Deterministic 6GB-Assisted Quantum Networks with Slicing Support: A New 6GB Use Case

Jonathan Prados-Garzon, Tarik Taleb, Lorena Chinchilla-Romero, and Masoud Shokrnezhad

***Abstract*—The Quantum Internet (QI) is a hypothetical global network infrastructure that exploits quantum mechanics principles to distribute qubits worldwide. The QI will enable breakthrough applications like unconditional security, distributed quantum computing, and quantum metrology. Nonetheless, the QI is currently a research-stage technology with daunting challenges until fully-functional quantum networks (QNs) can be realized. QNs are not standalone but require classical networks to assist the qubits exchange between remote places through quantum teleportation. On the other hand, QNs control and management planes will remain classical due to quantum networking technology manufacturing complexity and cost. This article addresses integrating QNs with Sixth Generation and Beyond (6GB) mobile networks. Sixth Generation and Beyond (6GB) are the foreseen next generations of wireless networks, offering extensive ubiquity and improved ultra-reliable low-latency support over larger distances than their predecessors. Therefore, it is the best-suited candidate to enable potential mobile and non-terrestrial quantum applications. Unlike existing literature highlighting quantum technology's potential benefits to mobile networks, this work presents a fresh vision in which 6GB enhances the QI and even contributes to accelerating its development. To that end, we identify target QNs scenarios enabled, facilitated, or benefited by 6GB. We propose a Software-Defined programmable 6GB-integrated QN architecture with slicing support and the associated procedure to create virtual QNs or slices. Last, we present a proof-of-principle showing that QNs can impose deterministic low-latency requirements out of 5G reach.**

***Index Terms*—Quantum Internet (QI), Quantum Communications, Software-Defined Programmable Quantum Networks, 6G & Beyond (6GB), QNs-6GB integration, Quantum Networks slicing, 6GB use case, Deterministic Networking**

I. Introduction

The Quantum Internet (QI) is a hypothetical global infrastructure that leverages quantum mechanics principles, such as quantum entanglement, to distribute quantum systems' states worldwide [1]. It is seen as an extension of the classical Internet, enabling breakthrough applications like unconditional security, distributed quantum computing, and quantum metrology [2]–[7]. However, the development of the QI faces daunting challenges, including the realization of quantum repeaters to extend the communication range and robust quantum error correction techniques to mitigate noise and decoherence. Currently, quantum communications are in the research stage. Recent achievements include successfully operating a telecom-wavelength quantum repeater over a 50 km channel [8]. This remarkable progress underscores the significant challenges in manufacturing fully-functional carrier-grade QN hardware.

Quantum networking technology is not standalone but needs classical networks to assist its operation. Instead of directly transmitting qubits as physical particles over the Quantum Network (QN), they are teleported. This approach is convenient due to the fragile nature of qubits and the impossibility of cloning them. This teleportation process involves sharing entangled states among Quantum Application (QApp) peers using the QN while transmitting information through classical networks. As shown later, QApps might impose stringent deterministic low-latency requirements for these classical communications. Additionally, the principle of keeping classical networks as much as possible is implicitly adopted in QNs due to manufacturing quantum hardware being extremely complex and expensive. Consequently, the QN control and management planes, including signaling messages exchange and processing, will primarily remain classical. On the other hand, integrating QNs with classical network technologies is crucial for the adoption and viability of quantum networking [4], allowing the utilization of existing infrastructures and processes, thus reducing expenditures in QNs deployment and operation.

The envisioned next-generation wireless networks, known as 6G and Beyond (6GB), surpass the capabilities of 5G, driven by ambitious use cases and urgent societal needs [5], [9]. These networks will enhance current 3GPP standards to achieve greater ubiquity, versatility, and effectiveness in supporting diverse traffic types. With extended resources, innovative capabilities, and improved interworking with pivotal technologies, 6GB will provide advanced wireless access, connecting the most remote locations on Earth and non-terrestrial environments like space and underwater communications. They will offer end-to-end deterministic low-latency support over large distances, even for data-hungry applications like high-fidelity holograms. Therefore, 6GB holds promise in meeting the classical connectivity needs of QNs and facilitating mobile and non-terrestrial QApps. Furthermore, 6GB could deliver precise synchronization and positioning services to QNs, which are crucial for the QN operation and helpful in assisting over-the-air quantum communications.

This article aims to identify target quantum scenarios that benefit from 6GB, explore the integration of QNs with 6GB and their softwarization, and examine the importance of deterministic classical connectivity in QNs. Existing literature [5], [6] recognizes quantum communications as a key enabler of 6GBs. However, we address the opposite vision where QNs are regarded as a target 6GB use case, enabling wireless

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and ubiquitous QApps and facilitating the softwarization and automation of QNs intelligence. This approach could influence future mobile network standards to cater to QNs requirements and potentially accelerate the development of the QI. The contribution of this work is threefold:

- We identify target scenarios that can benefit from integrating QNs with 6GB, supported by concrete examples. Specifically, we highlight the suitability of 6GB for mobile QApps, non-terrestrial QApps, and the facilitation of QNs softwarization and automation.
- We propose a Software-Defined (SD) architecture for QN networks. While prior literature acknowledges SDN's suitability for QN control planes [4], [10], our proposal goes beyond by addressing the zero-touch QN management plane to facilitate QN slicing and seamless integration with 6GB, regardless of the QN functionality or target application. We also outline the key steps involved in QN slice creation.
- We present a proof-of-principle (PoP) demonstrating how QApps can impose stringent deterministic low-latency constraints on classical communications to support quantum teleportation. The results emphasize the key role of deterministic networking in enabling QApps. These requirements go beyond 5G capabilities and warrant further research in this direction.

The rest of this article is organized as follows. For comprehensiveness, we provide background on quantum and deterministic networking in Sections II and III, respectively. Section IV describes scenarios benefiting from QN-6GB integration. Section V details the SD-programmable 6GB-integrated QN architecture proposal. The proof-of-principle is reported in Section VI. Finally, Section VII draws the main conclusions and outlook.

II. Quantum Networks

This section is devoted to briefly present the key concepts related to quantum networks.

A. Basics

QNs aim to facilitate the exchange of qubits (quantum bits), the fundamental units of quantum information, between arbitrarily remote locations. A qubit is a quantum system that can exist in a superposition of two states (e.g., electron spin). The state (wave function) of a qubit has the form $a \cdot |0\rangle + b \cdot |1\rangle$, where a and b are two complex numbers, meaning that when the qubit state is measured (wave function collapse), the outcome will be the state $|0\rangle$ or $|1\rangle$ with probabilities $|a|^2$ or $|b|^2$, respectively.

We focus on QNs using quantum teleportation to exchange qubits between end devices [11]. These networks comprise a set of Quantum Repeaters (QRs) interconnected through quantum channels or links to allow for entangled states (e.g., Bell pairs or Greenberger-Horne-Zeilinger (GHZ) states) distribution between endpoints. Quantum entanglement is a non-classical phenomenon where quantum particles properties become correlated, making their states inseparable regardless of distance. For instance, the Bell or EPR (Einstein, Podolsky, and Rosen) pair is a two-qubits state with wave function $1/\sqrt{2} \cdot (|00\rangle + |11\rangle)$, resulting in a $1/2$ probability of getting either $|0\rangle$ or $|1\rangle$ when measuring one qubit, with the subsequent other qubit's measurement always producing the same outcome.

A quantum link is a channel (e.g., optical fiber or air) for transmitting quantum particles like photons. Quantum channels are susceptible to disturbances, such as environmental noise, absorption, and scattering, causing quantum signal decay. QRs or quantum nodes (Qnodes) are essential to overcome this issue. Their primary role is to enable reliable, high-quality entanglement distribution over long distances. QRs utilize entanglement swapping and, optionally, quantum error correction techniques to mitigate transmission loss and decoherence. They might also implement purification and entanglement distillation to improve the quality of the delivered entangled states. To that end, QRs are equipped with quantum hardware to realize quantum memories and apply the required quantum gate networks over a set of qubits.

B. Operation

Figure 1 illustrates quantum teleportation, the process of transferring the state of a qubit ($|\Psi\rangle$), which may be an output of a Quantum Processing System (QPS), from Alice to Bob without physically moving the particle.

First, it is required that Alice and Bob share a pair of entangled qubits, whose states are denoted as $|\phi_{11}\rangle$ (Alice) and $|\phi_{12}\rangle$ (Bob) in Fig. 1. To that end, a remote entanglement generator is shown that conveniently applies the single qubit Hadamard and controlled-NOT (C-NOT) gates over two independent qubits to induce an entangled state between them, generating a Bell pair. Next, each Bell pair's qubit is transmitted to Alice and Bob's sites through the QN. Second, Alice conveniently applies a C-NOT and Hadamard gates over the target qubit $|\Psi\rangle$ she wants to send and $|\phi_{11}\rangle$. Third, after this quantum processing, she measures the resulting states of the two involved qubits that result in two classical bits, b_X and b_Z. Fourth, these bits are sent to Bob through a classical network. Last, Bob uses these two bits for controlling the application of Pauli-X and Pauli-Z gates to finally get the state $|\Psi\rangle$. After, Bob might want to apply further quantum processing on this state and perform a measurement to extract classical information.

It is important to note that teleportation adheres to the no-cloning theorem that forbids making exact copies of an arbitrary unknown quantum state. Another remarkable observation is that teleportation needs classical networks to transmit qubits between distant locations.

III. 6G Deterministic Networks

Deterministic networking is an emerging paradigm for upgrading packet-switched networks based on open standards, enabling predictable communications. This involves achieving low and bounded packet delay with high reliability while ensuring compatibility with traditional non-deterministic services. To achieve these goals, these standards must incorporate advanced capabilities, including synchronization, intricate

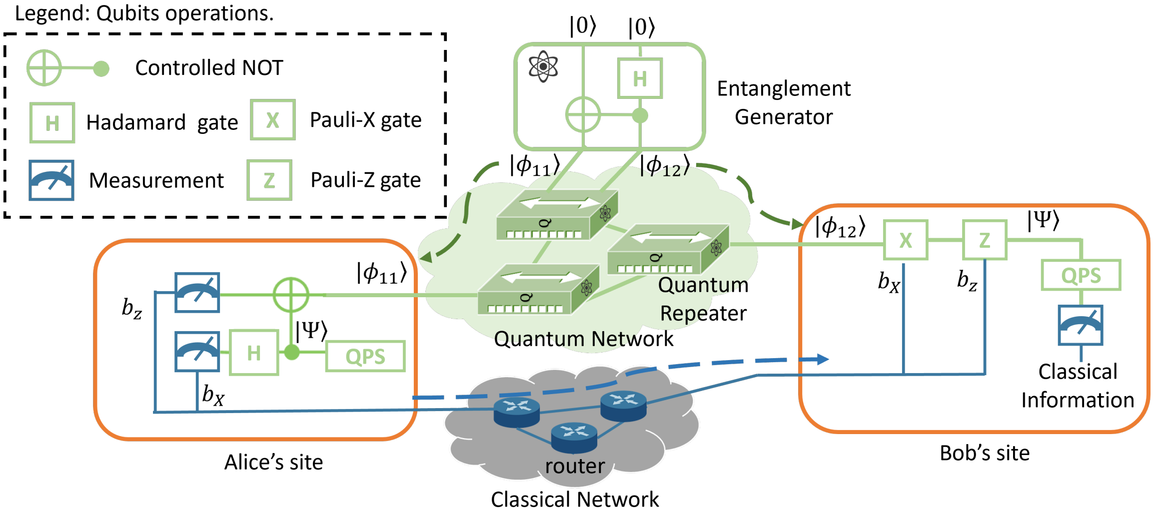


Fig. 1: Quantum network model and qubit teleportation process.

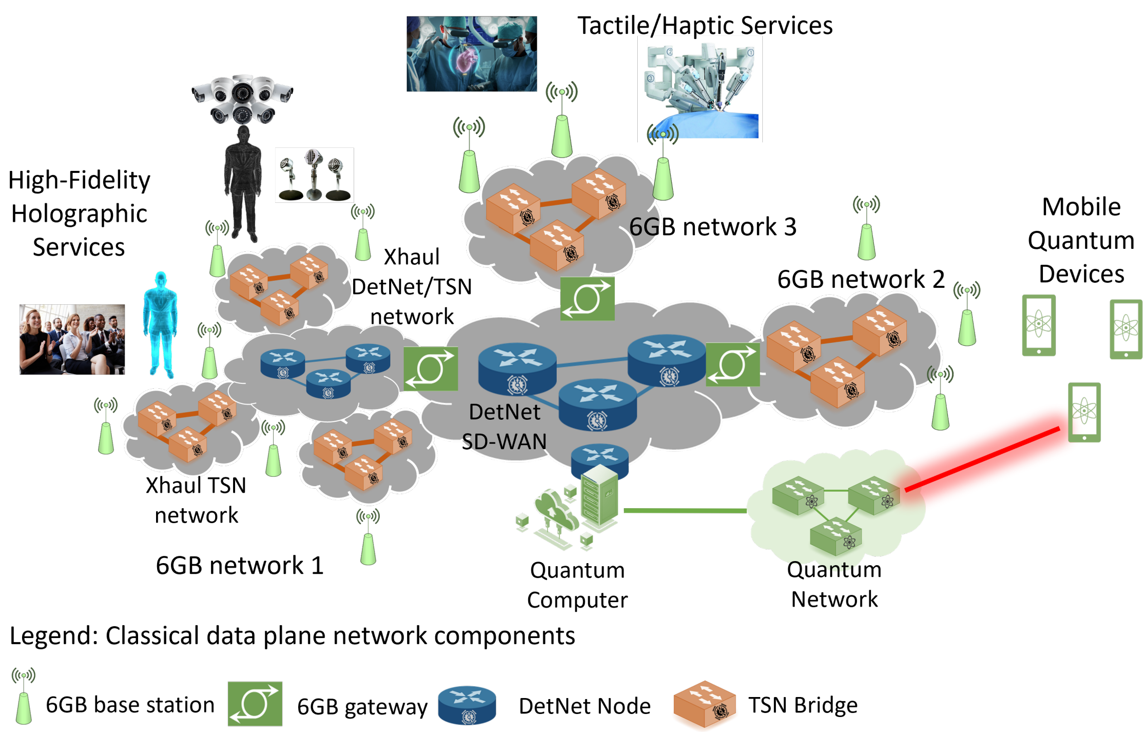


Fig. 2: Seamless integration of 6GB with TSN and Detnet data planes to provide long-range and truly end-to-end ultra-reliable low-latency connectivity for high-fidelity holograms, tactile/haptic and quantum services.

schedulers for packet transmission at every network interface, and network redundancy support.

Mobile systems, as defined by 3GPP, have embraced deterministic networking since Release 16 of the 5G standard. This was achieved by introducing new features in both Radio Access Network (RAN) and Core Network (CN) to support Ultra-Reliable Low-Latency Communications (URLLCs) with one-millisecond end-to-end latency and six nines of reliability targeting industrial automation in well-controlled local environments (see 3GPP TS 22.104). Driven by more ambitious use cases like high-fidelity holograms and tactile/haptic services as shown in Fig. 2, upcoming 3GPP releases for 6GB standards aim to meet more stringent deterministic low-latency requirements over longer distances [5], [9]. Specifically, this translates into the fact that 6GB URLLC capabilities must further evolve to achieve end-to-end delay around few hundreds microseconds in non-local environments [5], [9].

It is essential to highlight that 6GB must seamlessly integrate with wired deterministic technologies to achieve global end-to-end deterministic connectivity. These wired technologies are vital for connecting mobile network components like base stations and gateways, which fall outside the scope of 3GPP standards. Notably, technologies such as Time-Sensitive Networking (TSN) and Deterministic Networking (DetNet) have been recognised as appealing candidates for providing deterministic layer 2 and layer 3 connectivity in 3GPP transport networks [12], as shown in Fig. 2 under 6G network 1. Additionally, deterministic wired technologies are crucial for interconnecting various mobile networks, as exemplified by the DetNet Software-Defined Wide Area Network (SD-WAN) in Fig. 2, and for accessing remote services with ultra-reliable low-latency.

As suggested by the results reported in Section VI, quantum services may necessitate end-to-end latency requirements of less than 1 ms, aligning with the latency targets of current 6G applications [5], [9]. This highlights the importance of considering quantum use cases in shaping future mobile standards to enhance URLLC capabilities and facilitate integration with other deterministic technologies. Neglecting this aspect could cast doubt on the ability of upcoming generations to adequately support emerging quantum services.

IV. 6GB-Enabled Quantum-Based Scenarios

This section underlies the advantages of 6GB in terms of providing classical connectivity for wireless and non-terrestrial QApps and assisting QNs intelligence. Figure 3 illustrates a range of potential quantum scenarios, which are described below.

A. 6GB-Enabled Wireless QApps

Wireless-enabled QApps require wireless access for quantum and classical connectivity due to either the involved end devices are mobile or the environment restricts or prohibits wired access.

In early quantum scenarios, quantum memory might impose strict delay requirements on classical connectivity, as we will see in Section VI. Specifically, the total latency to execute protocols involving multiple rounds of Quantum Entanglement Distribution (QED), classical communications, and quantum processing must be lower than the devices' memory coherence times [3]. As quantum technology advances and incorporates quantum error correction techniques, coherence times are expected to increase. Nonetheless, the growing complexity of quantum protocols, such as exchanging a larger number of qubits prior to quantum processing, can maintain stringent delay requisites for classical connectivity. Hence, a dependable wireless technology with native deterministic low-latency support like 6GB could be crucial for the feasibility of many wireless QApps.

The top-left scenario depicted in Fig. 3 involves a Unmanned Aerial Vehicles (UAVs) fleet from the military sector requiring access to a remote quantum computer. Specifically, a master UAV is responsible for mission planning, which requires solving complex optimization problems for trajectory computation and UAVs tasks assignment. These computations exceed the onboard computational capacity of the master UAV or may compromise its autonomy. Consequently, the master UAV may seek to utilize a quantum computer for either quantum advantage, speeding up the optimization processes compared to classical computers, or for enhanced security. In the latter case, Blind Quantum Computing (BQC) service might be used to perform the desired computations without revealing information about the input data, quantum algorithm, or outcome to the quantum computer and detecting any attempts of tampering or eavesdropping on the quantum computation and communication. The QED is facilitated by a QN with air-based access, while classical connectivity for teleportation is provided by 6GB, TSN, and DetNet networks.

B. 6GB-Enabled Non-Terrestrial QApps

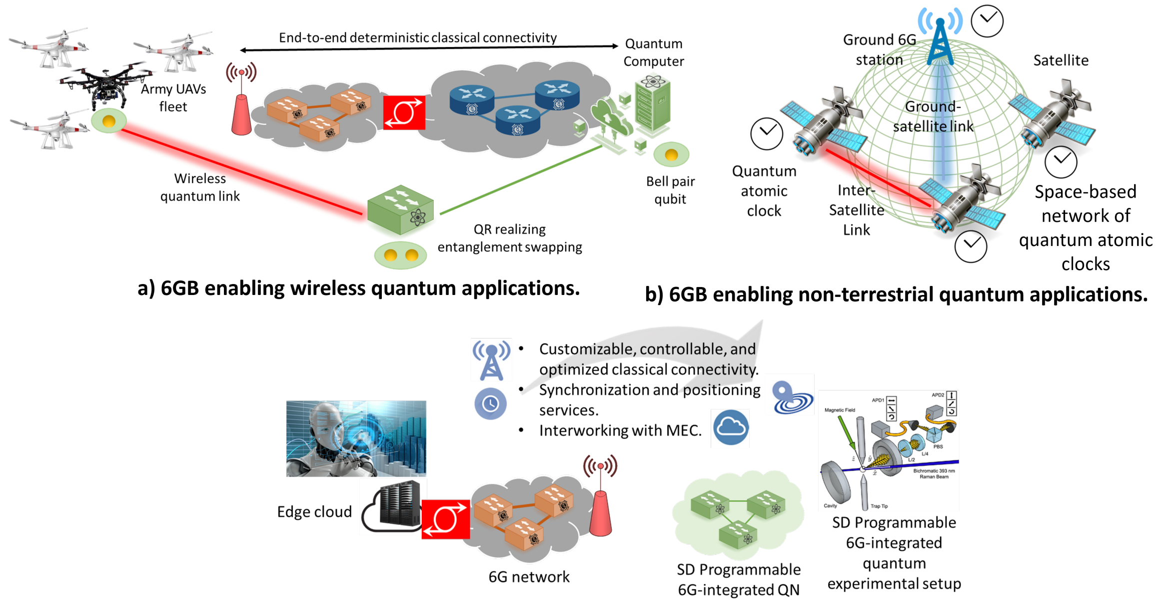
Non-terrestrial QApps are wireless applications that utilize quantum and classical connections in environments beyond Earth's surface, such as space or underwater. To support these applications, widespread wireless classical networks like the envisioned 6GB network play a crucial role. In Release 17, 3GPP's technical specifications already include features for satellite communications, which will be further extended and improved in future releases. Additionally, the integration of high-frequency bands, such as the THz-band (0.1 - 10 THz) and Visible Light Communications (400 - 800 THz), will enhance communication capabilities in these environments [5]. As a result, 6GB is poised to become the natural choice for classical connectivity in non-terrestrial settings.

The use case illustrated in the top right of Fig. 3 is an example of a satellite-based QApp proposed in [2]. It aims to establish an ultra-precise network of quantum atomic clocks, enabling unparalleled levels of synchronization precision. By entangling the atoms of multiple quantum atomic clocks, such as aluminum-based clocks, the application achieves synchronization precision limited only by the fundamental boundaries of quantum metrology. The degree of synchronization precision gained depends on the number of entangled quantum clocks and the number of atoms within them. This application has significant potential to enhance the positioning precision of Global Positioning Systems (GPS), as synchronization accuracy directly influences it. Furthermore, an expanded version of this application could involve the deployment of quantum atomic clocks on Earth, contributing to further improving the synchronization accuracy of GPS systems.

C. 6GB Empowered QNs Intelligence

The adoption of SDN and programmability through open interfaces by QNs in conjunction with the capabilities offered by 6GB can create an advantageous ecosystem for automating their management, operation, and configuration. In Fig. 3, the bottom scenario highlights three key reasons why QNs intelligence can benefit from 6GB:

1) **Synergistic Service Delivery**: 3GPP standards incorporate capabilities that support various service delivery models, opening up business opportunities for collaboration between mobile and QN operators. This facilitates the consumption of 6GB services by QNs. For instance, QNs could utilize a flexible 6GB slice as a service to autonomously create, customize, and control 6GB slices



a) 6GB enabling wireless quantum applications. **b) 6GB enabling non-terrestrial quantum applications.**

c) 6GB-empowered QNs control and management planes.

Fig. 3: Potential 6GB-enabled quantum-based scenarios.

tailored to their classical connectivity requirements for user, control, and management planes.

2) **Edge Computing Integration**: The Multi-Access Edge Computing (MEC) ecosystem combines telecommunications and IT services to offer cloud computing at the edge of RANs [13]. This environment is conducive to the development of AI/ML solutions that can automate various aspects of QNs' intelligence, such as zero-touch path selection or coordination among quantum nodes, in near real-time. Automation is crucial for managing the increasing complexity of quantum technology as it matures, mirroring the evolution of classical networks. Furthermore, leveraging edge computing for quantum research can streamline experimentation by delegating AI tasks like protocol design, deployment, configuration, and execution. This approach accelerates quantum innovation development and optimizes costs by utilizing existing edge computing infrastructures and processes.
3) **Synchronization and Positioning**: 3GPP mobile networks inherently support synchronization among RAN components, a feature essential for functions like Time-Division Duplexing (TDD) operation. This synchronization capability aligns with the requirements of quantum devices, particularly for tasks like particle detection. Additionally, 3GPP networks include the Location Management Function at the control plane, enabling the deployment of precise positioning solutions. Quantum networks can directly benefit from these positioning capabilities, facilitating tasks such as beam alignment, quantum channel modeling for automation, and location-based security.

V. Software-Defined Programmable QNs with 6GB Connectivity

This section introduces an architecture for SD-programmable QNs supporting discussed use cases, as shown in Fig. 4. SDN has been recognized as an ideal candidate for QN control planes [4], [10]. Our architecture's key innovation is the zero-touch service-based QN management plane, a topic receiving limited attention in the literature for generic and QApp-agnostic QNs. It offers:

1) Seamless integration with 6G networks, other classical network technologies, and various QN domains. This enables flexible synchronization and positioning services consumption from 6G, reducing QN complexity. It also simplifies the composition of customized classical connectivity for teleportation across diverse classical network technologies. Additionally, it supports interworking among different QN domains, defined, for example, by vendor technology or administrative zones.
2) QN slicing, allowing autonomous creation and management of multiple virtual QNs, or QN slices, tailored to tenant and QApps needs over a shared QN infrastructure. This facilitates diverse quantum services and multi-tenancy. We outline QN slice creation steps, including 6G connectivity provision for teleportation.

Our proposal primarily focuses on SD QNs control and management plane functionality, excluding aspects like QNs protocol stacks or scalability architectures for entanglement distribution [11], [14]. However, it can complement existing proposals, and vice versa.

A. Architecture

The QED Infrastructure (QEDI) comprises a set of QRs (Qnodes) interconnected through quantum links. Our proposal introduces a novel Qnode architecture, distinguishing it from existing literature. Each Qnode is equipped with a

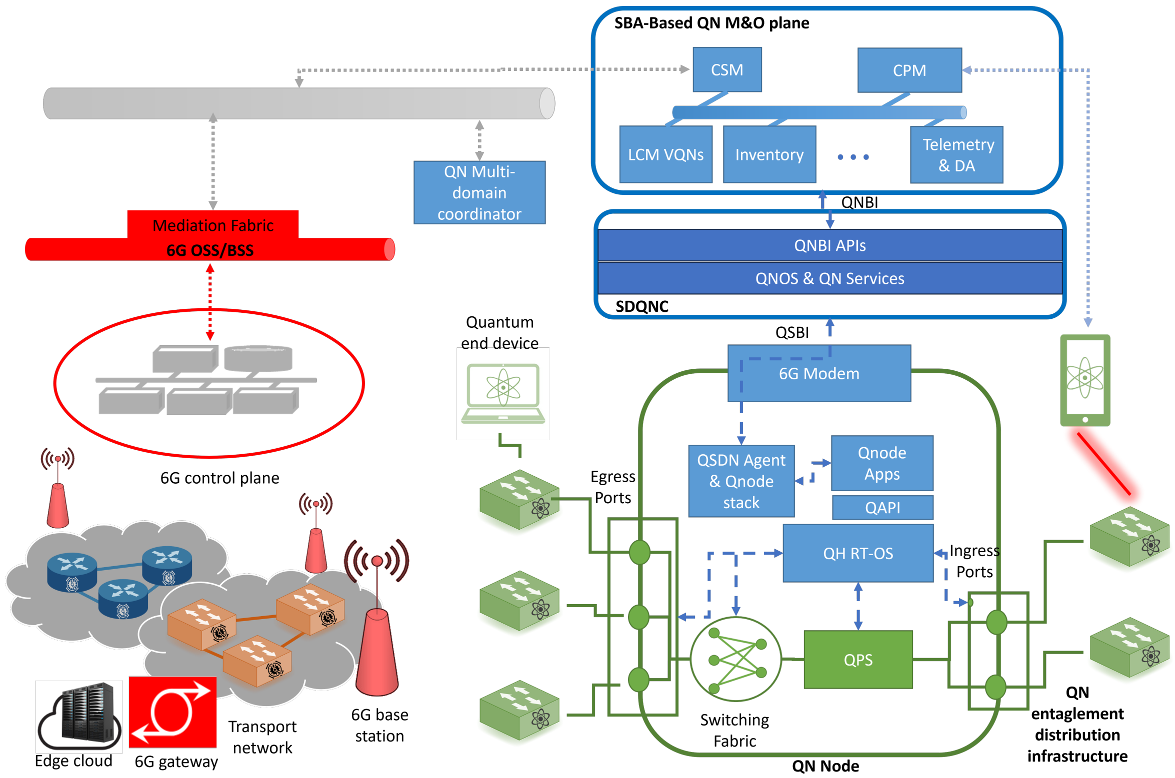


Fig. 4: Software-Defined programmable quantum network leveraging 6GB connectivity, exposure of management, synchronization and positioning services.

real-time Operating System (OS) (labeled as 'QH RT-OS' in Fig. 4), abstracting the underlying hardware to enable the execution of Qnode Apps. These Apps efficiently automate local functions, including entanglement swapping protocols, resource management, monitoring, and event handling, with immediate responsiveness. Furthermore, we consider a Qnode Application Programming Interface (API) to add an extra level of abstraction, simplifying Qnode Apps development and portability. This reduces dependence on specific vendors and technologies while shielding programmers from associated intricacies.

In addition to the Qnode Apps, which may handle some control plane tasks with low-latency, the *QN control plane* is realized by a logically centralized controller called SDQNC. It includes QNOS, which acts as an abstraction layer and provides a set of QN services to upper layers through quantum northbound interface (QNBI) APIs. These APIs hide the complexities of the underlying QN topology and substrate QEDI. The services exposed by SDQNC include high-level Virtual Quantum Networks (VQNs)' Life Cycle Management (LCM) operations, such as QN slices creation, scaling, or deactivation, as well as telemetry and data analytics provisioning. These services can be utilized by business and M&O applications.

The SDQNC communicates with QSDN agents in Qnodes to monitor, configure, control and manage them using quantum southbound interface (QSBI). The QSDN agents' protocol stack could be programmed using a domain-specific language, similar to P4 in classical networks [10], allowing for flexible and customizable packet processing within Qnodes.

The *QN M&O plane* adopts a service-based architecture (SBA) that strikes a favorable balance between microservices-based and software-oriented architectures for cloud-native virtualized functions. It encompasses the necessary functionality for autonomous management and operation of QN slices, including data processing and management, and interfacing with customer and classical network providers. The interfacing functions are realized by the Customer Provision Manager (CPM) and the Classical Services Manager (CSM), respectively.

B. Operation Use Case: QN Slices Creation

Below are the main steps for creating a QN slice integrating QED and classical connectivity with guaranteed QoS among multiple endpoints. For simplicity, we focus on a single QN domain where the entire configuration process is handled by a SDQNC instance, eliminating the need for multi-domain coordination or interactions among SDQNC interfaces. Although we specifically discuss integration with 6GB, this procedure also applies to scenarios involving other classical network technologies.

1) Step 1 (QN Slice Creation Request): The customer issues a quantum communication request to CPM. This request includes the endpoints identifiers and Quality of Service (QoS) requisites for QED and classical communications for teleportation. Potential QoS metrics of interest for QED are:

- *Entanglement Distribution Rate (EDR)*: Average entangled qubits delivered per unit time between endpoints.

Minimum guaranteed EDR may be relevant for stricter QApps.

- *Entanglement Distribution Quality (EDQ)*: Fidelity or degree of similarity between the delivered entangled state and the target ideal one (e.g., $1/\sqrt{2}\cdot(|00\rangle+|11\rangle)$ for Bell pairs).
- *Entanglement Distribution Reliability (EDRel)*: Probability of QN slice success to achieve an effective QED, adhering to EDR and EDQ constraints, during its lifetime.

Upon processing the request, the CPM generates and forwards two requests:

a) One to the CSM, querying end-to-end classical connectivity with the desired QoS profile.
b) Another to the SDQNC, requesting the creation of the QN slice.

2) Step 2 (Classical Connectivity Services Provision): The CSM interacts with the 6GB OSS/BSS to establish the necessary classical communications between the endpoints. The specific interactions may vary depending on the service delivery model and the control and management exposure of 6GB. Handling this composition across different classical networks, such as when dealing with end devices attached to different mobile networks, can increase the complexity for the CSM. In such cases, it must ensure the coherence of the classical connectivity provided by the independent networks, including aspects like packet delay budget distribution. Once the process is completed, the CSM notifies the CPM about the successful provision of the classical connectivity service. Otherwise, the QN slice creation procedure is aborted.

3) Step 3 (QN Slice Composition): Upon receiving a QN slice request, the SDQNC seeks a suitable QEDI configuration meeting QED QoS requirements. Optimization goals may guide this process, like minimizing rejection probabilities for future requests. Then, the SDQNC's decisions might be influenced by anticipated QN slice creation requests based on historical data and predictive analytics. For simplicity, the SDQNC may choose configurations from a catalog including precomputed paths between endpoints and a reduced set of QED QoS profiles for each path. This approach works well for QNs with moderated functionality and scale. However, more powerful tools, like AI/ML or quantum computers (universal or specialized), may be required for configuring fully-functional QEDIs or when more customized and fine-grained configurations are desired. Decisions involved in QN slices composition and configuration are:

- *Path selection*: Choosing reliable paths to connect source-destination endpoints, based on quantum resource availability and potential QED performance.
- *QRs protocols*: Specifying QR operation and coordination with other QRs, including entanglement swapping procedures and quantum error correction techniques.
- *Egress port configurations*: Setting quantum link resources, beam alignment, and particle detection.

4) Step 4 (QN Slice Deployment): When a feasible composition is found, SDQNC populates the configurations among the involved Qnodes through the QSBI. Each SDQN agent processes these messages and interacts with the Qnode control apps to apply the configurations. Once this process is successfully completed, the SDQNC notifies the CPM, which then confirms the QN slices creation to the customer.

VI. Proof-of-Principle

We will now present a proof-of-principle to showcase quantum services might impose stringent delay constraints on classical connectivity.

The proof-of-principle is based on the model in [7] for analyzing quantum protocols with time-constrained quantum states generation. In these protocols, a sender transmits multiple qubits ($s > 1$) before the receiver begins quantum processing. Each qubit transmission follows the teleportation process as described in Section II-B. We assume the sender requests on-demand the distribution of the required Bell pairs [15] and they are consecutively distributed using the same QN path and QRs resources. Minimizing latency is critical for these protocols, as the storage of qubits in the server's memory is susceptible to time-dependent noise. The initial transmitted qubit experiences degradation during storage in the memory. Therefore, the subsequent transmission of Bell pairs, teleportation bits, and the server's quantum processing must all be completed within a time window $w^{(max)}$. This delay budget is primarily determined by the requirements of the QApp, the features of the QN, and the coherence time T of the memory. We adopt the assumptions made in [7], except for assuming immediate classical communication for teleportation assistance. This allows us to assess the impact of classical communication delays on quantum protocols' performance.

The proof-of-principle focuses on the verifiable BQC application. BQC enables a client to delegate a quantum computation task to a server while keeping the data and quantum algorithm confidential, preventing even the server from accessing them. Verifiable BQC enhances trust by including tests, interweaved with normal rounds, to verify the server's honesty. Since a test can fail due to server dishonesty or noise, the client estimates the average test failure probability p_{av} and compares it to a threshold p_{av}^{th} determined by the level of noise. Thus, if $p_{av} > p_{av}^{th}$, the client concludes that server is dishonest and aborts the protocol.

In our evaluation, the client and server are connected through a QR. The client uses two qubits ($s = 2$) as input for executing a quantum algorithm on a server. We define three scenarios, labeled as 'S1', 'S2', and 'S3', with parameters in Table I. These scenarios represent gradual improvements in quantum hardware performance. p is the success probability of distributing a Bell pair between the peers within a time slot τ. p and τ depend on QR technology and operation, the distance between the QR and each peer, the transmission medium, and particle detection technology. Besides the three scenarios, we consider three different values of τ to simulate a representative range of configurations for the QN. The parameters γ and T denote the quantum computation error probability and the coherence time of the server's quantum memory, respectively. Note that p_{av}^{th} is given by:

$$p_{av}^{th} = \frac{2\cdot\gamma - 1}{k\cdot(2\cdot\gamma - 2)} \tag{1}$$

where k is the vertex colouring of the BQC graph [7]. $k = 2$ for all the scenarios.

Figure 5 demonstrates the degradation of BQC application D as the delay d for transmitting teleportation bits increases across different scenarios and τ values. The degradation is quantified using the formula:

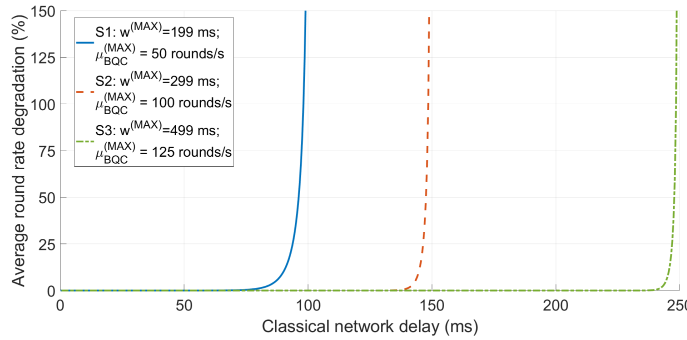
$$D = 100 \cdot \frac{\left(\mu_{BQC}^{(MAX)} - \mu_{BQC}(d)\right)}{\mu_{BQC}^{(MAX)}} \tag{2}$$

Here, $\mu_{BQC}(d)$ represents the estimated BQC rounds rate as a function of d, and $\mu_{BQC}^{(MAX)} = \mu_{BQC}(0)$ is the maximum BQC rounds rate calculated as the inverse of the minimum expected time for one round, considering a fixed p and $w^{(MAX)}$ as given by Eq. (46) in [7]. Classical delay requisites for transmitting teleportation bits and different BQC requirements ($D = 0\%$, $D \leq 3\%$, $D \leq 50\%$, and $D \leq 75\%$) are provided in Table I.

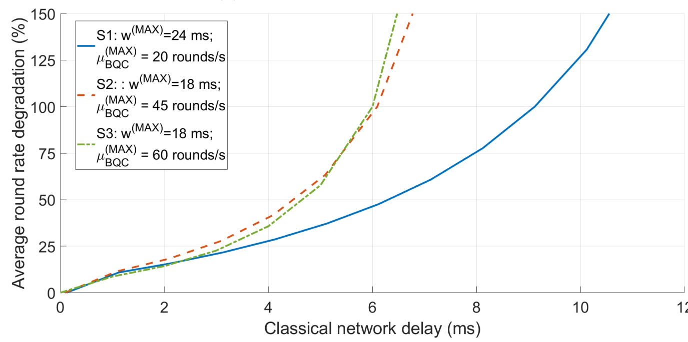
The performance of BQC deteriorates with increasing d, as it reduces the delay budget for the Bell pair distribution. This leads to a decreased success probability for transmitting the second qubit within the given timeframe $w^{(MAX)}$.

Let us consider an example involving three users accessing a BQC service. The quantum setup, which includes the quantum computer and QN, remains consistent across these users, resembling scenario S1 with $\tau = 2$ ms. However, each user employs a different mobile network technology to assist the teleportation process, namely, 6G, 5G with URLLC, and 5G Release 15 networks with respective delays of 500 μs, 1 ms, and 10 ms. In this scenario, the BQC performance degradation will be negligible for the 6G user, approximately 9% for the user on 5G with URLLC, and above 125% for the user on a 5G network (see Fig. 5b).

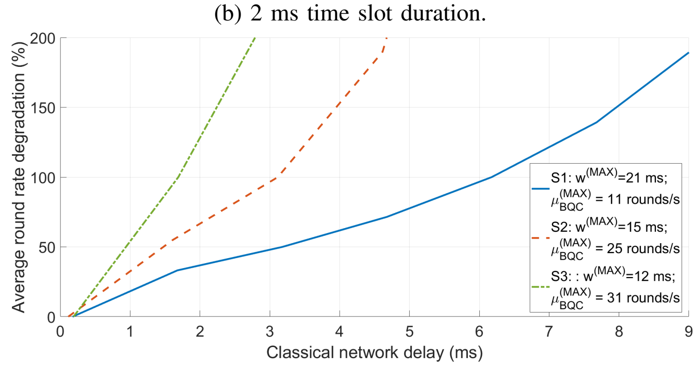
Now, let us consider the same mobile network technologies and classical latencies as mentioned earlier, but this time, we have a quantum setup resembling scenario S3 with $\tau = 3$ ms. In this case, if the BQC service has the requirement of $D \leq 50\%$, only the 6G network could meet this criterion (see Table I).



(a) 1 ms time slot duration.



(b) 2 ms time slot duration.



(c) 3 ms time slot duration.

Fig. 5: Two-qubits blind quantum computing service performance degradation versus the classical network delay to assist the quantum teleportation process.

VII. Conclusion and Outlook

This work explores the potential of 6G and Beyond (6GB) networks in facilitating wireless and ubiquitous quantum applications (QApps) and addressing the classical connectivity requirements of quantum communications. Firstly, we highlight how 6GB can support various quantum scenarios, including wireless and non-terrestrial QApps, as well as QN control and management planes, providing specific examples. Secondly, we propose a software-defined programmable architecture for integrating quantum networks into 6GB and present a high-level protocol for creating and deploying quantum network slices. 6GB can offer synchronization, positioning, low-latency access to computing resources, and customizable connectivity for QN control planes. Lastly, we present a proof-of-principle that underscores the importance of ultra-reliable low-latency connectivity for QApps, with a focus on a blind quantum computing application. Our results suggest QApps might demand stringent deterministic latency on classical communications beyond what 5G can offer.

This preliminary work aims to motivate further research in 6GB support for QNs. First, it is essential to identify a broader range of use cases and classify them based on the demanded QN functionality and performance. In this way, the urgency to address each of them can be assessed as quantum technology development state will primarily determine their feasibility. Second, a comprehensive analysis of these use cases is required to determine their functional and performance requirements across all network layers and planes, including QApp-level, quantum entanglement distribution, and control and management planes. Third, it is important to identify key enabling technologies and capabilities that may need to be incorporated into mobile network standards to address these classical requirements, if necessary.

Lastly, it is important to highlight that our QN architecture,

	Delay budget for classical connectivity (ms)								
	Time slot = 1 ms			Time slot = 2 ms			Time slot = 3 ms		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
$D = 0\%$	0,137	0,500	0,500	0,121	0,093	0,002	0,176	0,115	0,190
$D \leq 3\%$	84,645	142,119	243,551	0,398	0,354	0,349	0,312	0,196	0,235
$D \leq 50\%$	96,206	147,575	247,760	6,303	4,476	4,649	3,179	1,476	0,940
$D \leq 75\%$	97,389	148,125	248,188	7,963	5,411	5,410	4,860	2,279	1,315
Scenarios setup									
Scenario 1 (S1: lowest performance): $p = 0.1$, $\gamma = 0.35$, $T = 200$ ms, $p_{av}^{th} = 0.115$ Scenario 2 (S2: medium performance): $p = 0.2$, $\gamma = 0.2$, $T = 300$ ms, $p_{av}^{th} = 0.188$ Scenario 3 (S3: highest performance): $p = 0.25$, $\gamma = 0.1$, $T = 500$ ms, $p_{av}^{th} = 0.222$									

TABLE I: Delay budget and scenarios configuration.

inspired by software-defined classical networks, serves as an initial blueprint, tailored for QN autonomy and seamless integration with classical technologies. While the QN slice creation use case provides insights into QN slicing, it offers a high-level overview. Thus, further research is needed to delve deeper into QN slicing.

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