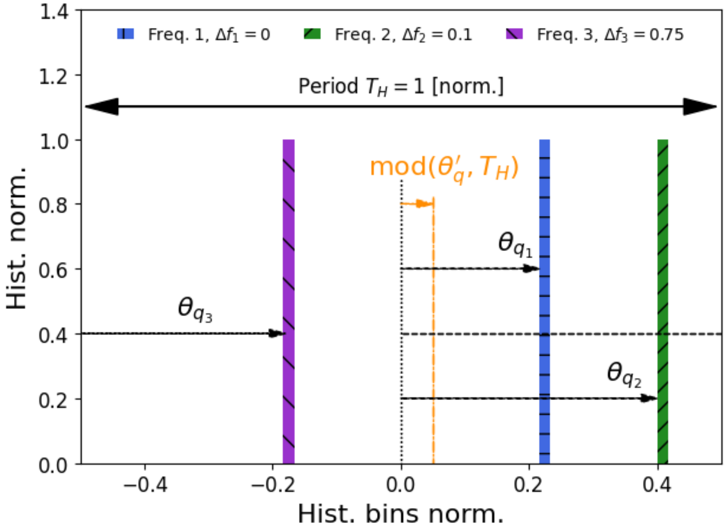
Improved Quantum plane synch. with SyncE!

QuBit-Rate mechanism

Global **offset** retrieval for qubits and **wandering** effects (which are not corrected in the control plane nor real-time part)

By **modulating** the **qubit rate emission**, it is also possible to tests and continuously **adjust frequency deviations** in the quantum plane.



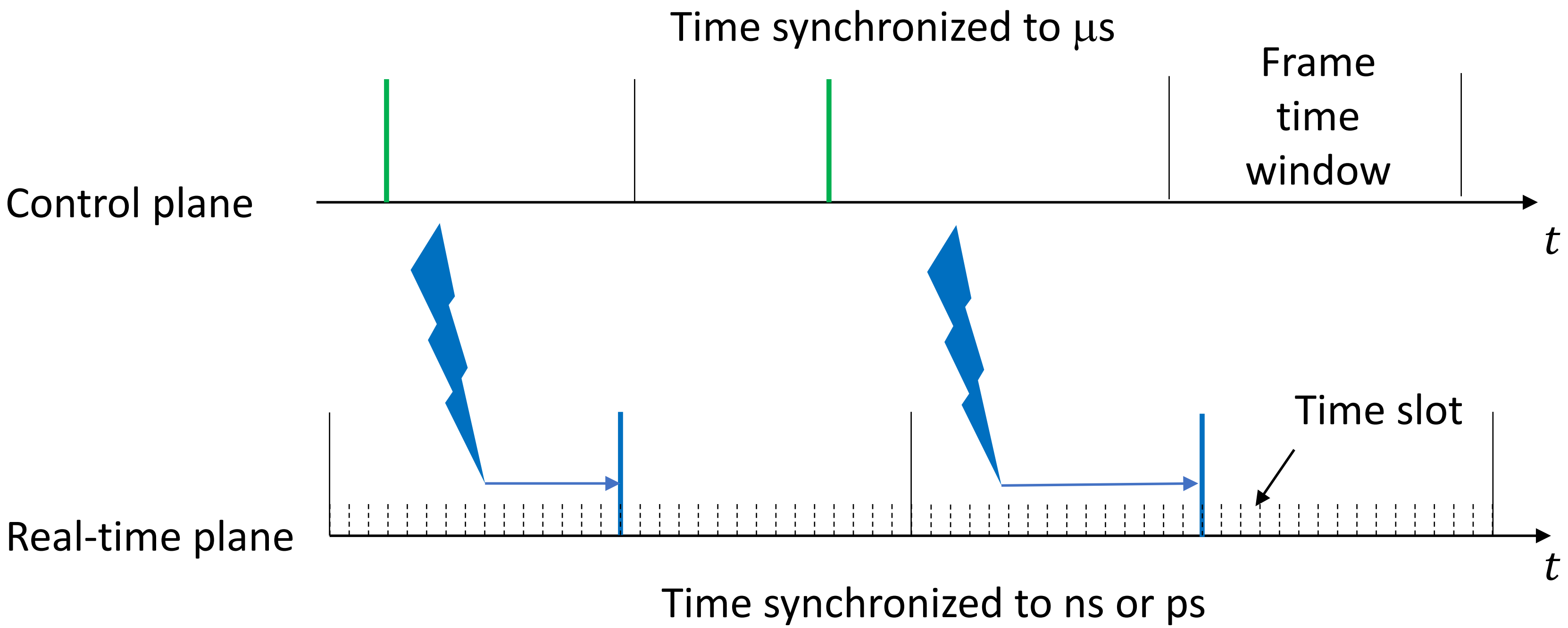


Synchronous operation allows to continuously **correct** synchronization **deviations!**

Temporally bridging the planes – Simplified version

The **command** to start transmitting qubits (or detecting) is **initiated** in the **control plane** (it has received a **petition** from **another node**).

Control plane, wait until **middle of time window** to send an **interrupt** to the real-time plane



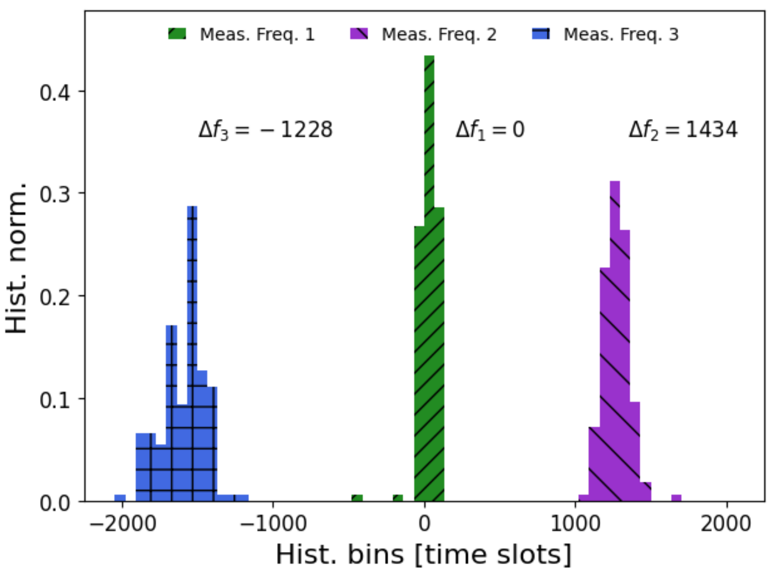
Real-time plane, wait until **end of time window** to start transmitting qubits synchronously

Results Qubit Rate Synchronization

Presence of **residual** time **offsets** and/or **relative frequency** differences in the **Quantum plane**

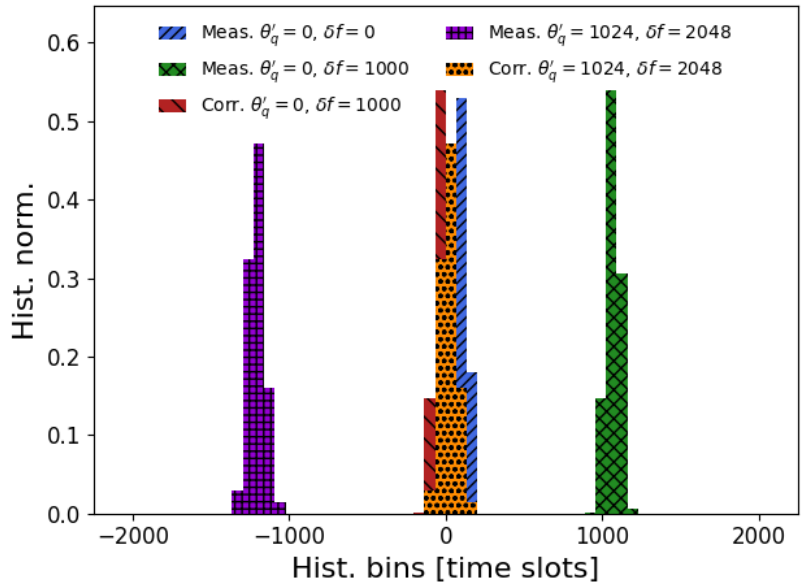
→ Qubit rate frequency testing mechanisms

Not applying mechanism



Deviation due to deviations

Applying mechanism



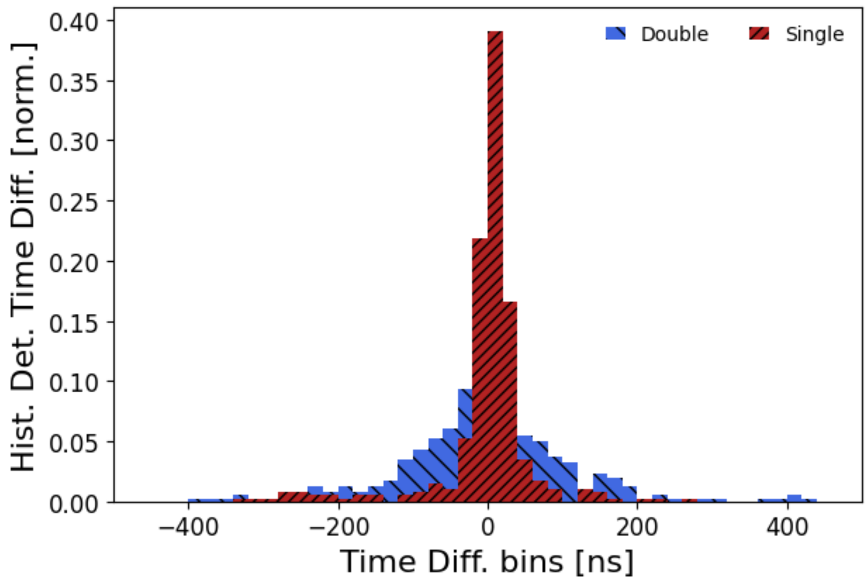
Corrected

Improved with SyncE+PTP

Results Common Quantum Operations

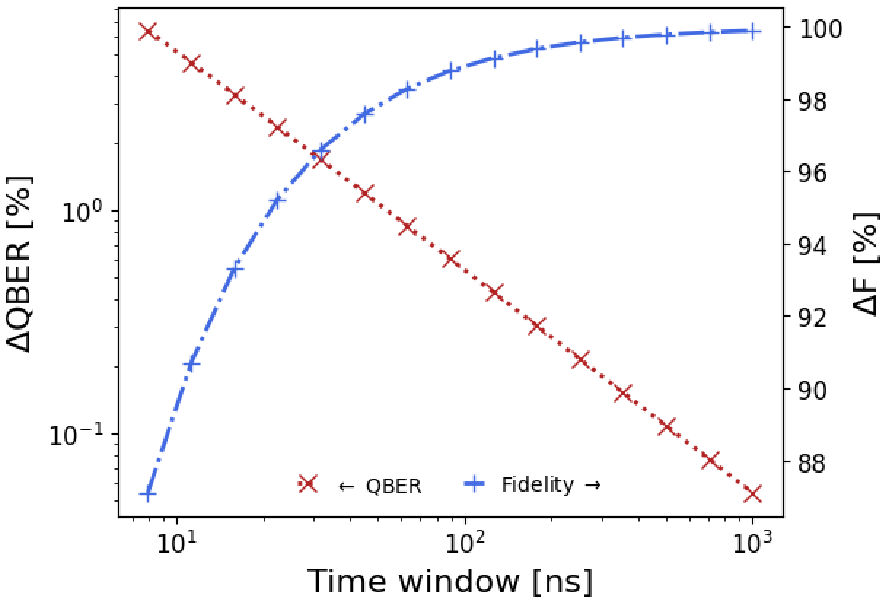
Operating through 24 hours – continuously correcting deviations

Temporal jitter



Single: 65 ns.
Coincidences: 100 ns.

Quantum performance



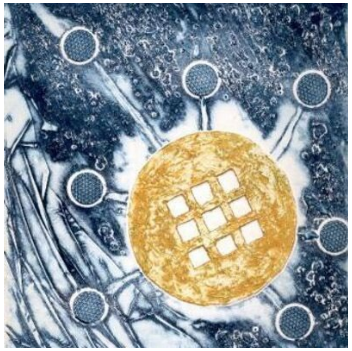
Considering a 100 ns time window:
QBER: <1%.
Fidelity degradation: 2%.

Improved with **SyncE+PTP to few ns** (resolution **of current real-time electronics**)

Projects

- **2025 - 2027 | Physical/Link Layer Interfaces for Multi-Node Quantum Networks (QuNet)**, State Research Agency - Research Consolidation 2024, Spain.
- **2023 - 2026 | EnablIng Native-AI Secure deterministic 6G networks for hyPer-connected envIRonmEnts (6G-INSPIRE)**, State Research Agency - Knowledge Generation Projects, Spain.
- **2022 - 2025 | Design and Evaluation of Broadband Networks and Services**, Generalitat of Catalonia - SGR-Cat 2021, Spain.
- **2022 – 2025 | UPC's Open Scientific-Technological Laboratory for 6G Research (6GOpenLab)**, Government of Spain - ÚNICO I+D 6G, Spain.

Team & Open Positions



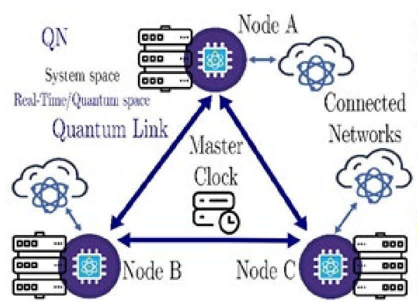
BAMPLA research group
Design and Evaluation of Broadband Networks and Services

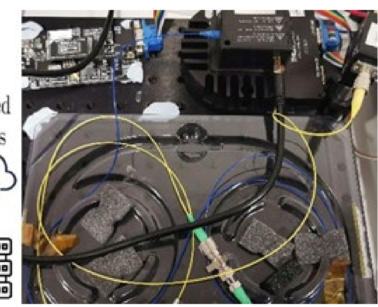
CCABA research center
Advanced Broadband Communications Center

CCABA

Open positions:

- **Post-Doctoral researcher. Quantum Networking.**
- **Research engineer. Electronics and Photonics.**
- **PhD students and Industrial PhD students.**





Thanks for your attention

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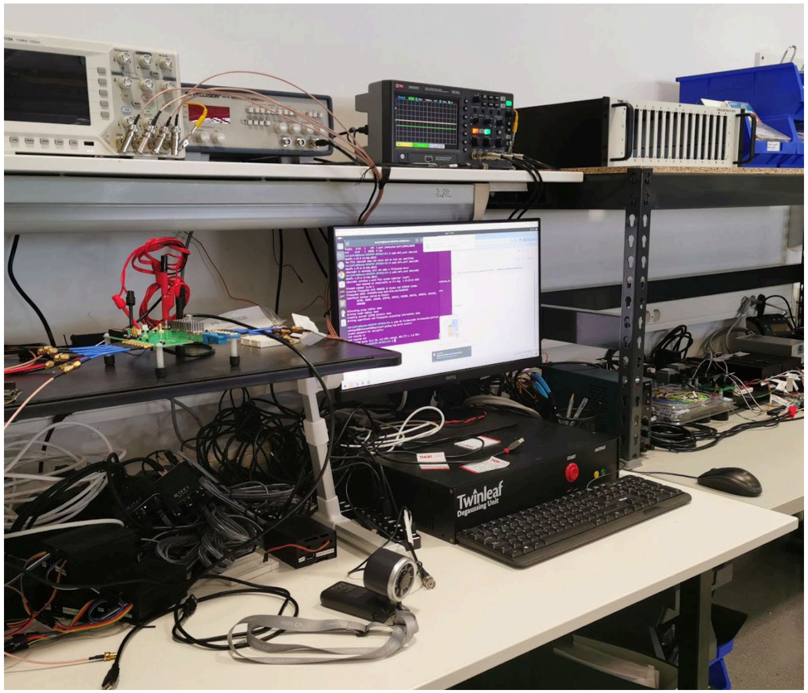
Research Lab – Quantum Networks



Quantum Networks - Resources and Capabilities:

- Quantum sources, links, sensors and detectors.
- Computational resources.
- Network and Interconnection devices.
- Temporal and Spectral measurement instrumentation.
- Advanced programmable electronic cards.
- Collaboration with other Laboratories and Research groups.

Barcelona Metropolitan Area