

Quantum and PNT Intersatellite Communications with Data Aggregation

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ABSTRACT

Future quantum communication networks are expected to combine terrestrial and space-based infrastructures, with inter-satellite optical links providing a potential mechanism for extending quantum connectivity over global distances. Such links require not only the transmission and detection of quantum optical signals, but also accurate and deterministic synchronization between remote nodes. QUPIDO (Quantum and PNT Intersatellite Communications with Data Aggregation) investigates the integration of White Rabbit high-accuracy timing and single-photon optical communications within a shared free-space optical infrastructure. The project follows a technology de-risking approach based primarily on commercial off-the-shelf components and focuses on the interfaces between timing, quantum and optical subsystems rather than on the implementation of a complete QKD protocol or flight-qualified terminal. The proposed laboratory demonstrator combines White Rabbit synchronization, deterministic triggering, photon-event timestamping, weak optical pulse generation and detection, wavelength-division multiplexing, complementary time-division multiplexing functionality, and a shared free-space propagation section. This paper presents the motivation and architecture of the QUPIDO concept, the main technical developments performed within the project, and the adopted integration and validation strategy. At the current stage, the demonstrator is progressing towards complete system integration and experimental validation. The activity is expected to provide an initial assessment of the feasibility and practical constraints associated with combining deterministic timing and single-photon communications over a common optical link, supporting future developments towards more representative quantum inter-satellite communication systems.

Keywords: Quantum communications, inter-satellite links, White Rabbit, time synchronization, free-space optics, single-photon communications, wavelength-division multiplexing, quantum networks

1. INTRODUCTION

Background and motivation

Modern digital infrastructures increasingly depend on two capabilities that are becoming simultaneously more critical: secure communications and accurate Positioning, Navigation and Timing (PNT). Telecommunications networks, transportation systems, energy grids, financial infrastructures and space-based services rely on trusted data exchange and precise timing, while the growing exposure of these systems to cyberattacks, jamming and spoofing is increasing the need for more resilient communication and navigation architectures.

In parallel, advances in quantum computing pose a long-term threat to currently deployed public-key cryptographic algorithms. Cryptographically relevant quantum computers could eventually compromise schemes such as RSA and Diffie-Hellman, motivating the development of quantum-resistant communication infrastructures. Quantum Key Distribution (QKD) represents one of the most mature quantum communication technologies, allowing remote parties to establish shared cryptographic keys with security properties derived from the principles of quantum mechanics. QKD is

therefore being investigated, together with post-quantum cryptography, as an enabling technology for future secure communication networks.

One of the main limitations of terrestrial quantum communications is transmission distance. Optical attenuation strongly constrains the achievable range of fibre-based quantum links, while free-space propagation provides a potential route towards much longer communication distances. Satellite quantum communications have consequently received considerable attention during the last decade. The Micius mission demonstrated the feasibility of space-to-ground quantum links and long-distance quantum state distribution [1], while European initiatives such as SpaceQUEST have investigated space-based quantum communication experiments [2]. More recently, constellations incorporating quantum inter-satellite links have been proposed as a possible architecture for extending quantum networks towards global coverage [3].

Quantum communication systems, however, impose stringent synchronization requirements. Photon emission and detection events at spatially separated nodes must be accurately time-referenced in order to correlate valid events and distinguish them from background detections. Accurate temporal coordination therefore becomes an enabling function of distributed quantum communication systems. Space-oriented quantum experiments have already demonstrated timing resolutions in the sub-nanosecond and even hundred-picosecond regime, highlighting the importance of precise synchronization for these applications [2].

Accurate and resilient time distribution is also an important capability in its own right for future distributed space infrastructures. GNSS and other PNT services fundamentally depend on highly stable time references, while future satellite constellations are expected to require increasingly precise coordination between spacecraft. Direct inter-satellite timing exchange could complement existing synchronization architectures by supporting distributed operation and additional redundancy across satellite networks.

In this context, White Rabbit (WR) represents an attractive candidate for deterministic time and frequency distribution. White Rabbit combines IEEE 1588 Precision Time Protocol mechanisms, Synchronous Ethernet and hardware-assisted phase measurements to achieve sub-nanosecond synchronization over optical networks. The foundational WR work demonstrated sub-nanosecond accuracy over a 5 km fibre link, with timing precision below 10 ps [4]. Since then, the technology has been deployed in demanding scientific infrastructures and investigated in increasingly heterogeneous timing applications.

Its potential relevance to optical and quantum communications has also started to be demonstrated experimentally. Recent work has shown picosecond-level White Rabbit synchronization over optical free-space links, including a reported 24-hour drift of 20.5 ps and TDEV values down to 3.9 ps [5]. Other experiments have investigated the coexistence of White Rabbit timing with quantum channels and the use of WR as a synchronization backbone for quantum-network applications.

These developments suggest a complementary relationship between deterministic timing and quantum communications. White Rabbit can provide the common temporal reference required to coordinate remote nodes, trigger optical events and timestamp single-photon detections. Conversely, future quantum communication systems could provide cryptographic key material to protect sensitive digital timing, control or PNT-related information exchanged between those nodes. Their integration therefore represents an interesting direction for future distributed optical networks.

This technological convergence is also consistent with the current European roadmap for quantum communications. The Quantum Flagship Quantum Communication Roadmap identifies the integration of quantum networks with existing classical infrastructures as a key requirement for their evolution towards scalable and operational systems, while recognising free-space and satellite optical links as essential elements for extending quantum connectivity beyond metropolitan distances. The roadmap further highlights precise classical electronics for timing, control and synchronisation as critical enabling technologies for quantum communication systems. In this context, early laboratory demonstrators addressing the coexistence and integration of quantum and classical functions, such as the approach investigated in QUPIDO, contribute to the progressive transition from isolated technological building blocks towards integrated higher-TRL quantum communication architectures [6].

The QUPIDO project

The **QUPIDO** — **QU**antum and **PNT** **I**ntersatellite communications with **D**ata **A**ggregati**O**n — project investigates this convergence as an initial technology de-risking activity within the European Space Agency General Support Technology Programme (GSTP). Its objective is to assess the feasibility of operating deterministic White Rabbit synchronization and single-photon communications within a shared free-space optical link, as a first step towards future hybrid optical inter-satellite communication systems.

QUPIDO deliberately addresses this objective through a limited laboratory demonstrator rather than through the development of a flight-ready terminal or a complete QKD implementation. The project is based primarily on Commercial Off-The-Shelf (COTS) technologies, complemented by project-specific timing, FPGA, software and optoelectronic developments. This approach is intended to identify the key compatibility, synchronization and integration challenges at an early stage, before progressing towards more representative space-oriented implementations.

The underlying hypothesis of the project is that deterministic timing and single-photon communications can coexist within a common optical infrastructure without preventing the correct operation of either domain. Demonstrating this capability at breadboard level would provide an initial experimental basis for subsequent developments targeting more integrated and representative inter-satellite optical terminals.

At the time of writing, QUPIDO is still under development and the complete integration and validation campaign has not yet been performed. Consequently, this paper focuses on the motivation, system concept, requirements, architecture, technical developments and planned integration and validation approach rather than on final experimental performance results. The objective of the present work is to describe the technological rationale of QUPIDO, the development activities performed to date, and the expected contribution of the breadboard demonstration to future hybrid quantum–timing optical systems.

2. QUPIDO CONCEPT, OBJECTIVES AND SYSTEM ARCHITECTURE

Following the motivation introduced in the previous section, QUPIDO investigates the integration of deterministic high-accuracy timing and single-photon optical communications within a common free-space optical infrastructure. The activity is conceived as an early technology de-risking step, intended to assess the compatibility of the different technological building blocks and to identify the main challenges that would have to be addressed in subsequent developments towards a representative inter-satellite optical terminal.

The project does not target the implementation of a complete Quantum Key Distribution (QKD) system or a flight-qualified payload. Instead, the emphasis is placed on demonstrating the fundamental functions required to combine both domains at laboratory breadboard level: deterministic White Rabbit synchronization, generation and detection of single-photon-level optical signals, propagation through a shared optical path, and mechanisms allowing both signal types to coexist without preventing their correct operation.

Project Concept and Objectives

The QUPIDO Proof-of-Concept combines four main technological elements: **White Rabbit data and timing transfer, single-photon communication, free-space optical propagation, and multiplexing techniques**. These elements are brought together in a laboratory demonstrator intended to reproduce, in a simplified and controlled environment, some of the key functions that would be required by a future hybrid optical inter-satellite link. The purpose of the activity is not to independently improve each of these technologies, but rather to investigate their interaction when integrated within the same communication system. The project therefore focuses on the interfaces between the different domains and on the functions required to operate them in a coordinated manner.

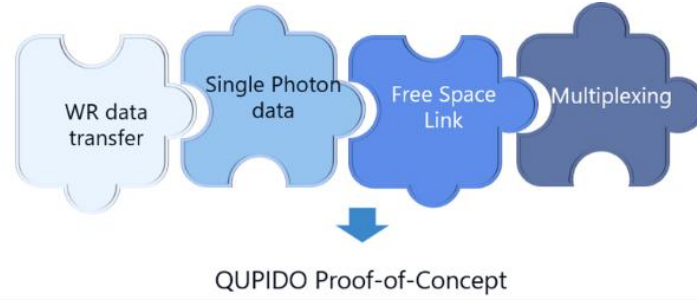


Figure 1. *QUPIDO Proof-of-Concept and main technological building blocks.*

The timing domain is based on **White Rabbit (WR)**, providing a common deterministic time and frequency reference between the two communicating nodes. Beyond synchronization, this reference supports the quantum subsystem by enabling controlled optical pulse generation and WR-referenced timestamping of photon-detection events, establishing a direct temporal relationship between transmission and detection. The quantum domain uses attenuated optical pulses and single-photon detection to reproduce the physical-layer conditions relevant to quantum communications, without implementing a complete QKD protocol. Both domains are integrated over a shared **Free-Space Optical (FSO)** path, providing a controlled laboratory environment in which their combined operation and mutual compatibility can be investigated before progressing towards more representative inter-satellite implementations. To enable this coexistence, **Wavelength Division Multiplexing (WDM)** is adopted as the baseline approach, allowing WR and single-photon signals to operate simultaneously at different wavelengths over the common optical path. In addition, **Time Division Multiplexing (TDM)** is investigated as a complementary experimental mechanism, providing configurable temporal separation between the different signal domains and enabling alternative coexistence strategies to be assessed.

The project objectives can therefore be summarised around the demonstration of three fundamental capabilities: maintaining deterministic synchronization between remote nodes, exchanging single-photon-level optical signals referenced to that common time base, and enabling classical and quantum signals to share the same free-space optical infrastructure. These high-level objectives are translated into a set of target capabilities used to guide the development and subsequent validation of the demonstrator.

A further objective of QUPIDO is to perform this assessment using **primarily Commercial Off-The-Shelf (COTS) components**. This approach reduces the amount of custom hardware required during the initial de-risking stage and allows the project to concentrate on system-level integration and interfaces. Project-specific developments are introduced where the available platforms do not directly provide the functionality required by the demonstrator, particularly in timing control, triggering, event timestamping and selected optical functions.

Based on these objectives, a limited set of target capabilities was defined to guide the design and development of the QUPIDO demonstrator. Rather than representing the performance of a future flight system, these targets establish the conditions under which the feasibility of the proposed concept can be assessed at breadboard level. The main capabilities considered in the present development are summarised in Table 1.

Table 1. Key target capabilities of the QUPIDO demonstrator.

Capability	Target / Approach	Purpose
Timing synchronization	Sub-nanosecond WR synchronization	Provide a common deterministic time reference between the two nodes
Photon-event timestamping	WR-referenced detection timestamps	Correlate single-photon detection events with the common system time
Quantum optical signal	Weak coherent pulses at single-photon level	Reproduce the optical power regime relevant to quantum communications
Shared optical propagation	Common free-space optical path	Assess coexistence of timing and single-photon signals over shared optical infrastructure

Baseline multiplexing	Simultaneous WDM operation	Enable continuous coexistence of WR and quantum optical signals
Complementary multiplexing	Experimental TDM operation	Investigate controlled temporal separation between the different signal domains
Bidirectional operation	Two-node TX/RX architecture	Represent the bidirectional functionality required by an inter-satellite optical link
Implementation approach	COTS-based laboratory breadboard with project-specific developments	De-risk the concept before progressing towards more representative space-oriented implementations

Consequently, QUPIDO should be regarded as an enabling technology demonstrator rather than as a prototype of the final space payload. A successful breadboard would establish an initial basis for future iterations addressing higher levels of integration, improved optical performance, space environmental constraints and, ultimately, the implementation of complete quantum communication protocols.

System Architecture

The QUPIDO demonstrator is based on a two-node architecture, representative at functional level of two communicating optical terminals. Each node incorporates quantum transmission and reception capabilities together with a White Rabbit timing subsystem. The nodes are interconnected through a common bidirectional optical path, allowing the main transmission, synchronization and photon-detection functions to be exercised between both ends of the link.

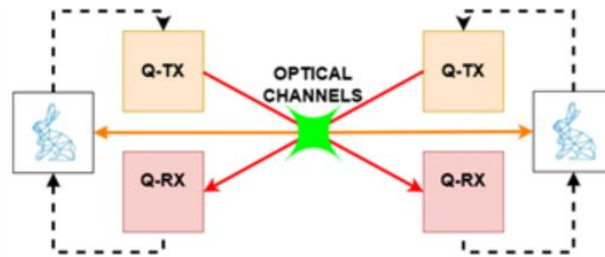


Figure 2. Simplified functional architecture of the bidirectional QUPIDO demonstrator.

Figure 2 above provides a simplified representation of the proposed architecture. Each side contains a quantum transmitter (Q-TX) and quantum receiver (Q-RX), while the White Rabbit subsystem provides the timing reference and coordination required by the node. The optical channels are combined through the central free-space path, resulting in an architecture in which both terminals support transmission and reception rather than operating exclusively as fixed transmitting and receiving endpoints.

The timing subsystem maintains a common time and frequency reference between the two nodes and provides the temporal basis for coordinating system operation. This reference is also made available to the quantum subsystem, establishing a direct functional relationship between synchronization and the generation and detection of optical events. Project-specific interfaces provide the triggering and timestamping functionality required to exploit this common time reference. Their implementation is described in greater detail in Section 3.

At optical level, the baseline WDM architecture separates the classical timing and quantum domains spectrally. The laboratory implementation considers a quantum optical channel at 780 nm, while the White Rabbit link operates using bidirectional optical channels on the 1310 nm and 1490 nm bands. Wavelength-selective optical elements combine these signals before the shared propagation path and separate them again at the receiving side. This spectral separation is particularly important because of the large difference in optical power between the classical WR signals and the single-photon-level quantum channel.

The quantum transmission chain generates and attenuates optical pulses to reach the weak coherent pulse regime required by the experiment. At the receiving side, single-photon detection devices register incoming optical events, which can

subsequently be referenced to the common WR time base through the dedicated timestamping functionality. This establishes the basic relationship between quantum transmission, detection and deterministic synchronization that the demonstrator is intended to investigate.

Although simultaneous WDM operation constitutes the baseline configuration, the architecture also supports dedicated TDM experiments. In this case, programmable temporal intervals derived from the synchronized time base can be used to coordinate transmission windows between the different signal domains. Importantly, this functionality is implemented as an additional experimental capability while the WDM optical configuration remains the primary architecture of the demonstrator. The corresponding project-specific timing and multiplexing developments are presented in Section 3.

The breadboard is implemented following an incremental integration strategy. Timing and quantum functions are initially developed and characterised at subsystem level, after which the interfaces between both domains are introduced. The system is then progressively extended towards combined optical operation and finally towards transmission through the common free-space section. This approach allows integration issues to be identified progressively and provides the basis for the validation strategy described in Section 4.

3. TECHNICAL DEVELOPMENTS

Following the definition of the system concept and architecture, the QUPIDO development activities have focused on implementing the functions required to integrate the timing and quantum domains within the laboratory demonstrator. Rather than developing all elements from scratch, the project builds upon existing COTS platforms and established technologies, introducing dedicated hardware, FPGA, software and optical developments where additional functionality is required.

The main developments can be grouped into three closely related areas. The first concerns the adaptation of the White Rabbit timing platform and the implementation of dedicated triggering, timestamping and TDM functions. The second addresses the generation, manipulation and detection of single-photon-level optical signals. Finally, the third covers the optical integration of both domains and the multiplexing mechanisms required for their coexistence over a shared optical path.

Timing and White Rabbit Developments

The QUPIDO timing subsystem is built upon the existing White Rabbit hardware and software ecosystem. Standard WR functionality provides the fundamental synchronization mechanism between the two nodes, including frequency distribution, clock recovery and the common time reference required by the demonstrator. The project-specific developments are therefore focused on extending this baseline platform with the additional functions required to interface WR timing with the quantum subsystem.

These developments have been implemented mainly within the FPGA architecture of the WR platform, complemented by software-accessible configuration and control mechanisms. The resulting architecture preserves the standard synchronization functionality while incorporating three main project-specific capabilities: photon-event timestamping, programmable TDM signal generation, and dedicated test and characterization functions.

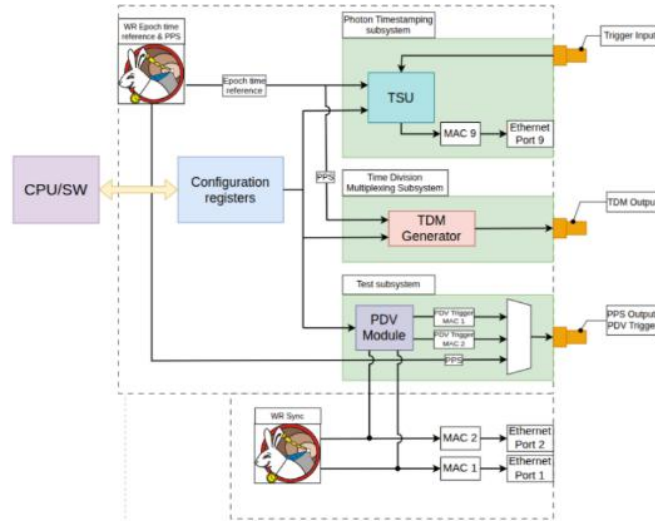


Figure 3. Simplified FPGA architecture of the QUPIDO timing developments integrated within the White Rabbit platform.

Figure 3 provides an overview of the resulting FPGA timing architecture. The standard WR synchronization functionality, represented in the lower part of the diagram, provides the synchronized clock and time reference used by the additional QUPIDO modules. A common set of configuration registers allows the embedded software to configure the project-specific functionality, while dedicated physical and Ethernet interfaces provide access to timing signals, detected events and configuration data.

Photon timestamping

One of the main developments is the Photon Timestamping Subsystem, which establishes the interface between the quantum receiver and the common WR time base. Detection events generated by the single-photon detector are provided to the FPGA through an external trigger input and processed by a dedicated Time Stamping Unit (TSU).

The TSU associates each incoming event with the synchronized WR time reference, allowing photon detections to be represented within the same temporal framework at both nodes. Timestamp information can subsequently be transferred through a dedicated Ethernet interface for acquisition and further processing. This functionality is essential for the QUPIDO concept, since it provides the mechanism required to correlate quantum detection events with the deterministic timing infrastructure without requiring an independent timestamping reference.

The implementation builds upon the timing capabilities already available within the WR platform while adapting them to asynchronous external photon-detection events. The objective is not to implement the complete event-processing chain of a QKD protocol within the FPGA, but to provide accurately referenced detection information that can subsequently be analysed at system level.

Time Division Multiplexing functionality

A second project-specific development is the Time Division Multiplexing Subsystem. Although WDM constitutes the baseline multiplexing approach of QUPIDO, dedicated TDM functionality has been implemented to investigate controlled temporal separation between the timing and quantum domains.

The TDM generator operates from the synchronized WR time base and generates configurable output intervals that can be used to control external optical or electronic elements. Because both nodes share the WR reference, transmission windows can be defined deterministically and coordinated between spatially separated terminals.

This functionality provides a flexible experimental mechanism for evaluating scenarios in which classical and quantum transmissions are separated in time. It also represents an example of how the deterministic timing infrastructure can be used not only for synchronization but also for direct control of the optical communication functions. In the baseline WDM

configuration, however, the timing and quantum signals are intended to coexist continuously and the TDM functionality can remain disabled.

Test and characterization functionality

Dedicated test functionality has also been included to support the characterization of the timing implementation. As shown in Figure 3, a specific PDV module and configurable output selection allow internally generated timing events and the standard PPS reference to be exposed through external interfaces.

These functions provide controlled signals for evaluating the behaviour of the timing chain and facilitate calibration and laboratory characterization using external measurement equipment. They are particularly useful during development because implementation-dependent delays can arise from the placement and routing of FPGA resources, making calibration necessary when comparing timestamps generated through different internal paths.

Together, these developments extend the standard White Rabbit platform from a synchronization system into a timing subsystem directly interfaced with the quantum experiment. The same common time reference can consequently be used for node synchronization, deterministic control and timestamping of externally generated photon-detection events.

Quantum Communication Developments

The quantum subsystem provides the optical transmission and reception functions required to reproduce the single-photon regime relevant to quantum communications. As established in Section 2, QUPIDO does not implement a complete QKD protocol. The development instead focuses on the physical-layer functions necessary to generate, transmit and detect weak optical pulses and to integrate these functions with the timing and multiplexing architecture.

On the transmission side, the optical chain is based on a pulsed laser source and a controlled attenuation stage. Electro-optical modulation allows the optical emission to be driven by external electrical signals, providing the interface through which the timing subsystem can control the temporal characteristics of the transmitted optical pulses. The resulting signal is subsequently attenuated to reach the weak coherent pulse regime used for the QUPIDO experiments.

This architecture enables the quantum optical transmission to be referenced to the deterministic timing system rather than generated from an independent asynchronous source. The temporal relationship between the electrical trigger and the resulting optical pulse is therefore an important parameter for subsequent characterization and integration.

At the receiving side, Single-Photon Counting Modules (SPCMs) are used to detect incoming optical events. Their electrical detection outputs are connected to the timestamping functionality described in Section 3.1, closing the functional chain between photon generation, optical propagation, photon detection and WR-referenced event acquisition.

Particular attention is also given to the optical power difference between the quantum and classical channels. Whereas the WR signal operates at conventional optical communication power levels, the quantum channel is intentionally attenuated towards the single-photon regime. Appropriate attenuation, spectral filtering and optical isolation are therefore required to prevent unwanted classical optical contributions from dominating the photon detections.

The experimental implementation is also intended to reproduce selected non-idealities that would arise in a more representative architecture. In particular, although the laboratory breadboard uses a simplified optical-source configuration, controlled electrical perturbations can be introduced through the EOM driving chain to investigate the sensitivity of the quantum signal to source-related disturbances. This provides a practical mechanism for increasing the representativeness of the experiment without requiring a complete duplication of the optical source hardware.

The quantum developments therefore provide the physical-layer counterpart to the WR timing developments: optical pulses are generated under deterministic timing control, propagated through the optical architecture and detected at the remote node, where the corresponding events are returned to the timing subsystem for timestamping.

Multiplexing and Optical Coexistence

The third development area concerns the integration of the timing and quantum signals into a common optical infrastructure. This represents one of the central technical challenges of QUPIDO because the two domains operate under very different optical conditions: White Rabbit relies on comparatively strong classical optical signals, whereas the quantum channel operates close to the single-photon level.

The baseline solution adopted by QUPIDO is Wavelength Division Multiplexing. The large spectral separation between the quantum signal (780 nm), and the WR communication wavelengths (1310 nm and 1490 nm) allows wavelength-selective optical components to combine and separate the different channels. The objective is to preserve continuous WR synchronization while quantum optical signals are simultaneously exchanged through the same propagation path.

This choice is particularly important for the QUPIDO concept. Rather than alternating between independent WDM and TDM operating architectures, WDM remains the baseline optical configuration throughout the experiment. The WR timing link can therefore remain continuously active, providing the common time reference required by the system without repeatedly changing the optical configuration.

The coexistence problem nevertheless extends beyond wavelength allocation. Classical-to-quantum leakage, component isolation, insertion losses, reflections and detector sensitivity must all be considered when combining signals whose optical powers differ by several orders of magnitude. The optical architecture therefore incorporates wavelength-selective filtering and appropriate attenuation to reduce unwanted contributions at the quantum receiver while maintaining sufficient optical power for reliable operation of the WR link.

In addition to the baseline WDM configuration, the TDM functionality described in Section 3.1 enables complementary experiments in which controlled time intervals can be assigned to the different signal domains. These tests are particularly relevant because the corresponding control capability constitutes one of the project-specific developments and allows alternative coexistence strategies to be investigated without replacing the underlying WDM architecture.

The final integration stage introduces a shared free-space propagation section. Optical signals originating from the fibre-based subsystems are collimated into free space, propagated through the laboratory optical path and subsequently coupled back into the receiving chain. This configuration provides a controlled environment for investigating the transition from guided propagation towards the type of shared optical channel required by a future inter-satellite implementation.

The free-space breadboard is intentionally limited in scope. It does not reproduce representative orbital distances, relative spacecraft motion, atmospheric effects or autonomous pointing and tracking. Instead, its purpose is to determine whether the timing and single-photon functions developed independently can be brought together within a common optical path and remain operational after integration.

The combined timing, quantum and optical developments therefore establish the technical basis for the final QUPIDO breadboard. Their progressive integration is intended to determine whether deterministic WR synchronization can be maintained while single-photon-level signals are generated, transmitted and timestamped through the same optical infrastructure, and to identify the principal limitations and integration issues to be addressed in future iterations.

4. INTEGRATION AND VALIDATION APPROACH

The developments described in the previous section are brought together in a laboratory breadboard intended to demonstrate the complete QUPIDO functional chain. The integration activities follow a progressive approach, moving from independently characterised timing, quantum and optical functions towards their combined operation over a shared free-space optical path.

At the current stage of the project, the focus is on implementation and integration rather than on reporting final system performance. Consequently, this section describes the planned validation approach adopted to assess the main capabilities introduced in Section 2. Experimental results will be obtained during the subsequent integration and validation campaign.

Laboratory Breadboard Implementation

The QUPIDO breadboard combines the White Rabbit nodes, the quantum transmission and reception chains, and the free-space optical section within a common experimental setup.

Two WR nodes establish the deterministic timing link and provide the timing interfaces required by the experiment. The classical WR optical signals are combined with the quantum channel through wavelength-selective elements before entering the common optical propagation path. At the opposite side, the different spectral components are separated and routed towards their corresponding receivers.

The quantum transmission chain uses a laser source together with an electro-optic modulator (EOM) and a variable optical attenuation stage to generate controlled weak optical pulses. An RF coupling stage provides a mechanism for introducing controlled perturbations. This allows selected source-related effects to be emulated within the simplified laboratory architecture.

At the receiving side, the quantum optical signal is directed towards a single-photon counting module (SPCM). The resulting electrical detection events are returned to the timing subsystem and processed by the timestamping functionality described in Section 3.1. In this way, the breadboard closes the complete experimental chain from optical pulse generation to WR-referenced photon-event acquisition.

The central free-space breadboard provides the shared propagation section of the demonstrator. Fibre-coupled signals are transferred to and from the free-space path through the corresponding optical interfaces, while mirrors and wavelength-selective elements define the bidirectional optical path. This configuration enables the coexistence of the timing and single-photon channels to be investigated under controlled laboratory conditions without attempting to reproduce the complete complexity of an operational inter-satellite optical terminal.

Integration and Validation Strategy

Integration is performed incrementally to reduce the complexity associated with combining subsystems operating at substantially different optical power levels and with different timing requirements. Rather than assembling the complete breadboard directly, individual functions are first characterised independently and subsequently combined into progressively more representative configurations.

The initial activities address the timing and quantum chains separately. On the timing side, these include verification of WR synchronization and characterization of the project-specific triggering, timestamping and TDM functionalities. On the quantum side, the generation, attenuation and detection chains are characterised to establish the operating conditions required for single-photon-level transmission.

Once the individual functions have been verified, the interfaces between the two domains are introduced. Particular attention is given to the deterministic relationship between the WR time reference, optical pulse generation and photon-event timestamping. The multiplexed optical configuration is then progressively integrated, initially under controlled conditions and subsequently through the free-space section.

The validation campaign is structured around the key capabilities identified in Section 2.1. In particular, it is intended to assess whether the integrated demonstrator can maintain WR synchronization while supporting the quantum optical channel, generate and detect weak optical pulses referenced to the common time base, timestamp detection events, and support coexistence of the timing and quantum signals over the shared optical infrastructure. Complementary TDM experiments are also foreseen to evaluate controlled temporal separation as an alternative operating mode.

This staged approach is intended not only to determine whether the complete Proof-of-Concept can operate as expected, but also to identify the main integration constraints and technological limitations relevant to subsequent developments. The outcome of the validation campaign will therefore provide the experimental basis for assessing the feasibility of the QUPIDO concept and defining the next steps towards more representative implementations.

5. DISCUSSION AND EXPECTED OUTCOMES

At the current stage of the QUPIDO project, the individual technological building blocks have been defined and the project-specific developments required for their integration are being implemented. The next activities will focus on the progressive integration and validation of the complete laboratory breadboard described in Section 4. Therefore, no final experimental performance results are reported in this paper.

The main expected outcome of QUPIDO is the demonstration, at Proof-of-Concept level, that deterministic White Rabbit timing and single-photon optical communication can be integrated within a common free-space optical infrastructure. In particular, the experimental campaign will assess whether WR synchronization can remain operational while weak optical signals are simultaneously transmitted and detected, and whether photon-detection events can be accurately referenced to the common WR time base.

An important aspect of the activity is the investigation of the mutual relationship between the timing and quantum domains. Accurate and deterministic timing provides the temporal reference required for controlled photon generation and event correlation, while the integration with a single-photon channel introduces stringent coexistence constraints due to the large difference in optical power between classical and quantum signals. The QUPIDO demonstrator is intended to provide a controlled environment in which these interactions can be experimentally assessed.

The project is nevertheless subject to the limitations associated with an early-stage laboratory demonstrator. The breadboard is primarily based on COTS components and does not reproduce representative inter-satellite distances, spacecraft dynamics, autonomous pointing and tracking, environmental conditions or space-qualified hardware. Furthermore, the quantum channel is intended to reproduce the relevant single-photon optical regime rather than implement a complete QKD protocol. Consequently, the project should not be interpreted as demonstrating a flight-ready quantum inter-satellite link.

Instead, the expected contribution of QUPIDO is to provide experimental evidence on the feasibility and practical limitations of combining these technologies and to identify the main issues requiring further development. A successful demonstration would provide a basis for subsequent activities addressing improved optical integration, more representative link conditions, increased system robustness and, ultimately, the progression towards space-compatible quantum communication terminals.

6. CONCLUSIONS

QUPIDO investigates the integration of deterministic high-accuracy timing and single-photon optical communications over a shared free-space optical infrastructure as an enabling step towards future quantum inter-satellite links. The project follows a technology de-risking approach based primarily on COTS components, complemented by dedicated developments where additional timing, control and optical functionalities are required.

The proposed demonstrator combines White Rabbit synchronization, WR-referenced photon-event timestamping, controlled generation and detection of weak optical pulses, wavelength-division multiplexing and a shared free-space optical path. In addition, dedicated TDM functionality provides a complementary mechanism for investigating the temporal coordination of classical and quantum signals. Together, these developments provide a laboratory platform for studying the interfaces and coexistence constraints arising when deterministic timing and single-photon communication are integrated within the same system.

At the time of writing, the project is progressing towards the integration and validation of the complete breadboard, and final experimental results are therefore not yet available. The validation campaign will determine the extent to which the target capabilities can be achieved simultaneously and will identify the principal limitations of the proposed approach.

QUPIDO is not intended to demonstrate a flight-ready quantum communication terminal, but rather to provide an experimental basis for subsequent developments. The knowledge obtained from the integration and validation activities is expected to support future work towards more representative optical links, increased system integration and robustness, space-compatible implementations and, ultimately, quantum communication capabilities for future satellite networks.

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