

Supplement

ITU-T Y Suppl. 98 (11/2025)

SERIES Y: Global information infrastructure, Internet protocol aspects, next-generation networks, Internet of Things and smart cities

Supplements to the Y-series Recommendations

**ITU-T Y.3800-series – Technical considerations
towards quantum networks**



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Supplement 98 to ITU-T Y-series Recommendations

ITU-T Y.3800-series – Technical considerations towards quantum networks

Summary

A quantum network is expected to enable enhanced applications by leveraging fundamental principles of quantum mechanics – such as entanglement, superposition and the no-cloning theorem – which are not achievable using classical (non-quantum) networks, including conventional digital networks.

Supplement 98 to ITU-T Y-series Recommendations aims to identify technical considerations for quantum networks, including relevant components and their configurations. It also introduces potential migration scenarios from quantum key distribution networks (QKDN) towards quantum networks. Furthermore, it outlines a standardization roadmap within ITU-T.

NOTE – ITU-T Supplement 75 "ITU-T Y.3000 series – Quantum key distribution networks – Quantum-enabled future networks" has been published. It focuses on the activity status of studies and research from academia, research institutes and standards development organizations (SDOs). This Supplement 98 introduces more technical aspects which might be required towards quantum networks.

History *

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FOREWORD

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The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

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Supplement 98 to ITU-T Y-series Recommendations

ITU-T Y.3800-series – Technical considerations towards quantum networks

1 Scope

This Supplement aims to introduce the technical considerations towards quantum networks. It provides guidance for standardization work on quantum networks in ITU-T.

In particular, the scope of this Supplement includes:

- Technical considerations for quantum networks;
- Migration scenarios of quantum key distribution networks (QKDN) towards quantum networks;
- Standardization roadmap including technical readiness.

2 References

- [[ITU-T Y.3800](#)] Recommendation ITU-T Y.3800 (2019), *Overview on networks supporting quantum key distribution*.
- [[ITU-T Y.3804](#)] Recommendation ITU-T Y.3804 (2025), *Quantum key distribution networks – Control and management*.
- [[ITU-T Y.3805](#)] Recommendation ITU-T Y.3805 (2021), *Quantum key distribution networks – Software-defined networking control*.
- [[ITU-T Y Suppl. 75](#)] Supplement 75 to ITU-T Y-series Recommendations (2023), *ITU-T Y.3000 series – Quantum key distribution networks – Quantum-enabled future networks*.
- [[ITU-T Y Suppl. 89](#)] Supplement 89 to ITU-T Y-series Recommendation (2025), *ITU-T Y.3800 series – Analysis of synchronization in quantum key distribution networks*.

3 Definitions

3.1 Terms defined elsewhere

This Supplement uses the following terms defined elsewhere:

3.1.1 quantum information technology (QIT) [b-FG QIT4N D1.1]: Refers to the fusion of quantum physics and information technology.

3.1.2 quantum key distribution (QKD) [b-ETSI GR QKD 007]: Procedure or method for generating and distributing symmetrical cryptographic keys with information theoretical security based on quantum information theory.

3.1.3 quantum key distribution network (QKDN) [ITU-T Y.3800]: A network comprised of two or more quantum key distribution (QKD) nodes connected through QKD links.

3.1.4 qubit [b-ETSI GR QKD 007]: Unit of quantum information, described by a state vector in a two-level quantum mechanical system, which is formally equivalent to a two-dimensional vector space over the complex numbers.

3.2 Terms defined in this Supplement

This Supplement defines the following terms:

3.2.1 entanglement purification: A quantum protocol for obtaining a smaller number of high-fidelity entangled states from a larger number of low-fidelity states through local operations and classical communication.

3.2.2 entanglement swapping: A quantum process that establishes entanglement between two particles that have not interacted directly, by performing a joint measurement involving intermediate entangled particles.

3.2.3 quantum computer: Physical devices for high-speed mathematical and logical operations, storage and processing of quantum information in accordance with the laws of quantum mechanics.

NOTE – Definition based on [b-FG QIT4N D1.1].

3.2.4 quantum entanglement: In quantum mechanics, because the properties of each particle have been integrated into a whole, it is impossible to describe the properties of each particle individually

NOTE – Definition based on [b-FG QIT4N D1.1].

3.2.5 quantum fidelity: A measure that quantifies the degree of similarity between two quantum states or the accuracy of an actual quantum state compared with an ideal one.

3.2.6 quantum network: An entangled-qubits assisted network enabled by quantum information technologies that provides quantum communication capabilities.

3.2.7 quantum repeater: A quantum network node that allows for long-distance transmission of quantum information by using entanglement swapping.

3.2.8 quantum router: A quantum network node that connects multiple quantum networks and directs quantum information between them, based on their identifiers and/or addresses.

3.2.9 quantum state: A set of quantum representations is used to represent the motion state of a microscopic particle in quantum mechanics.

NOTE – Definition based on [b-FG QIT4N D1.1].

3.2.10 quantum superposition: The smallest unit that exhibits the properties of a substance or physical quantity.

NOTE – Definition based on [b-FG QIT4N D1.1].

3.2.11 quantum switch: A quantum network node that connects multiple quantum network components (quantum end devices and quantum network nodes) and facilitates the efficient transmission of quantum information between them.

4 Abbreviations and acronyms

This Supplement uses the following abbreviations and acronyms:

B-ISDN	Broadband-Integrated Service Digital Network
EID	Entanglement Identifier
FCAPS	Fault, Configuration, Accounting, Performance and Security
FMF	Few-Mode Fibres
HD-QKD	High Dimensional – Quantum Key Distribution
IoT	Internet of Things
IP	Internet Protocol
IT-secured	Information Theoretically secured
MDI-QKD	Measurement Device Independent – Quantum Key Distribution
MCF	Multi-Core Fibres
MMF	Multi-Mode Fibres

NGN	Next Generation Network
OSI	Open Systems Interconnection
OTP	One-Time Password
QKD	Quantum Key Distribution
QKDN	Quantum Key Distribution Network
QIT	Quantum Information Technology
QoE	Quality of Experience
QoS	Quality of Service
SDN	Software Defined Networking
SDO	Standards Development Organization
SMF	Single-Mode Fibres
SSC&C	Smart Sustainable Cities and Communities
TDM	Time Division Multiplexing
TF-QKD	Twin Field – Quantum Key Distribution
TRL	Technology Readiness Level

5 Introduction

A quantum network is an entangled-qubits assisted network enabled by quantum information technologies between quantum end devices and quantum network nodes. Figure 1 shows a conceptual configuration of a quantum network. The quantum end devices refer to quantum key distribution (QKD) modules, quantum sensors, quantum computers, etc. which host user applications. On the other hand, quantum network nodes are expected to be quantum repeaters, quantum switches and quantum routers incorporated with quantum memories, quantum entanglement sources and quantum entanglement distributors.

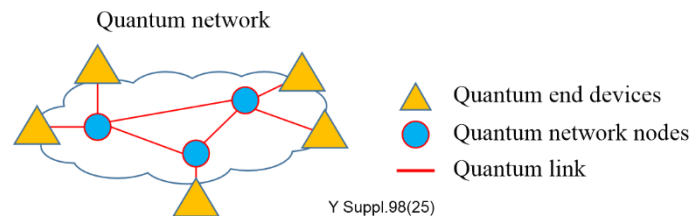


Figure 1 – Conceptual configuration of a quantum network

Due to the collapse of a quantum state's superposition when a qubit's state is measured in a network node, a direct reading of the quantum state is impossible. Just copying a qubit without measurement can be considered, but that is not possible in quantum mechanics, nor is cloning.

Considering the above understanding of quantum physics, the conventional 'store and forward' process in network nodes is not possible in quantum networks. The delivery of control information (e.g., signalling protocols) to engage/disengage an end-to-end quantum state connectivity should be collaborated with conventional digital networks. Figure 2 shows the basic concept of a combined quantum network with a conventional digital network for this purpose.

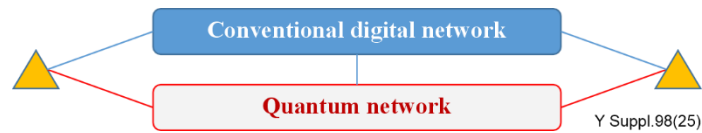


Figure 2 – Combined quantum network with conventional digital network

The QKD module is one of the quantum end devices in a quantum network. In [ITU-T Y.3800], the intermediate QKD node is assumed to be secure against intrusion and attacks by any unauthorized parties. However, the QKD node is not information theoretically secured (IT-secured) and is assumed as the trusted node.

In a quantum network, information is retained in quantum form at the intermediate nodes, ensuring its protection at the QKD node as well as in transit in the quantum channels between nodes. A quantum network works by distributing entanglement between a series of intermediate stations placed along the link. Theoretically, such an approach represents the ideal solution to distribute keys over long distances, as the intermediate stations do not need to be trusted.

Quantum entanglement is a key resource for quantum networks. Entanglement is a phenomenon in quantum mechanics where two or more particles become correlated in such a way that the state of one particle cannot be described independently of the state of the other, no matter the distance between them. This correlation persists, even if the particles are separated by vast distances, instantaneously affecting the state of the other, which Albert Einstein famously referred to as "spooky action at a distance".

Quantum networks distribute quantum information to enable functions that are impossible on classical networks. Key to these applications is the sharing of entanglement between many users over large distances, allowing quantum key distribution and quantum-enhanced sensing. While entanglement distribution has been demonstrated over short distances, long-distance quantum networking is hampered by the exponential loss of photons in optical fibres. Quantum repeaters can overcome this problem by forming chains of entangled nodes.

Scaling to large quantum communication networks further requires the generation of multi-qubit entanglement, entanglement swapping, entanglement purification, qubit storage and so on.

6 Technical considerations of quantum end devices

NOTE – Quantum end devices play crucial roles in quantum networks. They serve as endpoints or terminals in quantum networks and are responsible for various tasks related to the transmission and reception of quantum information.

6.1 QKD module

A QKD module is connected to a quantum network, acting as a quantum end device in which a cryptographic key is generated.

QKD can be accomplished through diverse kinds of protocols, and realizing entanglement-based QKD across long-haul optical fibre connections is developing, especially over deployed fibre networks. The QKDNs with trusted nodes based on the prepare-and-measure protocol have been obtaining a definitive popularization. Based on realistic security, QKDNs with trusted nodes have gradually begun to evolve into QKDNs without trusted nodes in recent years. Measurement-device-independent QKD (MDI-QKD) and the twin-field QKD (TF-QKD) are immune to the attacks on measurement devices. Currently, for the QKD without trusted nodes via optical fibre channels, the transmission distance between two nodes can reach the thousand-kilometre magnitude. In addition, high-dimensional QKD (HD-QKD) can effectively increase the key transmission bandwidth and enhance the anti-noise ability, which can be considered as a technical approach.

In the quantum network, information is retained in quantum form at quantum network nodes (quantum repeater, quantum switch, quantum router, etc.) ensuring its protection at the quantum node as well as in transit in the quantum links between quantum nodes.

A quantum network node (i.e., quantum repeater) works by distributing entanglement between a series of intermediate nodes placed along the link. Theoretically, such an approach represents the ideal solution to distribute keys over long distances, as the intermediate quantum nodes do not need to be trusted, differing from the QKD network.

6.2 Quantum sensors

A quantum sensor is a quantum end device utilizing properties of quantum mechanics, such as quantum entanglement, quantum interference and quantum state squeezing, which have optimized precision and surpass current limits in classical sensor technology.

Quantum sensors, which are highly sensitive to external disturbances, can detect and measure a variety of physical phenomena (e.g., time, gravity, temperature, pressure, rotation, acceleration, frequency, and magnetic and electric fields). A group of distributed quantum sensors, if connected by a quantum network, can further enhance the estimation of a single continuous parameter.

6.3 Quantum computers

A quantum computer is a type of computer whose computations take advantage of the quantum physics, such as quantum superposition, quantum interference and quantum entanglement.

The computational capability of a quantum computer is limited by the number of qubits and the topological complexity of the computer. It is known that connecting a number of quantum computers through a quantum network will yield greater computing capability than the direct sum of the computing abilities of individual computers.

7 Technical considerations of quantum network nodes and quantum links

7.1 Quantum repeaters

A quantum repeater is a component used to extend the range of quantum communication and quantum networks by enabling entanglement to be distributed over long distances.

The standard paradigm for a quantum repeater consists of many basic technologies, such as entanglement swapping, entanglement purification, quantum memory and so on.

- Entanglement swapping, which is a core component of quantum networks and an important platform for testing the foundation of quantum mechanics, can enable the entangling of two independent particles without direct interaction, both in discrete variable and continuous variable systems. Quantum repeaters use entanglement swapping at intermediate nodes along the communication channel. These nodes perform the entanglement-swapping operation to create new entangled pairs and extend the range of entanglement.
- Entanglement purification provides a method to alleviate these nonidealities, by distilling impure states into higher-fidelity entangled states. When entangled states suffer from errors during transmission, entanglement purification processes can be employed at intermediate nodes of a quantum repeater system to enhance the quality of entanglement.
NOTE – The relevant parameters for the quality of entanglement are for further study.
- Quantum memory is a component designed to store and retrieve quantum information, crucial for certain quantum computing and communication applications. It is used to temporarily store entangled quantum states, allowing for the synchronization of entanglement generation and the preservation of quantum information during transmission. Quantum repeaters can be built with either quantum memory or with the help of exotic quantum states such as graph

states. In other words, quantum repeaters can be built with two approaches, namely, non-quantum memory-based approach and quantum memory-based approach.

7.1.1 Non-quantum memory-based approach

In this approach, an all-optical quantum repeater eliminates the need for matter quantum memories. An all-photon quantum repeater is used to leverage the properties of photons to preserve and extend quantum entanglement across the communication channels.

NOTE – The characteristics and configuration for the corresponding communication channels are for further study.

7.1.2 Quantum memory-based approach

In this approach, quantum memory is a key component of the quantum repeater. Quantum memory allows for the temporary storage and retrieval of entangled quantum states during the entanglement-swapping process, which is fundamental to the operation of quantum repeaters. Besides that, quantum memory helps preserve the coherence of entangled states over longer distances by temporarily storing the quantum information. It mitigates the effects of signal loss and decoherence, allowing for the extension of entanglement.

7.2 Quantum switches

A quantum switch is a quantum network node that connects multiple quantum network components (such as quantum end devices, quantum computers, quantum sensors and QKD modules, including other quantum network nodes, quantum repeaters, quantum switches and quantum routers) and facilitates the efficient transmission of quantum information between them. It operates primarily at the data link layer (layer 2) of the Open Systems Interconnection (OSI) model and sometimes at the network layer (layer 3), depending on its functionality.

NOTE 1 – Quantum switching is a quantum process that creates a coherent control between different unitary operations, which is often described as a quantum process which transforms a pair of unitary operations into a controlled unitary operation.

NOTE 2 – A layered model of quantum networks to identify the role and functions of quantum switches is for further study.

7.2.1 Entanglement swapping-based circuit-oriented switching

Entanglement swapping-based circuit-oriented quantum communication leverages the process of entanglement swapping, to establish stable quantum circuits between distant nodes without direct physical connections. This involves performing a Bell-state measurement on intermediate entangled particles to create entanglement between the target quantum network nodes and quantum end devices, enabling scalable and flexible quantum networks. Integrated with quantum switches, this approach allows dynamic reconfiguration of quantum connectivity, to adapt to network demands while optimizing resource usage. To ensure reliability, fidelity enhancement techniques such as entanglement purification are applied. These techniques address challenges like decoherence, noise and the need for precise synchronization.

This method is vital for applications like QKD, quantum repeaters and distributed quantum computing, forming a foundation for robust and scalable quantum networks.

7.3 Quantum routers

A quantum router is a quantum network node that connects multiple quantum networks and directs quantum information between them based on their identifiers and/or addresses. It operates primarily at the network layer (layer 3) of the OSI model. A quantum router determines the optimal path for forwarding and/or distributing quantum information across complex network topologies, including across quantum Internet.

NOTE 1 – Correct routing of a signal from its source to the destination is necessary in a complex network architecture, for both classical and quantum networks. Classical routers allow the transmission of signal information which is directed by control information in a classical network. It is known from classical networks that the impossibility of perfect cloning prevents multi-directional broadcast in a quantum network. Hence, quantum routing needs more elaborate protocols, as in contrast to classical routing, any arbitrary quantum information cannot be perfectly cloned.

NOTE 2 – In summary, while both quantum switches and quantum routers are essential for quantum network connectivity, the switches manage quantum information within a network and the routers manage quantum information between networks, enabling scalable and secure communication across distributed quantum networks.

NOTE 3 – A layered model of quantum networks to identify the role and functions of quantum routers is for further study.

7.3.1 Time division multiplexing-based qubits delivery (packet-oriented)

Time division multiplexing (TDM)-based qubits delivery is an approach that applies TDM to quantum networks, enabling efficient scheduling and routing of qubits in a packet-oriented manner. Each qubit or quantum packet is assigned a specific time slot, allowing multiple communication sessions to share the same quantum channel without interference. A quantum packet typically includes the qubit payload and classical metadata, such as routing instructions, transmitted via classical channels. Accurate synchronization between nodes ensures proper time slot allocation, while buffering in quantum memory manages contention and delays. This approach improves resource efficiency, minimizes crosstalk and enhances scalability, particularly in hybrid classical-quantum networks. Relevant technologies, such as synchronization complexity, noise, decoherence and the need for high-fidelity quantum memory, are also involved in this approach.

TDM-based qubit delivery is particularly suited for applications like QKD, distributed quantum computing and hybrid network integration, offering a pathway to efficient and scalable quantum communication.

7.4 Quantum links

A quantum link is a component that enables quantum-state connectivity between quantum network components, such as quantum end devices and quantum network nodes.

NOTE – A quantum link enables the transmission of qubits through space and/or time and is essential for quantum networks. It distributes entangled qubits between quantum nodes and end devices. Three main types are used: optical fibre, free-space and underwater channels. Optical fibre encompasses single-mode fibres (SMF), multi-core fibres (MCF), few-mode fibres (FMF) and multi-mode fibres (MMF), providing stable and cost-efficient transmission while supporting advanced technologies such as high-dimensional quantum communication. Free-space channels include the space links and atmospheric/terrestrial links, which enable satellite-based quantum networks and wireless quantum networks, overcoming fibre distance limits and supporting global coverage. Underwater channels, despite challenges like attenuation and noise, enable secure communication in specific maritime applications.

8 Other technical considerations for quantum networks

8.1 The role of conventional digital networks

Quantum networks cannot transmit information and data solely by means of quantum states. Therefore, the integration with conventional digital networks is essential.

In this context, the role of the conventional digital network refers to the use of classical communication and computing functions to support the operation of a quantum network without directly carrying quantum states.

For example, the conventional digital network can be used to exchange classical control messages for service set-up, to distribute time and frequency references for synchronization, and to coordinate

resource management between different network domains. It must be recognized that the conventional digital network complements the quantum plane and does not replace it, and that classical addressing and signalling remain mandatory for any quantum communication protocol, while quantum identifiers are applied for coherent quantum-state operations.

The roles of conventional digital networks in the operation of quantum networks may include the following:

- **Control and signalling:** Conventional link is required to exchange signalling information for entanglement distribution, quantum repeater/switch/router operations, and path set-up.
- **Error correction and feedback:** Conventional communication supports the exchange of management data and error detection/correction which are essential for quantum network protocols.
- **Synchronization and timing:** High-precision synchronization and clock distribution are able to be provided through conventional digital networks to enable reliable qubit transmission.
NOTE – The synchronization of quantum signals in the quantum layer of QKDN is introduced in [ITU-T Y Suppl. 89].
- **Management and orchestration:** The conventional digital network supports fault, configuration, account, performance and security (FCAPS)-based management and orchestration. In particular, software-defined networking (SDN)-based control, management and orchestration functions are implemented over the conventional digital network.
- **Application integration:** The conventional digital network is essential for applying quantum network services (e.g., symmetric keys generated by QKD) to higher-layer applications for encryption.

8.2 Control and management

8.2.1 Common control of QKDN and quantum network

Several approaches can be considered regarding the convergence of control protocols between QKDN and quantum networks. Leveraging existing QKDN-related standards provides a pragmatic migration path, minimizing the need to design an entirely new control framework.

In this regard, common control of QKDN and quantum networks refers to the coordination of QKDN and general-purpose quantum networking segments through a unified set of control functions and procedures under a single service policy.

For example, such common control can allow a quantum service request to specify target entanglement rate, fidelity, set-up time and coherence constraints, and then trigger coordinated resource allocation and routing across multiple domains that may include both trusted-relay and non-trusted segments. It must be understood that common control does not replace technology-specific mechanisms but, rather, harmonizes signalling, scheduling and telemetry conveyed over the conventional digital network, so that heterogeneous quantum infrastructures can interoperate coherently.

These approaches are summarized as follows:

- **Unified control layer/plane approach:** This approach facilitates forward compatibility, where experience gained (such as FCAPS functionalities) from QKDN operations can be directly extended to quantum networks.
- **Extension of existing QKDN control functions:** Existing control and management functions which are specified in [ITU-T Y.3804] can be extended to quantum networks.
- **Reuse of SDN-based control on QKDN:** Integration with SDN-based control and orchestration for multi-vendor and multi-domain environments which are introduced in [ITU-T Y.3805] can be reused to quantum networks.

8.3 Addressing

Quantum addressing as the quantum equivalent of the univocal network addressing provided by IP, and its consequences on routing within the quantum network is a mandatory prerequisite for any network functionality design. For example, quantumness can be exploited for enabling quantum networks to perform different tasks and to address other devices in a coherent fashion through control quantum registers. It must be noted that quantum addressing is not envisioned as a substitute for classical addressing. Indeed, a classical address is needed at the quantum network nodes for classical communication and classical signalling which are mandatory for any quantum communication protocol.

Several possible approaches for quantum network addressing which may be considered are as follows:

- **Classical identifiers with entanglement identifiers (EIDs):** In early deployments, a dual addressing scheme can be applied, where conventional digital network nodes or port identifiers are used for signalling and management, while EIDs are introduced for monitoring entangled pairs and their quality parameters. This pragmatic approach ensures compatibility with existing digital infrastructures.
- **Entanglement-aware addressing:** Resource-centric addressing can be considered, in which the addressing and routing functions directly reflect the availability and state of entanglement resources. This approach allows entanglement swapping to create remote overlay links and enhances scalability.
- **Hybrid interworking mechanisms:** During the migration stage, hybrid mechanisms can be introduced in which quantum-specific addresses coexist with classical identifiers. This ensures gradual interoperability between QKDN and entanglement-based quantum networks.

9 Migration scenario of QKDN towards quantum networks

In the early stage of quantum communication (including QKDN), sequential single qubits transmission was mainly considered. Differing from this technology, entangled qubits distribution is introduced for end-to-end connectivity of quantum states in quantum networks.

How to migrate towards fully quantum networking should be studied.

9.1 Trusted relaying, measurement-assisted relaying and fully quantum networking

[ITU-T Y.3800] concludes the following:

- **Trusted relaying:** In this scheme, keys are stored in QKD nodes (trusted nodes) and relayed to other distant QKD nodes via highly secure encryption, with one-time password (OTP) recommended. Currently, this is the only known solution widely adopted for long-range QKD fibre networks. The QKD node (trusted node) is assumed to be secure against intrusion and attacks by any unauthorized parties.
- **Measurement-assisted relaying:** MDI-QKD and TF-QKD are techniques for extending the range of QKD links, thereby allowing keys to be generated over longer distances or over channels with higher loss. MDI-QKD and TF-QKD utilize an intermediate measurement station in the link which does not need to be located in a guarded location and whose operation does not need to be trusted (in contrast to the situation for trusted relaying).
- **Fully quantum networking:** In the fully quantum network, information is retained in quantum form at the intermediate nodes, ensuring its protection at the node as well as in transit in the quantum channels between nodes. A quantum repeater works by distributing entanglement between a series of intermediate stations placed along the link. Theoretically, such an approach represents the ideal solution to distribute keys over long distances, as the intermediate stations do not need to be trusted.

9.2 Migration scenario towards quantum networks

[ITU-T Y.3800] specifies a layered model of QKDN, including the quantum layer, key management layer, QKDN control layer, QKDN management layer and service layer.

To evolve into a quantum network, enhancements are required. In particular, the present QKD-oriented layered model does not address entanglement-based transmission, quantum repeating/switching/routing, or reliable quantum information transport. Furthermore, transport and network functions are absent, limiting scalability with a quantum network. An evolved model would therefore extend the layered model of [ITU-T Y.3800] into a multi-layer quantum network comprising physical, link, network, transport, application layers, etc. This includes quantum error correction and quantum repeating at the link layer, entanglement-based switching and routing at the network layer, reliable quantum information delivery at the transport layer, and expanded quantum applications, such as quantum cloud services and quantum security, at the application layer.

It should be noted that, just as quantum computers will not surpass classical computers for every computational task, quantum networks will not supplant conventional digital networks. Instead, they open prospects for innovative communication and processing, expanding the capabilities of conventional digital networking to enable the transmission of quantum information. By analogy with current transmission infrastructures, requirements for different levels of networks – such as backbone, metropolitan and access networks – should also be considered, and migration tasks for different stages should be defined accordingly.

In conclusion, the [ITU-T Y.3800] layered model is well suited as a transitional framework, maintaining compatibility with conventional digital networks (i.e., IP-based networks) while supporting QKD services. However, to enable the quantum network, additional layers and functions, such as error correction, transport reliability and entanglement-based networking, should be incorporated, together with staged migration strategies aligned with deployment environments.

10 Standardization roadmap including technical readiness

10.1 Assessing standardization readiness for quantum networks

The Focus Group on quantum information technology for information networks concluded that (2021-11): "Standardization readiness should be assessed. There are many kinds of standards, developed by a diverse ecosystem of standards development organizations (SDOs), that support different phases of technology and market development. It is important to assess the maturity of the underlying science and business drivers before initiating and promoting specific standards for specific quantum technologies. Just as TRLs provide a tool for assessing the maturity of a given technology, SRLs are being envisioned to determine when a given technology/market would benefit from standardization, and which kind of standard is implied. International standards are under development for a small subset of quantum technologies. Standardization activity is underway in areas including terminology, quantum-safe cryptography, quantum key distribution, quantum random number generation, use cases and architecture. Additionally, SDOs are creating white papers to assess the landscape and identify eventual standardization needs".

The Technology Readiness Level (TRL) framework is a well-established method for assessing the maturity of a particular technology. In the context of quantum networks, TRLs can be used to gauge the development stage of various components and subsystems, from basic research and proof of concept to deployment and operational use.

- TRL 1-3 (Basic research and proof of concept): At this stage, fundamental principles of quantum networking are explored. Key activities include theoretical studies and experimental validations of concepts such as quantum entanglement and basic quantum communication protocols. These efforts typically involve small-scale laboratory experiments to establish the feasibility of the core ideas.

- TRL 4-6 (Technology development and demonstration): In these stages, the focus shifts to developing and refining prototype systems. Quantum network components, such as quantum repeaters, entanglement swapping mechanisms and initial QKD systems, are built and tested. Demonstrations are conducted in controlled environments such as laboratories, or through limited real-world trials, to validate the technology's functionality and performance.
- TRL 7-8 (System integration and testing): As quantum network technologies mature, they are integrated into larger systems and extensive testing is conducted in operational environments. This phase involves deploying quantum technologies such as QKD across existing communication infrastructures, testing the scalability and interoperability of quantum nodes, and evaluating the performance of the network in real-world scenarios.
- TRL 9 (Full deployment and operation): At the highest level of readiness, quantum network technologies are fully operational and integrated into existing communication infrastructures. This stage involves widespread deployment, continuous operation and ongoing maintenance. Upgrades are implemented as new advancements in quantum technology emerge, ensuring the network remains state-of-the-art.

The application of the TRL framework to quantum networks helps standardize the approach to technology development, ensuring a structured path from research to commercial deployment. By aligning development efforts with the TRL stages, stakeholders can better coordinate their activities, identify potential challenges and streamline the transition from experimental research to practical, market-ready solutions.

QKD and its networking technologies have attracted a lot of interest in multiple SDOs, e.g., ITU-T, ISO/IEC JTC1, IEEE, IETF and ETSI. The status of QKDN standardization in different SDOs is summarized in the following.

ITU-T was the first SDO to standardize QKD as a network. In July 2018, ITU-T SG13 initiated the first work item (i.e., ITU-T Y.3800) on QKD and first brought in the concept of QKDN. Since then, there have been more than 40 work items conducted by four different groups in ITU-T, under the umbrella of QKDN, which can be divided into four branches as follows:

- Study Group 13 (Q16/13 and Q6/13): focus on network aspects of QKDN.
- Study Group 17 (Q15/17, formerly Q4/17): focus on security aspect of QKDN.
- Study Group 11 (Q2/11): focus on QKDN high-layer protocols and signalling.
- Focus Group on quantum information technology for networks (FG-QIT4N): to study the implications of quantum information technologies (QITs) for both quantum and ICT networks.

10.2 Standardization roadmap in ITU-T

Based on the identifications for quantum end devices and quantum nodes in clauses 6 and 7, Figure 3 shows a possible configuration of an (entanglement-assisted) quantum network.

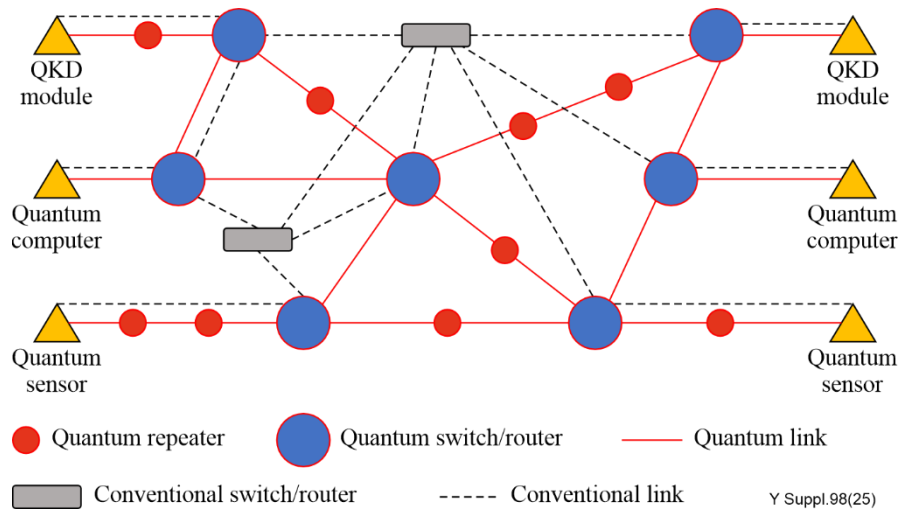


Figure 3 – Possible configuration of a quantum network

Conventional networking technologies which have been standardized in ITU-T, such as broadband-integrated service digital networks (B-ISDN), Internet protocol (IP)–based networks, next generation networks (NGNs) and QKDN, have developed by first identifying a layered model and defining the corresponding interfaces and functions. This approach has enabled in-depth research and development across relevant areas, facilitated the participation of experts across the technologies and improved clarity in protocol development.

Therefore, standardization of quantum networking should also begin with the development of a layered model to support the design, configuration, control, operation and maintenance of quantum networks. Subsequently, in accordance with ITU-T WSA Resolution 2, standardization efforts should be expanded based on the mandates of each Study Group as follows.

- **SG 2 (Operational aspects):** Focused on standardization for operational aspects of quantum networking, including numbering, naming, addressing and identification of a quantum network and its components, quantum end devices and quantum nodes.
- **SG11 (Protocols, testing and combating):** Responsible for developing signalling protocols, procedures and test specifications for quantum networks, including the interfaces and protocol stacks that integrate classical and quantum aspects.
- **SG12 (Performance, QoS and QoE):** The expert group responsible for the development of ITU-T Recommendations on performance, quality of service (QoS) and quality of experience (QoE) for quantum networking and quantum computing. This work spans the full spectrum of quantum end devices, quantum nodes, quantum networks/computers and services.
- **SG13 (Future networks):** Lead Study Group on network architectures for quantum networking. Tasks include the functional requirements, architectures, layered models, network management frameworks and interworking of quantum networks.
- **SG15 (Transport, access and home):** Focused on transport (optical and free-space/satellite media, quantum repeater and quantum memory) and synchronization aspects of quantum networking, including quantum-classical hybrid transport, timing and synchronization mechanisms.
- **SG17 (Security):** Responsible for developing security frameworks and threat models relevant to quantum networking, including secure quantum key distribution, authentication mechanisms, and integration with post-quantum cryptography.
- **SG20 (Internet of things (IoT), digital twins and smart sustainable cities and communities):** Responsible for the development of standards, guidelines, reports,

methodologies and best practices for quantum sensing and quantum networking in cities and communities.

- **TSAG (Telecommunication Standardization Advisory Group):** Coordinates inter-SG collaboration and ensures consistency across the standardization efforts related to quantum networking.

The standardization roadmap of quantum networks in ITU-T can be derived from the above understanding and considered as described in Figure 4.

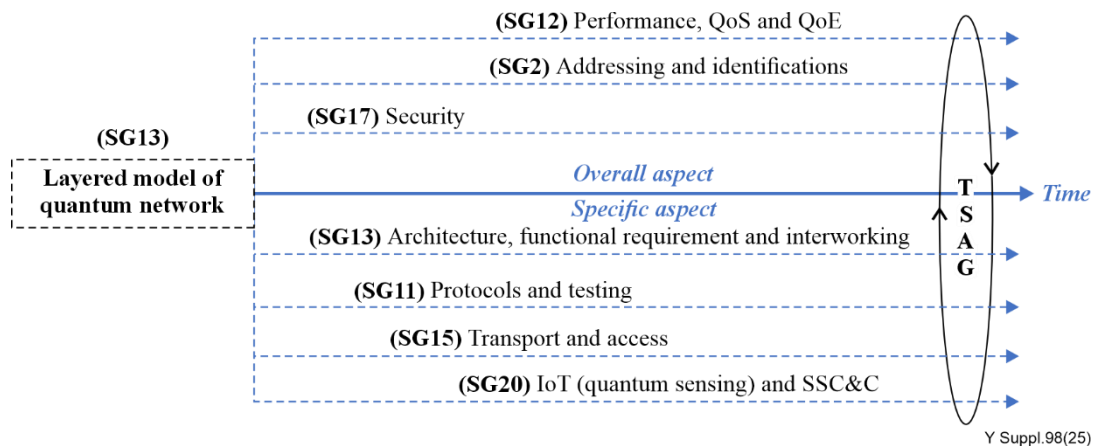


Figure 4 – Standardization roadmap for quantum networks in ITU-T

10.3 Implications for Study Group 13

10.3.1 Implication from the migration perspective

Considering that existing ITU-T Y.38xx-series Recommendations are focused on single photon transmission and its associated networking technologies with a layered QKDN model (see [ITU-T Y.3800]), how entangled qubits-based networking technologies can be introduced in cooperation with current QKD network-related recommendations should be developed, in terms of the migration towards fully quantum networking including relevant aspects such as architecture, functions, intermediate node (i.e., quantum network node rather than trusted node), network control and management and their corresponding functional requirements, etc.

Furthermore, the migration approach should leverage existing QKDN capabilities and include considerations for an efficient transition path.

10.3.2 Implication from new applications' perspective

Based on the capability derived from quantum physics, quantum networks are expected to provide significantly more enhanced levels of security, computation and precision than classical networks. Those new quantum applications should be considered to develop quantum network-related recommendations specifying architecture, functions, interworking, QoS, network control and management, etc.

In addition, research should be conducted on the novel capabilities enabled by quantum end devices and network nodes, such as quantum sensing, quantum computing, quantum repeating and quantum switching, among others.

10.3.3 Layered model for quantum networks

Both the standardization roadmap for quantum networks and the identified implications within ITU-T SG13 highlight the importance and urgency of establishing a layered model for quantum networks. A well-defined layered model, reflecting both the migration approach and new application-driven approaches, must be developed as a priority. This foundational framework will serve as a critical reference to ensure that the long-term standardization efforts on quantum networks within ITU-T proceed in a coherent and well-aligned direction.

Appendix I

Fundamental technologies for entanglement-assisted quantum networks

This Supplement describes technology considerations focusing on networking aspects for quantum networks. However, it is necessary to understand detailed quantum-oriented, in particular entanglement-related, technical aspects required for implementing these considerations. The following content introduces the fundamental technologies and their descriptions for this purpose.

I.1 Quantum state and qubits

A quantum state is a mathematical quantity used to describe the probability distribution for each possible measurement outcome of a quantum system.

A quantum state is a mathematical representation of a quantum system that defines the probabilities of all possible measurement outcomes. Qubits, the fundamental units of quantum information, exist in superposition states that combine classical "0" and "1" states. These states are physically realized using systems such as photon polarization, superconducting circuits or trapped ions. Mixed states, which account for environmental interactions, are described using density matrices. The preservation and manipulation of quantum states form the basis for quantum networking applications.

I.2 Quantum entanglement

Quantum entanglement is a phenomenon where two or more particles exhibit correlated properties that persist regardless of physical separation. These non-classical correlations enable protocols like quantum teleportation and secure communication. Entanglement types include bipartite (e.g., Bell pairs) and multipartite (e.g., multi-qubit GHZ states). Experimental verification relies on violating Bell inequalities which distinguish quantum correlations from classical ones. Entanglement distribution is a critical capability for scalable quantum networks.

I.3 Quantum decoherence and fidelity

Decoherence refers to the degradation of quantum states due to interactions with the environment, such as thermal noise or photon loss. This process erodes superposition and entanglement, limiting the operational lifetime of quantum information. Fidelity quantifies the accuracy of quantum state preservation or transmission, with high-fidelity operations requiring error suppression techniques like quantum error correction and dynamical decoupling. Mitigating decoherence is essential for practical quantum networking.

I.4 Entanglement preparation and distribution

Entangled states are generated using methods like spontaneous parametric down-conversion (for photon pairs) or quantum dots (for solid-state systems). Distribution relies on optical fibres or free-space links, with photon loss and polarization drift posing significant challenges. Satellite-based distribution has demonstrated long-distance entanglement sharing, while integrated photonics aims to improve scalability. Efficient entanglement distribution is foundational for interconnecting quantum network nodes across quantum links.

I.5 Quantum teleportation

Quantum teleportation enables the transfer of unknown quantum states between distant nodes, using pre-shared entanglement. The process involves joint measurements on the target state and a local entangled qubit, followed by classical communication of results, to enable state reconstruction at the receiver. This protocol avoids direct transmission of fragile quantum states, making it a cornerstone for quantum networking.

I.6 Entanglement purification

Entanglement purification protocols enhance the quality of imperfect entangled pairs by discarding low-fidelity states through iterative filtering. Techniques involve bilateral quantum operations and classical communication to distil high-fidelity entanglement from noisy resources. This process is vital for overcoming losses and errors in realistic quantum channels.

I.7 Quantum error correction

Quantum error correction protects logical qubits from errors using redundant encoding across physical qubits. Surface codes, for example, encode information in topological arrangements of qubits, enabling error detection and correction through periodic measurements. Achieving fault-tolerant operation requires physical error rates below critical thresholds – a key milestone for large-scale quantum networks.

I.8 Entanglement swapping

Entanglement swapping extends entanglement across multiple nodes by performing measurements on intermediate qubits. This technique allows end-to-end entanglement establishment without direct physical interaction between distant quantum network nodes. It underpins quantum repeater/switch/router architectures, enabling long-distance quantum networking by linking shorter entangled segments.

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