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Quantum-Native Architectural Tenets and Philosophy for the Quantum Internet

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Abstract

This document extends RFC 9340 by outlining a set of quantum-native architectural tenets for the design and evolution of the Quantum Internet. These principles should not be interpreted as dogmas but as pragmatic guidelines and criteria for harnessing the unique properties of quantum entanglement within networked systems. Such design perspectives, while departing from the classical Internet, remain aligned with a foundational insight: the principle of constant change, articulated in RFC 1958.

The document specifies quantum-native extensions to the Quantum Internet framework, defining an entanglement packet switching paradigm and an explicit separation between the Quantum Data Plane and Quantum Control Plane. It introduces Quantum Internet Addressing to extend quantum semantics into control and coordination, and generalizes the classical forwarding concept to quantum packets.

Status of This Memo

Note to Readers

This document is not an IETF Standards Track specification; it represents architectural thinking being developed within the IRTF Quantum Internet Research Group (QIRG). It may be further developed, replaced, or obsoleted by future documents.

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1. Introduction

The Quantum Internet interconnects quantum processors, memories, and repeaters to enable distributed quantum functionalities built upon shared entanglement. RFC 9340 laid the initial foundation for such an Internet, defining its motivation and goals. At that time, the role of a distinct Quantum Control Plane (QCP) was explicitly declared out of scope in RFC 9340. This document revisits that open question, by arguing that the control must evolve from classical coordination to quantum-native orchestration and by presenting an architectural framework that makes this separation explicit.

Recent theoretical progress [CalCac25] has underscored the critical importance of revisiting that open question. The stateful, volatile and non-local nature of quantum entanglement implies that purely classical network control cannot maintain global consistency as networks scale, becoming the limiting factor for performance and scalability. Indeed, in a quantum network, local operations at one node can instantaneously affect correlated states at remote nodes, as instance by dynamically reconfiguring which nodes are entangled with each other and thereby altering the network entanglement-based topology. Moreover, stateful metrics such as fidelity, residual coherence time, purification overhead and entanglement-link availability are essential for exploiting already established correlations for end-to-end entanglement distribution. In fact, since entanglement is not information per-se but conversely a non-classical communication resource, its value extends beyond the traditional source--destination paradigm. As entangled states decohere, continuous monitoring and latency control become essential. If left uncoordinated, these entanglement features can trigger the amplification principle [CalCac25], whereby uncontrolled entanglement resources cause routing ambiguities, resource inefficiencies and, ultimately, network instability. In summary, effective tracking and management of entanglement resources are essential prerequisites for scalable quantum network architectures. Building on the above considerations, this document updates and extends the architectural principles defined in [RFC9340], by introducing a set of quantum-native architectural tenets for the design of the Quantum Internet. These tenets should not be intended as dogmas, but as pragmatic guidelines to harness the unique physical properties of quantum entanglement within networked systems. In this sense, the proposed approach echoes the enduring ’’principle of constant change’’ articulated in [RFC1958], reaffirming that adaptability remains the cornerstone of Internet evolution. Specifically, this document introduces a quantum-native control and forwarding architecture composed of the following interlocking components:

* Quantum Data Plane (QDP): the operational plane that carries and manipulates entangled qubits (ebits) for applications, such as teleportation. It generalizes the classical notion of forwarding to the quantum domain through Generalized Quantum Forwarding (GQF).

* Quantum Control Plane (QCP): the entanglement-orchestrator plane that manages entanglement resources throughout their entire life-cycle, by encoding routing decisions into quantum states and by relying on the Entanglement-Defined Controller (EDC) -- a distributed control entity analogous to a Software-Defined Networking (SDN) controller, but operating on entanglement resources to maintain global coherence.

Accordingly, this document defines three core mechanisms -- Quantum Internet Addressing (QA), Generalized Quantum Forwarding (GQF), and Entanglement-Defined Controller (EDC) -- that together form the basis for scalable, entanglement-driven coordination across heterogeneous quantum domains.

2. Scope

This document is Informational. It proposes architectural tenets and guidance for researchers and implementers. It is not a protocol specification. Terminology and notation adhere to monospaced ASCII presentation for clarity in IRTF review contexts.

3. Terminology

This section defines key terms used throughout this document. Some definitions extend those introduced in [RFC9340], reflecting the evolution from classical coordination to quantum-native orchestration.

* Quantum Data Plane (QDP): The QDP is the operational plane of the Quantum Internet that generalizes entanglement forwarding to the quantum domain through GQF. It is responsible for the generation of elementary hop-by-hop entanglement and for the execution of quantum operations, including entanglement swapping and purification.

* Quantum Control Plane (QCP): The entanglement-defined plane responsible for orchestrating entanglement resources by encoding routing decisions into quantum states, and by relying on the Entanglement-Defined Controllers (EDCs).

* Entanglement Service Provider (ESP): Network entity belonging to the Quantum Data Plane that generates, stores, and manipulates entanglement, to provide and maintain entanglement resources for both end-nodes and peer ESPs. ESPs collectively form the ’’entangled-backbone’’.

* Entanglement-Defined Controller (EDC): Logical entity belonging to the Quantum Control Plane that orchestrates entanglement resources, coordinates routing through resource allocation, reconfiguration, and monitoring across ESPs. The EDC maintains a view of the network’ s entanglement states, enabling scalable and adaptive coordination.

* Quantum Internet Addressing (QA): An addressing scheme in which node identifiers are represented as quantum states to scale quantumness into the control plane.

* Generalized Quantum Forwarding (GQF): A forwarding logic that generalizes the classical prefix-matching forwarding to the quantum domain.

The above terminology forms the conceptual foundation of this document. The QDP and QCP represent the two key planes of the architecture. Within these planes, ESPs implement entanglement forwarding and maintenance, while EDCs orchestrate the entanglement resources. QA and GQF provide quantum-native mechanisms for addressing and stateful forwarding.

4. Architectural Overview

This section extends Section 5 of [RFC9340].

The Quantum Internet is an Entanglement-Packet Switching (EPS) network, where entangled qubits (ebits) replace classical packets as the basic network units, carrying quantum correlations across network nodes. The EPS paradigm is not merely an optimization or a refinement of the classical packet-switching paradigm, but a fundamental departure imposed by the unique constraints of quantum mechanics. Indeed, while the goal of the classical packet-switching paradigm is to determine the best next-hops toward a set of nodes (routing) and to forward packets through these next-hops from source to destination, entanglement-packet switching aims to distribute and manipulate entanglement among quantum nodes, ultimately entangling the source and destination regardless of their physical location.

By inheriting statefulness and non-locality, EPS departs from the end-to-end principle [RFC1958], [RFC3439], a key tenet of the classical Internet design, requiring in-network operations and persistent state awareness across all phases of the entanglement life-cycle -- from generation through distribution to storage and final utilization. Combined with the sophisticated and resource-intensive nature of state-of-the-art quantum hardware, this paradigm advocates concentrating the complexity inside the network, while keeping the edges simple. As a consequence, EPS mandates a clear decoupling between QDP, which handles qubit operations, and QCP, which manages entanglement orchestration and routing.

network feature	classical Internet	Quantum Internet
resource persistence	communication links are permanent (topology dynamics largely exceed the forward dynamics)	entanglement is ephemeral and depleted upon use
control plane	populates routing tables with best hops toward (set of) destinations	encodes routing decisions into quantum states; exploiting addressing scheme and orchestrates entanglement resources so that they are
data plane	packet forwarding	generalized quantum forwarding

4.1. Quantum Data Plane (QDP)

The QDP constitutes the operational plane of the Quantum Internet. It provides the substrate on which entanglement-based connectivity -- also referred to as quantum connectivity -- is established and maintained among remote nodes. Within the QDP, network entities exchange and manipulate ebits to establish, extend and refresh quantum correlations across the network.

The QDP supports a set of primitives, such as the generation of elementary hop-by-hop entanglement and the execution of quantum operations, including entanglement swapping and purification [AbaCub25].

Unlike its classical counterpart, the QDP does not act on user information directly (data in the traditional sense), but it operates on entanglement that applications later exploit for (e.g.) teleportation or distributed processing. Each entanglement-link represents a consumable network resource that must be created, maintained, and periodically refreshed as coherence decays.

The QDP interfaces closely with the QCP to expose real-time KPIs and metrics (such as fidelity, coherence time, and link availability). These metrics support adaptive entanglement management and allow the QCP to optimize resource allocation, path selection and recovery procedures. The logical interface between the QCP and QDP may be realized through classical or quantum signaling channels, functioning analogously to the control-to-data interface in software-defined networks [KreRam14]. Detailed protocol specifications are out of scope for this document.

4.2. Quantum Control Plane (QCP)

The QCP is the entanglement-orchestrator plane of the Quantum Internet. It controls the entanglement packet switching logic and maintains a consistent view of entanglement resources across the network.

In this document, the term control plane is adopted from classical networking terminology, where it denotes the network-wide logic that controls packet forwarding among a network’ s SDN-enabled devices, as well as the configuration and management of these devices and their services [KurRos10]. By analogy, the QCP orchestrates the life-cycle of entanglement resources -- from generation to distribution and exploitation. Unlike its classical counterpart, the QCP must account for the stateful and non-local nature of entanglement, while stringent coherence times demand time-aware coordination across the network.

As detailed in Section 1, effective tracking and management of entanglement resources are essential for scalable quantum network architectures. However, if such tracking relies solely on classical control and signaling, the resulting coordination overhead and latency prevent the system from maintaining global consistency, ultimately hindering scalability. Even in classical networks, where entanglement is absent, it has been shown that the number of control messages required per topology change (namely, the updating communication overhead) cannot scale better than linearly on Internet-like topologies [KriCla07]. In the quantum setting, this challenge becomes even more pronounced due to the intrinsic statefulness and fragility of entanglement, and it is further exacerbated when multipartite entanglement is considered [IllCal22].

The QCP coexists with the classical control plane, complementing it rather than replacing it. Architecturally, it forms a distinct yet tightly coupled control logic above the QDP. The QCP interfaces directly with Entanglement Service Providers (ESPs), which expose local entanglement capabilities, while ensuring consistent entanglement resource policies through Entanglement-Defined Controllers (EDCs).

4.3. Hierarchy & EDC

Classical Tenets	Quantum-Native Tenets
Complexity located at the network edges	Complexity concentrated in the core network
Stateless core network	Stateful core network
End-to-end protocol design	Network-mediated protocol design

Building on the above considerations, the network architecture is organized into a two-tier structure, that distinguishes between ESPs and quantum-edge nodes:

* Bottom Tier (tier-1): Edge quantum nodes, including processors, sensors, cryptographic devices. These nodes consume entanglement resources to support quantum applications and connect primarily to nearby ESPs via short-range quantum links.

* Top Tier (tier-2): ESPs form the entanglement-core network, by providing end-to-end entanglement-based connectivity to the lowest tier, via proactive maintenance of entangled resources among each other. The EPSs can be interconnected via long-range quantum

links, such as optical fibers, and they are equipped with the sophisticated and resource-intensive infrastructure required for entanglement generation and distribution.

Overall orchestration is achieved through EDCs, distributed logical entities that maintain coherent global or partial topological views. EDCs act as the quantum-native counterpart of SDN controllers, linking control logic directly to quantum states and enabling state-aware, entanglement-driven routing.

EDCs perform primarily three control-plane functions:

* Reconfiguration: dynamic management and reallocation of entanglement resources among ESPs.

* Monitoring: assessment of fidelity, coherence time, and availability of entanglement resources across ESPs.

* Policy enforcement: application of global policies for routing, resource allocation, and entanglement-loss recovery.

Although EDCs reflect a centralized control logic, the architecture supports multiple, potentially federated controllers. These EDCs coordinate to share partial topological knowledge and enforce consistent entanglement resource policies, while preserving local autonomy and scalability.

5. Quantum Internet Addressing (QA)

The architectural decoupling of the QCP and QDP is a necessary condition for scalability, but it is not sufficient. To manage in-network operations and maintain persistent state awareness required by entanglement, the control plane itself must be designed to embrace quantum principles and phenomena for effectively controlling entanglement dynamics. This requirement follows once again from the non-local nature of quantum entanglement: entanglement proximity cannot be confined to physical distance or restricted to fixed topological neighborhoods. As a result, a control plane, built upon locality and topological-driven addressing such as IP, cannot efficiently track, respond to, or propagate entanglement state changes across the network. A fundamental rethinking of network addressing and control mechanisms is therefore needed to embed quantum behavior directly into the node identifiers, thereby elevating the control plane to a quantum-native level.

Quantum addressing (QA) provides the logical foundation for this quantum-native control model. QA does not replace classical addressing; rather QA complements it by enabling control and forwarding processes to operate directly on quantum states. Hence, each network node is equipped with two types of identifiers: i) a classical address, such as an IP address, required for classical communications and signaling; ii) and a quantum address, represented by a quantum state |A > of a N-qubit system.

Since qubit states can exist in superposition, a sequence of N-qubits can encode a single node identity, i.e., a single quantum network address, or a superposition of node identities, with each state denoting a distinct network address. In this way, a single quantum address can represent a set of quantum nodes, inherently supporting compactness of routing tables.

5.1. Quantum Packet

In the EPS paradigm, packet forwarding does not rely on the physical transmission of qubits but on the manipulation of shared entanglement between nodes. The QA model requires a corresponding quantum packet structure that supports quantum-native forwarding and routing operations.

5.1.1. Quantum Packet Structure

A quantum packet consists of a quantum header and a quantum payload.

* Quantum Header: carries quantum addresses that enable the network nodes to interpret and ''forward'' (in the generalized sense) entanglement packets according to the quantum-routing logic.

* Quantum Payload: carries the entanglement resources |e_i > to be distributed to the destination node(s).

The following ASCII diagram illustrates the conceptual structure of a quantum packet for documentation only. The model is not limited to bipartite entanglement.

```
+----------------------------------+-----------------------------------+
|        Quantum Header            |      Quantum Payload              |
+----------------------------------+-----------------------------------+
|   - Quantum Address |A>          |  - Entangled qubits |e_i>         |
|   - Optional metadata            |   (bipartite or multipartite)     |
+----------------------------------+-----------------------------------+
```

6. Generalized Quantum Forwarding (GQF)

End-to-end entanglement distribution can be logically divided into two distinct phases: routing and forwarding [AbaCub25]. Routing determines the entanglement path, according to the selected routing metric, while forwarding performs the quantum operations on the entangled resources required to sustain quantum connectivity.

In classical networks, the forwarding logic follows a match-and-forward paradigm, where the destination address is extracted from the packet header and matched against the routing table. In the Quantum Internet, this logic is generalized toward entanglement manipulation, enabling forwarding decisions that act directly on quantum states in accordance with quantum-native principles.

6.1. Role within the Architecture

Within the architecture, forwarding operations result from the interaction between the QDP and the QCP, through the EDCs and ESPs:

* QCP populates ESP routing tables and maintains topological information.

* ESP performs the quantum operations required for forwarding based on locally available entanglement resources and policies provided by the QCP.

Forwarding decisions require the capability to operate directly on quantum identifiers. This is enabled by the quantum header in the packet, which carries the quantum equivalent of the source address and destination address.

7. Quantum-Native Principles

This section extends the architectural principles provided in [RFC9340] by introducing a set of quantum-native principles that guide the design and operation of scalable Quantum Internet. These principles reflect the physical properties of entanglement and the architectural requirements arising from entanglement-driven networking:

* Entanglement Packet Switching.
  The network adopts an entanglement-packet switching paradigm, where entangled bits (ebits) serve as the fundamental network units. These “quantum packets” carry quantum correlations across network nodes.

* Explicit Plane Decoupling.
  The architecture explicitly separates the Quantum Data Plane (QDP) from the Quantum Control Plane (QCP). This decoupling is essential for scalability.

* Quantum Addressing.
  The network logic adheres to a quantum-native control model, and Quantum Addressing (QA) provides the logical foundation for it.

* Stateful Core Network, Lightweight Edges.
  The network core -- formed by ESPs -- is inherently stateful. Conversely, edge nodes remain lightweight.

* Entanglement-Aware Metrics.
  Routing and orchestration decisions rely on quantum-aware metrics, such as fidelity, residual coherence time, purification overhead, and entanglement availability.

* Hybrid Control Coexistence.
  The architecture must support the coexistence of classical and quantum control planes.

8. Security Considerations

As an Informational document, this draft does not propose any specific mechanisms to ensure security. The security considerations provided in RFC9340 apply for this document as well.

9. IANA Considerations

This memo includes no requests to IANA.

10. Acknowledgments

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