International Telecommunication Union

ITU-T Technical Report

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

(24 November 2021)

ITU-T Focus Group on Quantum Information Technology for Networks (FG QIT4N)

FG QIT4N D2.2

Quantum information technology for networks use cases: Quantum key distribution network

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications, information and communication technologies (ICTs). The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

Quantum information technology (QIT) is a class of emerging technology that improves information processing capability by harnessing principles of quantum mechanics which is expected to have a profound impact to ICT networks.

The ITU Telecommunication Standardization Advisory Group established the ITU-T Focus Group on Quantum Information Technology for Networks (FG QIT4N) in September 2019 to provide a collaborative platform to study the pre-standardization aspects of QITs for ICT networks.

The procedures for establishment of focus groups are defined in Recommendation ITU-T A.7.

Deliverables of focus groups can take the form of technical reports, specifications, etc., and aim to provide material for consideration by the parent group in its standardization activities. Deliverables of focus groups are not ITU-T Recommendations.

FG QIT4N concluded and adopted all its Deliverables as technical reports on 24 November 2021.

Number	**Title**
FG QIT4N D1.1	QIT4N terminology: Network aspects of QITs
FG QIT4N D1.2	QIT4N use cases: Network aspects of QITs
FG QIT4N D1.4	Standardization outlook and technology maturity: Network aspects of QITs
FG QIT4N D2.1	QIT4N terminology: QKDN
FG QIT4N D2.2	QIT4N use cases: QKDN
FG QIT4N D2.3	QKDN protocols: Quantum layer
FG QIT4N D2.3	QKDN protocols: Key management layer, QKDN control layer and QKDN management layer
FG QIT4N D2.4	QKDN transport technologies
FG QIT4N D2.5	QKDN standardization outlook and technology maturity

The FG QIT4N Deliverables are available on the ITU webpage, at https://www.itu.int/en/ITU-T/focusgroups/qit4n/Pages/default.aspx.

For more information about FG QIT4N and its deliverables, please contact tsbfgqit4n@itu.int.

Technical Report FG QIT4N D2.2

Quantum information technology for networks use cases: Quantum key distribution network

Summary

This Technical Report is a deliverable of the ITU-T Focus Group on Quantum Information Technology for Networks (FG QIT4N). It consolidates the QKDN use cases gathered during the lifetime of the ITU-T FG QIT4N.

The QKDN uses cases are classified into 6 classes and the report highlights the competitive advantage of the use cases brought by QKDN and provides suggestions for future standardization efforts.

Note

This is an informative ITU-T publication. Mandatory provisions, such as those found in ITU-T Recommendations, are outside the scope of this publication. This publication should only be referenced bibliographically in ITU-T Recommendations.

Keywords

QKDN; Quantum key distribution network; Use cases.

Disclaimer

The editors have reviewed use cases that were submitted to FG QIT4N. The inclusion of use cases does not imply any endorsement of or judgment on the quality or applicability of the mentioned use cases.

Sample projects, reference articles, specific companies, products or services mentioned in this report are only for the purposes of technical analysis of the use cases. Their mention does not imply that the use cases and their technical aspects are endorsed or recommended by ITU, ITU's Secretariat, the Focus Group or the editors of this report, in preference to others of a similar nature that are not mentioned.

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Acknowledgments

The editors express their appreciation to all the contributors of this report and all participants of Working Group 2 of the Focus Group on Quantum Information Technology for Networks (FG QIT4N) for their invaluable inputs, thorough review and all comments provided during the development of this report.

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Technical Report ITU-T FG QIT4N D2.2

Quantum information technology for networks use cases: Quantum key distribution network

1 Scope

This Technical Report reviews use cases of quantum key distribution (QKD) network technologies. In particular, the scope of this report includes:

- Competitive advantage brought by QKDN
- Overview of QKDN use cases
- Collected QKDN use cases categorized into 6 classes
- Suggestions for future works

2 References

[ITU-T Y.3800] Recommendation ITU-T Y.3800 (2019), *Overview on networks supporting quantum key distribution*.

3 Terms and definitions

3.1 Terms defined elsewhere

This Technical Report uses QKDN related terms in [b-QIT4N D2.1] and the following term defined elsewhere:

3.1.1 DRKey [b-SCION]: A symmetric cryptographic keys derived on the fly by routers from a single local secret key using a pseudorandom function in SCION architecture.

4 Abbreviations and acronyms

This Technical Report uses the following abbreviations and acronyms:

AAA	Authentication, Authorization and Accounting
AKA	Authentication and Key Agreement (AKA)
AS	Autonomous System
DRKey	Dynamically Re-creatable Key
EAP	Extensible Authentication Protocol
ECC	Elliptic Curve Cryptography
OTP	One-Time Pad
PFS	Perfect Forward Security
PKC	Public Key Cryptography
PRF	PseudoRandom Function
QIT4N	Quantum Information Technology for Networks
QKD	Quantum Key Distribution
QKDN	QKD Network
QSSE	Quantum Secure Symmetrical Encryption

RSA	Rivest-Shamir-Adleman
SCION	Scalable, Control and Isolation on Next-Generation Networks
SCMP	SCION Control Message Protocol
SMC	Secure Multi-party Computation
UC	Universally Composable
UE	User Equipment

5 Introduction

This Technical Report identifies foreseeable, near-term use cases of QKDN technologies gathered during the life of the ITU-T Focus Group on Quantum Information Technology for Networks (FG QIT4N). It lists and presents descriptive information about each of the 21 use cases – for those applications and services based on QKDN technologies. These use cases were submitted by individuals within organizations from around the world and FG QIT4N only considered those use cases that had reached at least a demonstratable, proof-of-concept stage.

The report first introduces the potential competitive advantage brought by QKDN to various applications and services. Then, it categorizes the 21 collected QKDN use cases into 6 classes and provides an overview of each use case. Finally, it summarizes key findings, provides suggestions for further standardization and industrialization and offers a repository of all collected use cases in Appendix I.

The aims of this document are to:

a) assist technology-oriented decision makers in identifying future opportunities arising from recent advances in QKDN technologies,

b) support exchange information and best practices through peer learning and knowledge dissemination processes, and

c) identify possible standardization requirements and policy intervention.

6 The competitive advantage of using QKDN

Through QKD, the two parties of communication can realize secure symmetric key agreement based on the transmission and processing of quantum states. Moreover, any eavesdropping behaviour will be discovered in time due to the disturbance of the quantum state.

QKD is different from conventional key distribution based on computational complexity because its information theoretical security is based on the principles of quantum mechanics. As long as an adversary does not violate the principles of quantum physics, even if they were to have a computer with arbitrary computing power such as a quantum computer, the security of QKD will not be affected.

Depending on the combination of QKD and conventional cryptography, the application of quantum secure communication can have multiple implementations, e.g.:

- Combining QKD with an encryption scheme (such as OTP algorithm) and an authentication scheme (such as Universal-2 hash algorithm) providing information theoretic security, a quantum secure communication system with information theoretic security can be realized.
- The combination of QKD, encryption schemes and authentication schemes that are resistant to quantum computing attacks can realize a quantum secure communication system that can resist quantum computing attacks.

As a supplementary component of cryptography, QKD has rich application scenarios. For example, it can be combined with various existing information and communication protocols at different TCP/IP layers and can also serve various industrial application scenarios to meet the highest security requirements such as providing long-term security guarantees and countering quantum computing attacks.

QKDN has the following competitive advantages:

1) Quantum computing resistance: The threats posed by quantum computing have a wide range of impacts to various security protocols and applications based on conventional asymmetric and symmetric cryptography algorithms. As the security of these algorithms relies on the computing complexity to resolve certain difficult mathematical problems, quantum computing based on quantum algorithms such as Shor's or Grover's algorithm can effectively solves these mathematical problems. As studied in [b-ETSI GR QSC 006], conventional asymmetric algorithms based on RSA and ECC would be completely broken by Shor's algorithm. For symmetric algorithms, Grover's algorithm effectively halves the key size for these algorithms. Compared with conventional computation-complexity-based cryptography, QKD can be considered as one of the means to combat quantum computing threats by replacing traditional key exchange mechanisms.

2) Perfect forward security (PFS): Conventional symmetric cryptography, which is vastly applied in mobile networks (including 2G/3G/4G/5G), and Kerberos-based enterprise systems usually rely on the pre-shared root keys and exchange of random numbers to refresh the session keys. It is not easy to change the root keys. For example, the root key for a mobile phone stored in the SIM card cannot be changed during the entire lifecycle. Once the root key is revealed, all the historical data can be decrypted. Compared to conventional symmetric cryptography, QKD systems can guarantee PFS since the keys are continuously refreshed and can thus only be used once. Even if some keys are revealed, the security of the entirety of historical data cannot be breached.

NOTE – PFS can also be achieved via asymmetric cryptography, however, conventional asymmetric cryptography may encounter the threat from quantum computing attack.

3) High performance key generation: Most internet security applications including HTTPS, software update, VPN, email and blockchain, etc. are based on asymmetric cryptography, also called public key cryptography (PKC). Quantum-computing-resistant PKC, also called post-quantum cryptography (PQC), is under rapid development and standardization. Certain asymmetric cryptography can also provide PFS, however, asymmetric cryptography which relies on specific hard mathematical problems usually require high overhead for computing power and processing delay. Compared to asymmetric cryptography, QKD, as the key exchange method based on quantum physics means, can provide high throughput and low latency key generation which can be one attractive option for applications which require high performance, e.g., certain time-sensitive services.

7 Overview of QKDN use cases

As key distribution is one of the fundamental cryptographic primitives, QKD has very rich application scenarios which can be classified according to various perspectives, as shown in Figure 7-1.

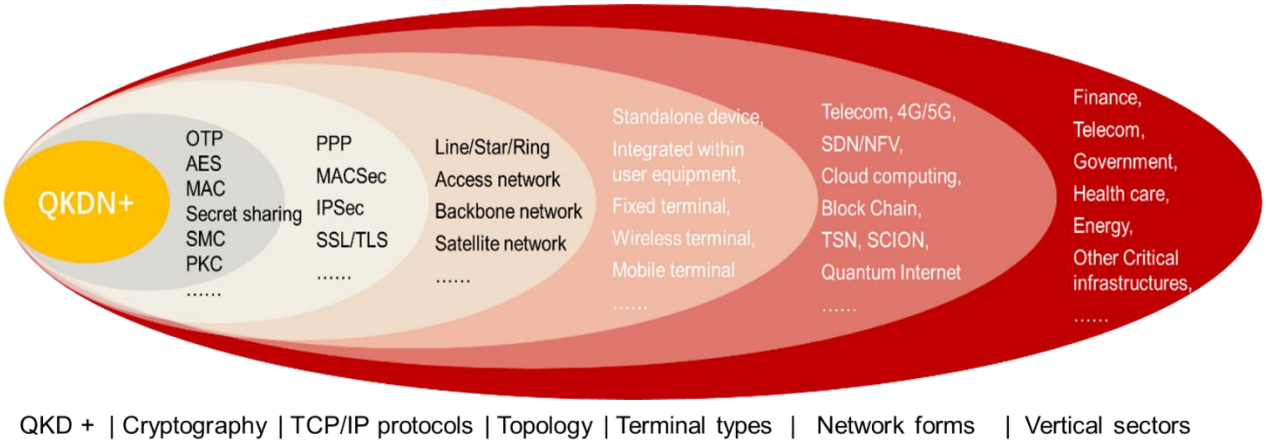


Figure 7-1 – QKDN use cases overview

In this Report, the collected QKDN use cases are classified into the following six use case classes (UCCs):

1) UCC1: QKD combined with other cryptographic primitives

- **Encryption**: QKD can be combined with either OTP or AES to perform symmetric encryption;
- **Message authentication**: QKD can be combined with other authentication primitives to perform message authentication function, e.g., universal-II hash functions, symmetric key based message authentication code (MAC);
- **Secret sharing**: QKD can be combined with Shamir's secret sharing algorithm to perform secure storage function;
- **Secure multi-party computation (SMC)**: QKD raw key can be used to implement oblivious key transfer to perform SMC;
- **Public key cryptography (PKC)**: QKD can be combined with PKC including PQC to provide hybrid security guarantee.

2) UCC2: QKD integrated with various TCP/IP protocols

QKD can be integrated with TCP/IP protocols at various layers, e.g., PPP and MACSec protocol at MAC layer, IPSec protocol at network layer, TLS protocol at transport layer.

3) UCC3: QKDN deployed in various network topologies

QKDN can be deployed with various network topologies connected via either fibre or free-space channels, e.g., line or ring or star topology, fibre-based metropolitan access network, fibre-based inter-city backbone network, free-space satellite-ground or inter-satellite network.

4) UCC4: QKD with different user device categories

QKD can be applied in different terminal types with different integration level, e.g.,

- Fixed user device connected to a standalone QKD module;
- Fixed user device which integrates QKD module as an internal component;
- Wireless user device which consumes offline keys provided by QKDN;

- Wireless user device which integrates QKD module to consume online keys provided by QKDN.

5) UCC5: QKD integrated in various network forms

QKD can be integrated in various ICT network forms which require high security guarantee, e.g., 4G/5G, SDN/NFV-based, cloud computing, blockchain, TSN, service chain and other future network evolutions, e.g., SCION, quantum internet.

6) UCC6: QKD applied in different vertical sectors

QKD can be applied in various vertical sectors which require high level and long-term security, e.g., finance, government, health care, energy, telecom, critical infrastructure.

8 UCC1: QKD combined with other cryptographic primitives

As QKD has the important property of being universally composable (UC) [b-Renner], it implies that QKD can be composed with other UC protocols, resulting in a composed protocol that is also UC. Some examples are listed as below:

- One-time pad (OTP) encryption is the only encryption scheme for which information-theoretic security can be proven. It is thus natural to combine it with QKD. As a consequence, when keys established by QKD are used to perform OTP encryption, the resulting protocol is an unconditionally secure message transmission protocol [b-Alléaume].
- Another frequent use case is QKD combined with a symmetric encryption scheme such as AES. This combination is the one that is currently adopted by existing commercial QKD vendors. It provides a practical solution to realize point-to-point link encryption applications with frequent key exchange.
- QKD can also be integrated with message authentication primitives, as reported in the SECOQC network, which combines QKD with an efficient implementation of universal-2 hashing authentication [b-ETSI GS QKD 002].

In addition, QKD has the potential to be integrated with other cryptographic schemes to provide various security enhancement solutions, as detailed in the following use case descriptions.

8.1 UC-1-1: QKD combined with secret sharing

8.1.1 Use case description

UC-1-1 describes a distributed cloud archive for long term storage of digital data with advanced security and privacy guarantees.

QKD links, as well as other technical and cryptographic means, ensure that data can be securely transported to the involved cloud providers while its integrity and confidentiality remain protected against the storage providers, other tenants of the involved storage clouds and any other non-entitled third parties.

The data is distributed among several cloud storage providers in a way that it remains available even when some cloud providers are not reachable (the minimum number of required cloud providers depends on the employed configuration).

The end user may at any time decide to exchange one cloud provider for another, without any consent or action required from the cloud provider, in a way that no exploitable information remains at the cloud provider.

8.1.2 Problem statement

Specific data with the highest confidentiality and integrity requirements cannot be stored and archived in external public cloud services or even private cloud services without being encrypted and integrity protected. The same is also true for the data transport to and from a cloud storage. The use of encryption in a long-term storage scenario requires safeguarding of cryptographic keys for long periods of time to keep the data accessible. Furthermore, to verify that the archive can still be decrypted and the data accessed, the entire archive needs to be downloaded and decrypted.

Even if a state-of-the-art encryption primitive is used, an adversary may, sometime in the future when advanced decryption capabilities become available, be capable of accessing the plaintext.

The use of external storage providers leads to further problems; a storage provider may not be online when the data needs to be accessed, or the storage provider ceases service, or for some reason loses the data. Further problems may arise with public storage providers; the extraction of all stored data from one storage provider and the secure (i.e., complete) deletion of data when moving from one provider to another "vendor lock-in".

8.1.3 Solution

The solution is to use a cloud archive with advanced privacy and security guarantees, based on a secret sharing primitive, and secure the data links to the single storage providers with QKD links.

The secret sharing cryptographic primitive (e.g., Shamir secret sharing) allows the data to be split into multiple shares which are given to different storage providers. The secret sharing primitive has the advantage that one single share does not contain exploitable information on the original data. A minimum number of shares, the threshold, is required to access the information. The threshold (e.g., 3 out of 5 shares) can be arbitrarily selected by the data owner. Together with QKD secured transport links, such a system yields a keyless cryptographic solution with highest security and availability guarantees. Furthermore, specific protocols can remotely verify that the single storage providers have intact shares and thus the integrity of the stored data can be verified without having to download all shares and recombine them.

In a long-term scenario, single shares can be invalidated and be replaced with new shares, potentially at another cloud provider, thus solving the 'vendor lock-in' and secure deletion issues.

8.1.4 Benefits and impact

The use case counters some of the most severe threats in current cloud solutions and provides a distributed cloud archive with advanced data availability as well as provable long-term confidentiality and integrity guarantees.

End users receive a distributed storage solution with highest confidentiality, integrity and availability guarantees. End users may select the parameters of the secret sharing scheme (i.e., the number of shares and the threshold) as well as the storage location of the shares in private and/or public clouds according to their particular security requirements and the assumed threat level.

The secure cloud archive tolerates the loss of single shares (availability) and enables effective revocation and deletion of shares from storage providers.

Note the security statement: The secret sharing primitive exhibits perfect secrecy, i.e., the observation of a number of shares less than the selected threshold provides exact zero information about the plaintext. Nevertheless, the security can only be guaranteed under the assumption that no number of storage providers greater or equal to the threshold collude against the end users – so that an attacker may get into the possession of enough shares to reconstruct the data (non-collusion assumption). That particular risk can be reduced if less shares than the threshold are stored in public clouds with the remaining shares being stored in private clouds of the end user.

The transport of the shares from the end user to the storage providers is secured with the perfect secrecy of OTP encryption, using ε-secure keys from a QKD link.

8.1.5 Economic considerations

The secure cloud archive requires a number of dedicated QKD link encryptors according to the number of shares selected for the secret sharing scheme. Furthermore, suitable infrastructure (direct optical links) is required between the end user and all storage providers.

The threshold scheme produces a storage and transportation overhead (in a 5-share configuration a 5-fold overhead). The maximum storage (and retrieval) rate depends on the capacity of the least performant QKD link.

For data with highest confidentiality, integrity, and availability requirements, the cost of such a system seems to be acceptable.

8.1.6 Stakeholders (Actors)/Domains

Individuals and organisations looking for an improved storage solution in the cloud with advanced security and privacy guarantees.

8.2 UC-1-2: QKD combined with secure multiparty computation (SMC)

8.2.1 Use case description

UC-1-2 consists of a service which enables quantum secure multiparty computation to perform private recognition of composite signals. The generation and distribution of quantum oblivious keys are the basis of this novel service. The quantum oblivious keys are generated from the raw keys of a QKD system.

For the sake of simplicity, only two entities, **A** and **B**, which are in possession of two private sequences, x_A and x_B are considered. **A** and **B** want to perform a composite signal analysis using x_A and x_B over a public database, such as a protein or genome DNA sequence database, **P**. A possible situation where the service is useful is the following: **A** and **B** want to know if both sequence x_A and x_B appear in the public sequence **P** within a certain distance but they do not want to reveal their own sequences (x_A and x_B). For this purpose, **A** and **B** need to evaluate a function to perform this analysis, but this function will operate with encrypted inputs, $\tilde{x}_A$ and $\tilde{x}_B$ and generate encrypted outputs, $\tilde{y}_A$ and $\tilde{y}_B$. Both entities will be equipped with an encoder/decoder able to generate, $\tilde{x}_A$ from x_A and y_A from $\tilde{y}_A$, respectively, and the same for entity **B**, see Figure 8-1.

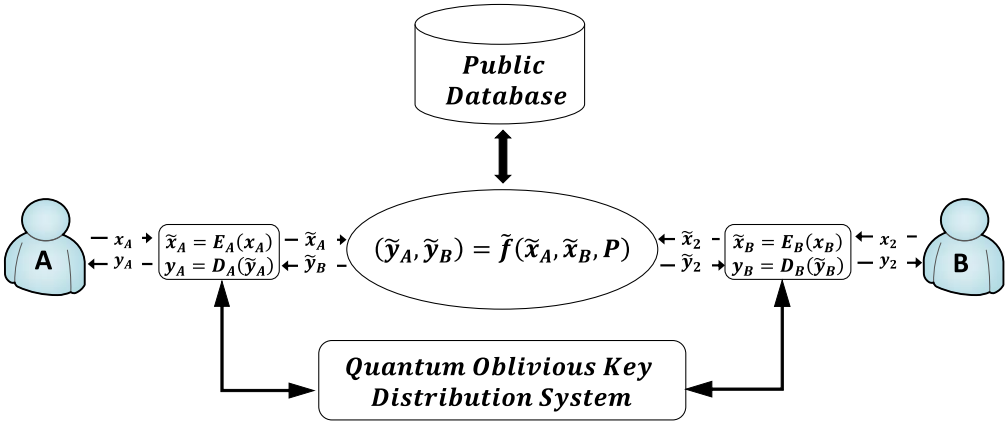


Figure 8-1 – Schema of the use case quantum enabled private recognition of composite signals

8.2.2 Problem statement

Genomic information in clinical practice is gaining traction since it makes genomic medicine possible. For this new sort of medicine, genome sequence alignment is a crucial tool in the study of new diseases, viruses and drug development as well as for the development of predictive and personalized medicine. However, the process of genome sequencing and signal identification in proteins and DNA is resource-intensive, both in terms of time and capital. These signals must be validated against noise. This poses a very significant problem in the field since most of them are considerably complex because they have multiple components where each component is found by different companies/researchers. On top of that, each player in the healthcare system and drug industry collects data typically stored in private databases. Due to privacy preserving laws and commercial reasons, these databases cannot be disclosed. Indeed, the amount and wealth of information stored in a database of a certain company greatly defines how competitive it can be in terms of developing new drugs for new diseases in a useful time.

8.2.3 Solution

The proposed service allows different competitors to share information without compromising privacy or their own profits. It is based on a garbled circuit secure multiparty computation protocol. The key element of the secure multiparty computation service is the oblivious transfer protocol. The oblivious transfer protocol is implemented based on quantum generated oblivious keys. Oblivious keys are cryptographic keys in which the parties only share half of the keys. These keys are generated in a procedure similar to the generation of symmetric cryptographic keys in such a way that, for each measurement, a commitment is performed and during basis reconciliation and error correction there is no leak to the other party about the half of the key that should be maintained oblivious. The commitments are based on classical hash functions which are assumed to be practically secure even against a quantum computer attack.

The service is a proof of concept with two competitors, **A** and **B**. Both entities have access to the raw keys of a QKD system and possess a potential component of a composite signal. With the service, the two entities can cooperate to validate their findings without leaking any sensitive information. Indeed, it allows a joint private pattern recognition of the union of their signals on public genome or protein data without revealing the content of their private patterns. This quantum enabled privacy-preserving system is going to be tested in the Madrid quantum network.

In this field trial, quantum systems from different providers are planned to be included to show that the present maturity of quantum technologies can leverage the surge of new services to end users very soon.

8.2.4 Benefits and impact

Secure multiparty computation has the potential to be a disruptive technique in the realm of data analysis and computation applied to the health sector as it enables cooperation between parties, preserving the privacy of their inputs. This is particularly important for health data, not only because of potential privacy problems with personal data, but also to preserve intellectual properties rights, a key issue in genomic medicine.

Virtually all secure multiparty computation protocols are based on some sort of oblivious transfer and their security and efficiency rely on the oblivious transfer security and efficiency. Oblivious transfer protocols based on quantum technologies have already been proposed, and despite the huge difference in terms of technological maturity, it is already clear the gains that quantum-based approaches can bring in terms of security and efficiency. Note that quantum technology is still in its infancy whereas classical based approaches have decades of development.

The advantages in terms of security of quantum-based solutions rely on the fact that classical oblivious transfer solutions require some sort of public-key distribution-like scheme, usually based on the discrete logarithm problem. Thus, classical based implementations rely on the assumption that

the receiver has limited computational power and is not able to compute the discrete logarithm of a random number in a useful time. It is usually believed that this is true if the attacker is restricted to the use of classical computers and large enough prime numbers are used. However, it is also known that this is not true anymore if the attacker has access to a quantum computer. Indeed, in 1995, Peter Shor published a quantum algorithm that can solve both prime factorization and discrete logarithm problems in polynomial-time. Researchers have been addressing this vulnerability following two different paths:

1) development of new classical public-key distribution protocols resistant to Shor's algorithm, this is known as post-quantum cryptography; and

2) development of protocols that make use of quantum technology.

The first approach is based on mathematical problems whose difficulty is unproven, as is the case for the discrete logarithm problem, and has just survived a few years of scrutiny, unlike the discrete logarithm problem which had been scrutinized for decades. The quantum-based approach has the potential to offer a solution without any computational assumption which makes it robust against quantum computer attacks and to "intercept now-decipher later" strategies.

In terms of efficiency, it is worth to note that any mitigation process used to increase security in a classical solution tend to increase the computational complexity with an expected downside effect in terms of efficiency. In literature, it has been shown that, presently, the quantum approach can provide a solution with similar efficiency to the fastest classical OT extension protocols with a much higher level of security. Further improvements in the security of classical approaches should increase their complexity and bias this comparison even more in favour of the quantum-based approaches.

The disadvantage of a quantum-based solution is only related to the need to provide end users access to a QKDN and the restrictions that this can impose in terms of end-user accessibility.

8.2.5 Economic considerations

The use of quantum based secure multiparty computation to assist genomic medicine requires that end users have access to a QKDN. Indeed, the oblivious keys that are required to implement the oblivious transfer are obtained from the raw keys of a QKD system. This extra cost, due to access to a QKDN, results in a large increase in the security and efficiency of the service, which in turn can promote its adoption on a large scale.

The large use of secure multiparty computation services in the health sector can have a huge economical and societal impact. Indeed, it can increase the cooperation among the health sector players – namely between hospitals, laboratories, physicians, pharmaceutical industries, governmental agencies, insurance companies, among others – without compromising the patients' privacy and preserving the industry intellectual properties rights. Secure multiparty computation can also be a strong dissuader of fraud and abuse in the health sector. With rising costs in the health sector, the use of data analytics is seen as the least costly and most effective path to keep improving people's health. Data analytics in the health sector solutions may lead to cost saving between 12 and 17 percent according to [b-McKinsey].

The economic benefits in the health sector can indeed be a strong driver to promote the installation of quantum key distribution networks.

8.2.6 Stakeholders (Actors)/Domains

Health care systems and pharmaceutical industry.

8.3 UC-1-3: Hybrid QKD and PQC for encrypted communications

8.3.1 Use case description

Quantum-safe cryptography is urgently needed to protect systems with high security requirements. Even though quantum computers are not available today, data can always be saved and decrypted later by quantum computers. A practical hybrid scheme with various quantum-safe technologies for encrypted communications between data centres has been demonstrated on Alibaba's platform [b-Leilei] to enhance data transfer security.

8.3.2 Problem statement

Both QKD and PQC present opportunities and obstacles. QKD can provide provably-random keys and information theoretic secure distribution of those keys. However, to deploy QKD systems in real networks must overcome the transmission distance problem as well as restrictions of point-to-point links, high manufacturing and maintenance cost and lack of scalability.

PQC, on the other hand, is similar to classical cryptography that is algorithm-based. However, deploying a new cryptosystem incurs potentially high cost, with the time and energy consumed by cryptographic computations. In addition, PQC in principle still faces the risk of potential attacks by future mathematical breakthroughs.

8.3.3 Solution

Quantum random number generators (QRNGs), QKD, post-quantum and classical cryptography algorithms are integrated in the hybrid quantum-safe scheme to enhance data transfer security. Compared to quantum cryptography and PQC solutions, the proposed triple-level security cryptographic scheme provides a layered cryptographic solution for different applications and is compatible with existing solutions, a practical implementation is illustrated in Figure 8-2.

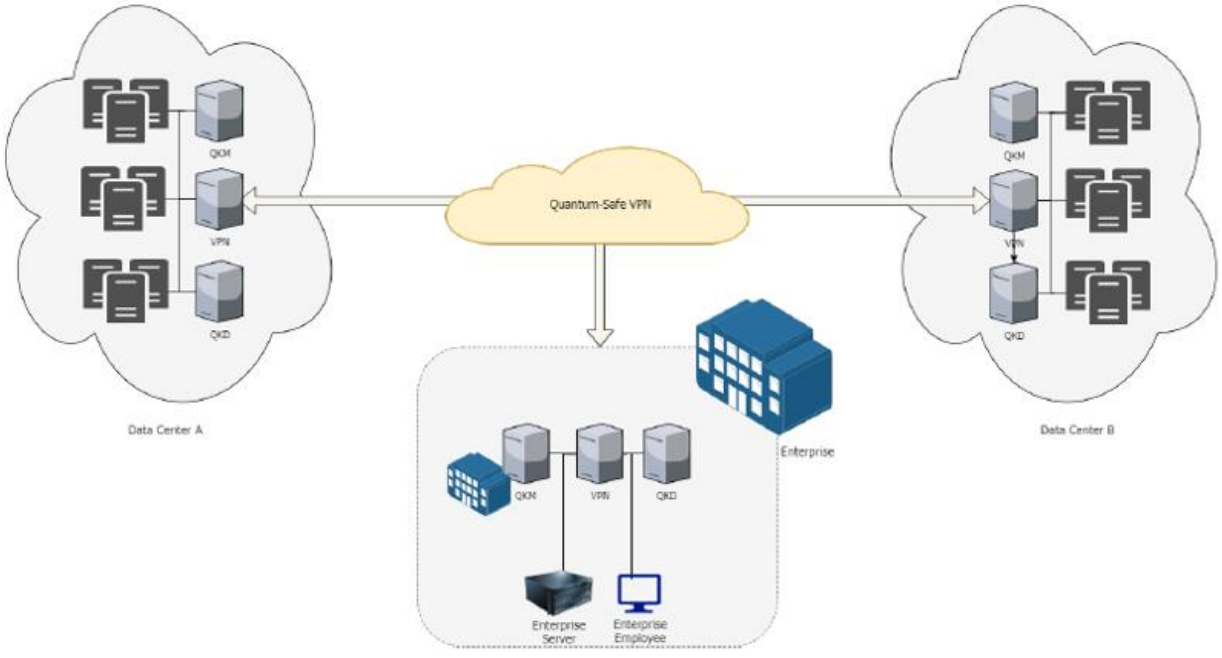


Figure 8-2 – Practical implementation of triple-level hybrid quantum-safe scheme (classical cryptography + post quantum algorithms + QKDs)

8.3.4 Benefits and impact

The hybrid quantum-safe scheme described in this use case provides a layered cryptographic solution for different applications which enhances data transfer security and is compatible with existing solutions.

8.3.5 Stakeholders (Actors)/Domains

QKDN and PQC service providers and users.

9 UCC2: QKD integrated with various TCP/IP protocols

As similar to the other key exchanging algorithms in cryptography, QKD can also be applied to the data link layer, network layer, transport layer, and application layer of the TCP/IP protocol stack which is commonly used in ICT systems, as shown in Figure 9-1.

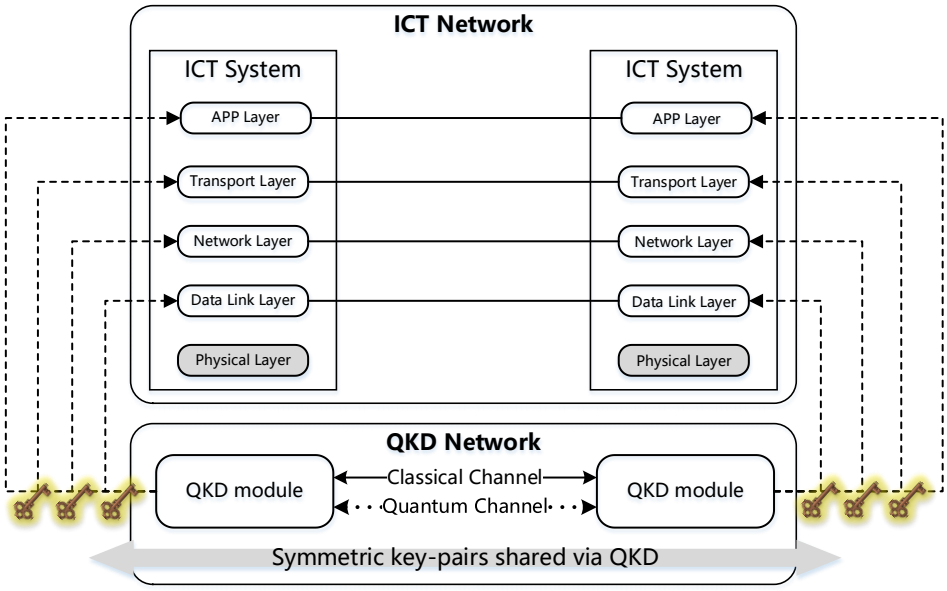


Figure 9-1 – QKDN integrated with TCP/IP protocol stack

9.1 UC-2-1: QKD integrated in data link layer

9.1.1 Use case description

On the data link layer, QKD may be used as a part of the point-to-point protocol (PPP) which is a layer 2 protocol widely used to connect two sets of nodes in a network. The encryption functionality in PPP is the encryption control protocol (ECP) [b-IETF RFC 1968]) which allows the use of encryption in PPP frames. QKD may be used as a key exchange protocol for PPP.

QKD may also be used to provide keys for the IEEE 802.1 MACsec layer 2 protocol which provides a connectionless service that supports data confidentiality, integrity and authenticity for authorized systems attaching to a local area network (LAN) or interconnecting LANs.

As QKD is presently mainly implemented as a point-to-point link involving two endpoints connected by a quantum channel, it is reasonable to combine a QKD link with a link encryptor to form a QKD link encryptor. A link encryptor is a network-transparent cryptographic system. A QKD link encryptor is a quantum cryptography appliance for point-to-point link encryption which may also be referred to as virtual private network (VPN) tunnel. The link encryptor usually uses the keys supplied by QKD as keys for a symmetrical block cipher (e.g., AES) or steam cipher (OTP for highest security) and can be used, for example, to encrypt traffic on an Ethernet of fibre channel link. The QKD link encryptor may be used to support communications between two adjacent network nodes employing QKD or it may provide protection for communications end-to-end across a network of nodes as a VPN tunnel. Key management is integrated in the link encryptor. For example, this solution may securely bridge two Fast Ethernet networks.

9.2 UC-2-2: QKD integrated in network layer

9.2.1 Use case description

Internet protocol security (IPsec) is a layer 3 protocol suite for securing internet protocol (IP) communications by authenticating and encrypting the IP packets of a data stream.

Internet key exchange (IKE or IKEv2) is the protocol used to set up a security association in the IPsec protocol suite. IKE uses a Diffie-Hellman public key exchange to set up a shared session secret, from which cryptographic keys are derived. Public key techniques or, alternatively, a pre-shared key, are used to mutually authenticate the communicating parties.

QKD may be used by a modified IKE protocol to provide the shared secret for IPsec payload encryption. The shared secret provided by QKD may either be used in a conventional block or stream cipher for OTP payload encryption in a high security context.

9.3 UC-2-3: QKD integrated in transport layer

9.3.1 Use case description

Transport layer security (TLS) and its predecessor secure sockets layer (SSL) are layer 4 protocols which provide an end-to-end security for network communication services. A session key, usually established with public key exchange, is used e.g., to secure the transmission of credit card information in e-commerce transactions. In a scenario involving QKD, the session key may be replaced by a QKD key or the QKD keys may immediately be used for OTP encryption of transmission data. QKD keys may also be used for message authentication, replacing hash-based message authentication codes (HMACs) as used in TLS, or the pseudo-random functions of standard SSL.

9.4 UC-2-4: QKD integrated in application layer

9.4.1 Use case description

Above the transport layer, QKD systems may be integrated in layer 7, the application layer of the OSI model. This may be useful for applications using pre-shared keys for user authentication or for the acquisition or certain rights, or as encryption keys for payload transmission between instances of the application.

10 UCC3: QKD implemented in various network topologies

10.1 UC-3-1: QKDN as metropolitan access network

10.1.1 Use case description

UC-3-1 describes a general-purpose high security communications network between several branches and offices within an area of about 100 km in diameter (metropolitan area). The single network nodes are interconnected with dedicated optical point to point links for classical digital communication and QKD. The network uses a dedicated optical infrastructure which is completely separated from the internet.

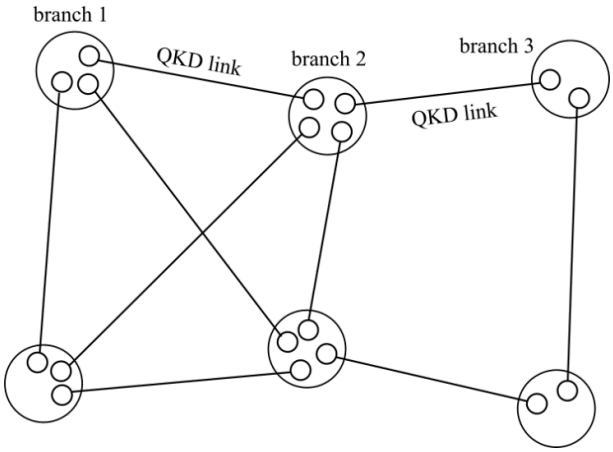


Figure 10-1 – High security metropolitan area network topology

QKD systems are used to generate symmetrical secrets in nodes connected by optical links. The secrets are used as cryptographic keys for authentication and encryption primitives with security levels fitting the purpose they are intended for. Provably secure OTP can be used for communications with strictest long term security requirements, while other algorithms, including PQC algorithms can also be used. To increase network connectivity (between links without direct connection), and availability and/or bandwidth, a trusted repeater network solution can also be considered.

10.1.2 Problem statement

Governments and other organisations with the highest communications security requirements are currently relying on communication networks which either use dedicated network infrastructures or are layered upon the internet. In both cases, cryptography is used with an uncertain prospect with regards to current and especially long-term security.

Current cryptographic protocols and paradigms have already been subject to severe (mostly insider) attacks. Examples of such attacks include compromised random number generators making brute forcing TLS keys a trivial task, compromised root certificates for trust validation etc. Some algorithms for securing governments' communications have later turned out to have contained deliberately introduced weaknesses; even AES is suspected to be susceptible to timing side channel attacks. Furthermore, in most jurisdictions, COTS telecom and network hardware, e.g., network switches are required by legislation to include access mechanisms for law enforcement which have already been exploited by rogue actors.

With regards to long term security, the prospects are even worse: secrets that need to remain secure for several decades may be revealed some time in the future when advanced decryption capabilities including quantum computers become available.

10.1.3 Solution

The solution would be to use a communications network with advanced security guarantees on a dedicated optical infrastructure that is completely separated from the internet. The advanced security is provided by QKD links delivering a continuous stream of symmetrical secrets used to authenticate and secure the communication between adjacent nodes of the network.

To increase network availability and/or bandwidth, a trusted repeater network solution may also be considered.

10.1.4 Benefits and impact

End users can rely on the security of proper network infrastructures which produce cryptographic secrets with the high security standards of QKD.

End users can select the cryptographic security for their communication and authentication primitives according to their needs. For most sensitive communications, with the strictest long-term confidentiality requirements, encryption primitives with perfect secrecy (e.g., OTP encryption or Shamir-secret-sharing) may be used and, for communications with ephemeral confidentiality requirements, symmetric ciphers with computational security may be used.

The advantage in comparison to alternative solutions not involving QKDNs is that QKD offers key distribution with stronger security guarantees than other non-quantum key distribution primitives. The use of dedicated infrastructure not (directly) connected to the internet ensures a relatively smaller attack surface towards attackers from the outside.

10.1.5 Economic considerations

QKD links and QKD encryptors (QKD links combined with symmetrical encryption devices) are currently still quite expensive (in the order of magnitude of USD 100,000 for one link) but, for organisations with the highest communication security requirements targeted by this use case, the cost will likely be acceptable. Generally, the number of required links depends on the number of nodes to be interconnected as well as on the density of the connection graph (i.e., how many links are spanned between the nodes of the metropolitan area network.

10.1.6 Stakeholders (Actors)/Domains

Administrations, corporations and other organisations with branches in a metropolitan area looking for a high security communications network solution.

10.2 UC-3-2: QKDN as inter-city backbone network

10.2.1 Use case description

In September 2017, the 2000 km Beijing-Shanghai backbone QKD network was put into operation and, at the time of this report's publication, was the longest QKD network in the world. The project was led by the University of Science and Technology of China (USTC) in partnership other with organizations including China Cable Television Network Co., Ltd, Shandong Academy of Information & Communication Technology, Industrial and Commercial Bank of China (ICBC), Xinhua Financial Information Exchange etc.

The backbone network consists of 32 physical nodes linearly connected by QKD links – the Beijing, Jinan, Fuli, Hefei, Nanjing and Shanghai nodes are the access points while the others are trusted repeater nodes. The backbone network has 135 links in total and two to eight multiple QKD links lie between adjacent nodes. The network rents dark fibres deployed by China Cable Television Network Co., Ltd. and, to conserve fibre resources, the network uses quantum wavelength division multiplexing technology which combines four quantum channels into a single fibre. The distance between adjacent nodes along the backbone line varies between 34 km and 89 km with fibre loss varying from 10.3 dB to 20.5 dB.

The backbone network deploys QKD devices (provided by QuantumCTek Co., Ltd) which implement decoy state BB84 protocol. Some of the devices integrate the up-conversion single photon detection technique and thereby achieve a 25% single photon detection rate.

The backbone network is designed to function as a high bandwidth channel that feeds quantum keys between metropolitan and QKD networks located in different cities. The backbone network has been connected to four metropolitan QKD networks already established in Beijing, Shanghai, Jinan and Hefei. A wide area QKD network thus has been formed and provides end users including banks, government agencies and large enterprises with versatile security services, such as video call, audio call, fax, text transmission and file transmission. The network is also scalable such that extra users can be easily added.

10.2.2 Stakeholders (Actors)/Domains

QKD network operators directly provide QKD services to customers.

10.3 UC-3-3: QKDN as free-space satellite-ground or inter-satellite network

10.3.1 Use case description

UC-3-3 describes a high security general-purpose long-haul network based on multi-layer satellites around the world. By using satellite as relay, long-distance QKD can be realized within global metropolises.

As shown in Figure 10-2, general-purpose long-haul network based on multi-layer satellites consists of three layers of geostationary earth orbit (GEO) satellite, medium earth orbit (MEO) satellite and low earth orbit (LEO) satellite. The multi-layer satellite in orbit provides the physical basis for the application of general-purpose long-haul network.

The general-purpose long-haul network based on multi-layer satellites can cover the whole world through satellite communication with flexible user access. It is suitable for remote areas with high cost of laying optical fibre to realize quantum key distribution. At the same time, it can solve the problem of difficult access for mobile users, such as marine mobile equipment, polar research station, desert detection station, etc.

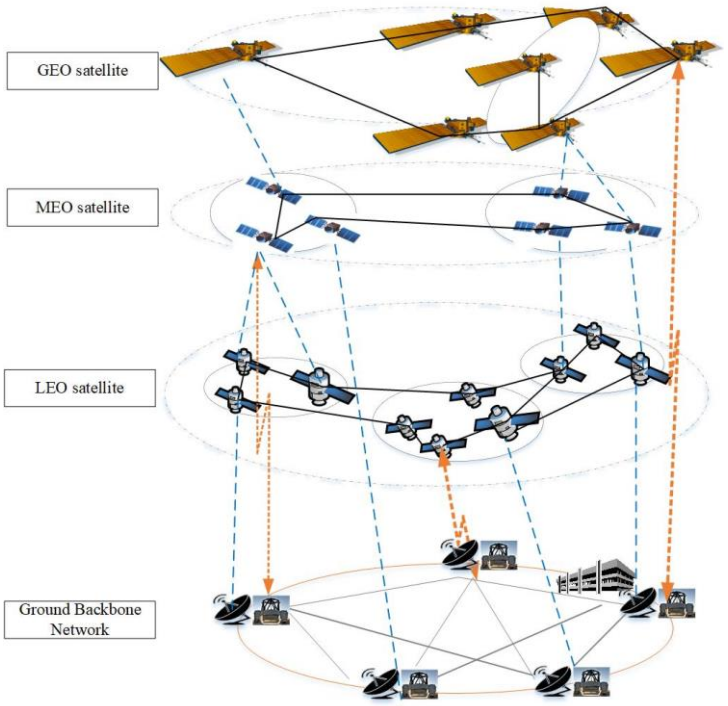


Figure 10-2 – Architecture of general-purpose long-haul network based on multi-layer satellites

Simpler satellite-based QKD networks, e.g., single layer satellite based QKDNs, may be less robust and produce less QKD keys but might still be adequate for some commercial and lower security applications.

10.3.2 Problem statement

With the popularity of global services, the requirements for the confidentiality of information transmission are becoming higher and higher. At present, it is difficult for governments and other commercial organizations to achieve end-to-end QKD worldwide only through ground base stations.

Presently, space network attack risks are increasing, and an effective encryption method is urgently needed to ensure the communication security of the satellite network.

Due to the physical distance limitation of QKD, satellites are needed to realize end-to-end QKD globally.

10.3.3 Solution

The architecture of the general-purpose long-haul network based on multi-layer satellites (as shown in Figure 10-2) consists of three layers of GEO, MEO and LEO satellites. The global QKDN architecture based on multi-layer satellite network is established, the centralized and distributed intelligent control mechanisms are designed and the nodes are interconnected through inter-satellite links and star-ground links.

The Micius satellite has proved the feasibility of the downlink and the performance of the uplink is constantly improving with the progress of technology. The available communication time between the ground base station and the satellite within the coverage of a single quantum satellite is about six minutes and multiple satellites in each layer of orbit can meet growing business needs. Each GEO satellite (QKDN control and management node) is responsible for key management and distribution of its respective coverage areas while the LEO and MEO satellites are QKDN transmitter and receiver terminals. The ground control node is responsible for key unified management and distribution in the whole general-purpose long-haul network, including both the satellite and ground networks.

There is a quantum key transceiver and laser devices on the satellite. As a QKD relay, it can complete the end-to-end QKD of intercontinental distances through laser communication. Through a three-layer satellite-based QKD network, it can complete multi-hop relays including satellite-to-satellite and satellite-to-ground QKD thereby achieving global end-to-end QKD.

Simpler, trusted node satellite networks can also provide global coverage if QKD links and key management is combined into LEO satellites. For example, LEO satellites can perform QKD with any ground station they pass over to generate and store private symmetric keys between that satellite and the ground station in their internal key manager. Each satellite maintains a continuous classical radio link with the ground network using only radio relay nodes in higher orbits, e.g., in geostationary orbit. When any two users on the ground (e.g., ground station A and B), need to communicate securely the network is queried for satellites that have keys stored with A and B on-board a secure key management module. Any such keys are combined using an XOR function and can be broadcast to A and B via the relay satellites with minimal latency. Station A and B can perform a reverse XOR operation to extract the key held by the other ground station and can then communicate securely. The used key for A and B is deleted from the satellites. Inter-satellite QKD links are optional in this configuration but can be used to re-distribute key across the constellation [b-Vergoossen].

10.3.4 Benefits and impact

The advantages for end users, specifically the security gains include:

- General-purpose long-haul network based on multi-layer satellites can counter space satellite network attacks and improve the defence performance of space networks.
- General-purpose long-haul network based on multi-layer satellites uses satellites as relays which can achieve end-to-end QKD between two cities worldwide and greatly enhance timeliness.
- A high security communication network can be obtained in the field of information security such as finance worldwide.
- General-purpose long-haul network based on multi-layer satellites provide wider and denser coverage and makes it easier for mobile and remote user terminals to use quantum encryption services.

- When the satellite acts as a relay, the key is XOR processed and the transport of the key from the end user to others is secured with the perfect secrecy of OTP encryption.
- The use of dedicated infrastructure (like laser communication devices), not (directly) connected to the internet ensures a relatively smaller attack surface towards attackers from the outside.

The advantage in comparison to alternative solutions not involving QKDNs is that QKD offers key distribution with stronger security guarantees than other non-quantum key distribution primitives. Using satellite nodes as quantum relay can effectively block external attacks and achieve the global availability of quantum key.

10.3.5 Economic considerations

The general-purpose long-haul network based on multi-layer satellites requires a number of satellites such as the Micius satellite. Furthermore, suitable infrastructure (such as laser diodes and telescopes) is required on the satellites.

At present, the cost of quantum satellites is relatively high. However, with the recent trends in the commercial space sector, the cost for space deployment can potentially be greatly reduced leading to greater proliferation.

10.3.6 Stakeholders (Actors)/Domains

Governments and organizations, especially end users who cannot connect to optical fibres (such as the Arctic Research Station) and those with strong mobility (such as naval ships), looking for a high security network solution for connecting different metropolises worldwide.

Commercial organizations whose sites are not connected to existing quantum networks or who do not trust their local quantum networks.

Network operators connecting separate quantum networks together.

11 UCC4: QKD with different user device categories

From a QKD end user's perspective, there are various use cases according to the different types of user devices consuming the keys provided by QKDN. The possible use cases include:

– **Fixed user device with standalone QKD module**: As current commercial QKD devices are typically bulky and require a fibre connection, the user devices placed at a user's office such as the router, the encryptor and the QKD devices are usually separate devices as shown in Figure 11-1. The encryptor connects to the QKD device with a physical connection to fetch keys and then encrypts or decrypts the data traffic passed in the router.

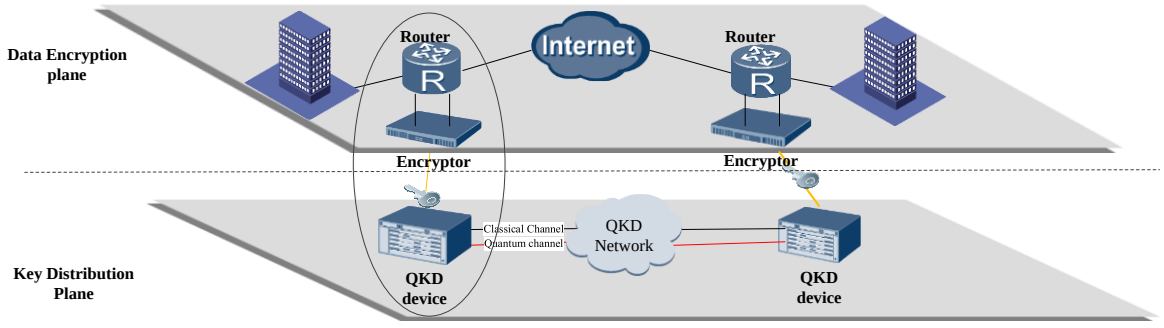


Figure 11-1 – QKD used via fixed user device with standalone QKD module

– **Fixed user device with integrated QKD module**: As the QKD module integration level grows, the functionality of QKD can be integrated into a router or encryptor device physically as a chipset or a PCI card.

– **Wireless user device which consumes offline keys provided by QKDN**: For a wireless user device without a fibre connection to the QKDN, it can store the keys provided by QKDN into the secure storage within itself and then consume the keys for secure data communication as shown in Figure 11-2. The detailed use case description is provided in UC-4-1.

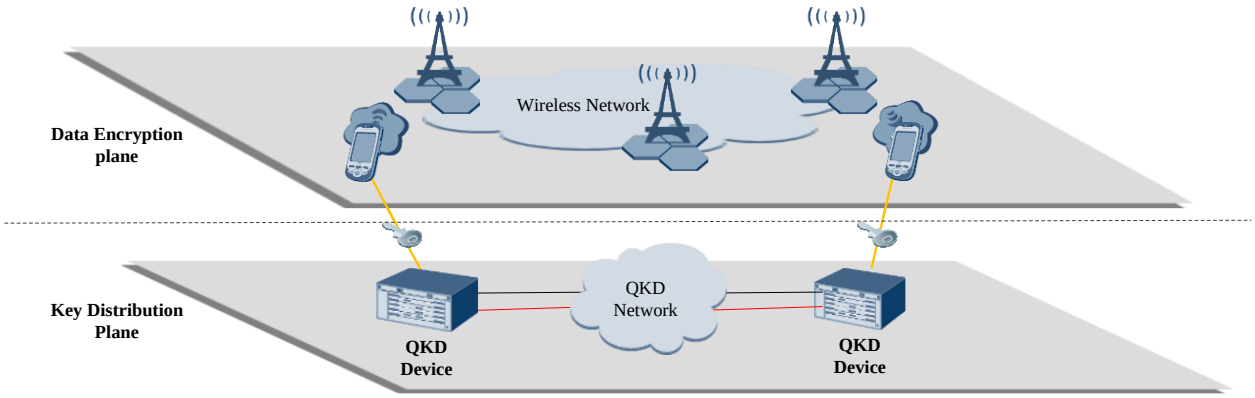


Figure 11-2 – QKD used via wireless user device with offline QKD-keys

– **Wireless user device which integrates a QKD module to consume online keys provided by QKDN**: As wireless and mobile QKD technology is developing, it is also possible to integrate QKD module into wireless devices and perform QKD directly via wireless channels. More details on this use case are provided in UC-4-2.

11.1 UC-4-1: Wireless user device with offline QKD-keys

11.1.1 Use case description

In UC-4-1, the proposed solution is to pre-install the QKD-key pool into the mobile user and network side to enhance security of mobile communication which is achievable with existing QKD techniques.

11.1.2 Problem statement

The extension of QKD services to mobile terminals is envisioned to be of high value but, the current physical layer limitations still restrict the direct application of QKD via the air interface between mobile user equipment and base stations.

11.1.3 Solution

As shown in Figure 11-3, the Q-key update terminal is introduced to cache the QKD-key pool and implant the QKD-keys to mobile user equipment (which contain certain secure storage to store the keys). The KDC at the QKDN side is introduced to store the symmetric key pools and perform key management. The mobile terminals embedded with the QKD-key pool can consume the keys provided by QKDN to perform secure communication and recharge QKD-keys from the QKDN once exhausted.

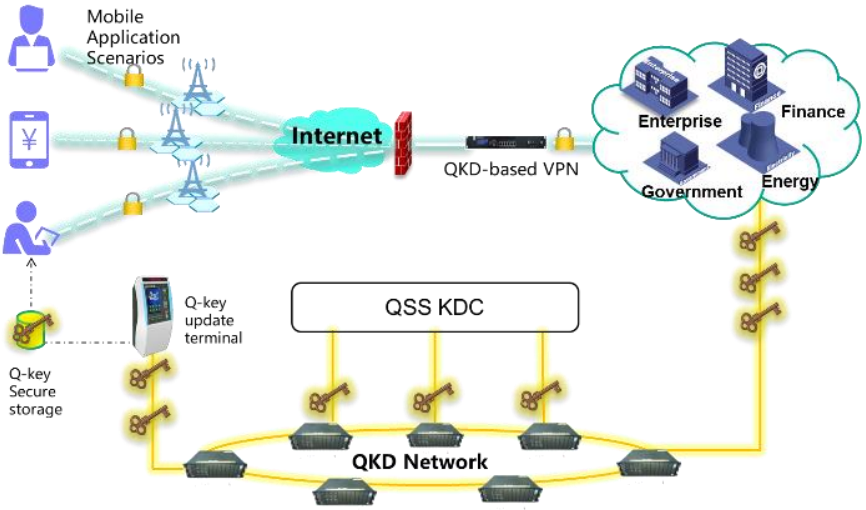


Figure 11-3 – QKD-key embedded secure mobile communication

As shown in Figure 11-4 and Table 11-1, the enhanced QKDN solution can be summarized into four steps:

1) First, PQC-based certificates are pre-installed in the user terminals for initial authentication.

2) The user terminals and the KDC can then obtain the QKD-key pool from the QKD network.

3) After that, the terminals with a QKD-pool storage can use symmetric QKD-keys for authentication with the KDC.

4) Then, the KDC can help negotiate peer-to-peer session keys for terminal A and B. With the session key generated, the terminals can perform secure communication consuming the QKD-keys in one-time manner. After the QKD-key pool is exhausted, the terminal can get updated via the Q-key update terminal from QKDN again.

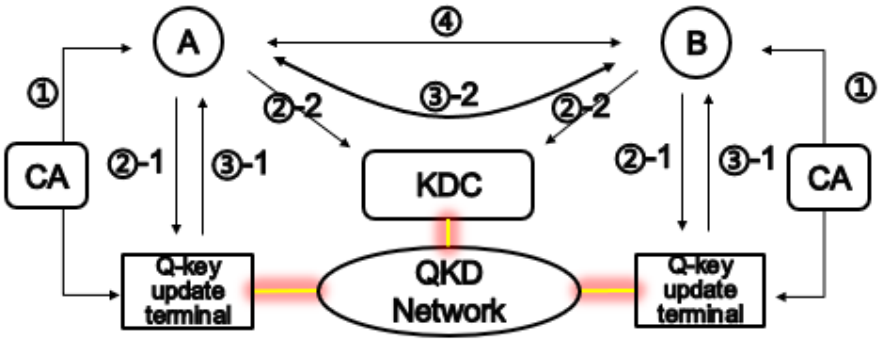


Figure 11-4 – QKD-key embedded secure mobile communication solution

Table 11-1 – QKD-key embedded secure mobile communication steps

	QKD enhanced with PQC and KDC	Vs. KDC	Vs. PKI
① Root key Pre-share	Pre-distribute PQC certificates to QKD node and terminal secure storage	Easy management	
② Identity Authentication	2-1: Use PQC certificates for QKD node and terminal initial authentication 2-2: Use symmetric Q-keys for authentication in following sessions		Q-safe
③ Session key agreement	3-1: Use QKD network to produce and distribute temporary session keys via OTP; and then Store t-session-key-pool to terminal and KDC 3-2: Use KDC to negotiate real-time session key	Forward security	Q-safe; Fast
④ Encrypted comm.	Use symmetric session key for AES encrypt/decrypt		

11.1.4 Benefits and impact

From an application perspective, this solution can support the extension of the QKD service to the vast mobile communication scenarios based on existing QKD techniques. Moreover, from a security perspective, this solution can provide the forward security feature for session keys compared to KDC-based scheme. It can also provide quantum-computing resistance feature compared to traditional PKI-based scheme.

11.1.5 Stakeholders (Actors)/Domains

UC-4-1 can be applied to many vertical sector scenarios, e.g., mobile working, mobile payment, industry internet of things.

11.2 UC-4-2: Wireless user device with integrated QKD module

11.2.1 Use case description

As the QKD module can be miniaturized into chip-scale, it is possible to be integrated into mobile devices to perform wireless QKD service. As shown in Figure 11-4, the University of Bristol in the United Kingdom has successfully demonstrated the QKD chip transmitter integrated on the credit card, and the QKD receiver in the ATM rack to achieve free-space QKD.

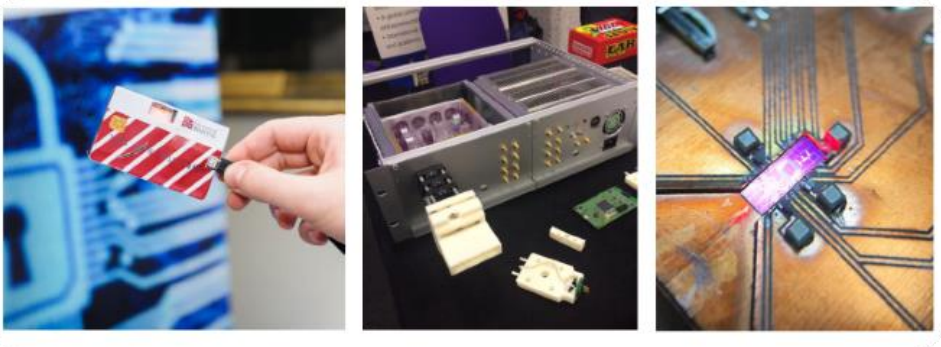


Figure 11-5 – Demo of QKD integrated credit card

12 UCC5: QKD integrated in various network forms

12.1 UC-5-1: QKD in 4G/5G networks

12.1.1 UC-5-1-1: QKDN for LTE backhaul and 5G backbone

12.1.1.1 Use case description

The first commercial QKD network in Korea (Rep. of) was deployed in June 2016. This network applied QKD to LTE backhaul between Sejong central office and one of SK telecom's DU site at Daejeon.

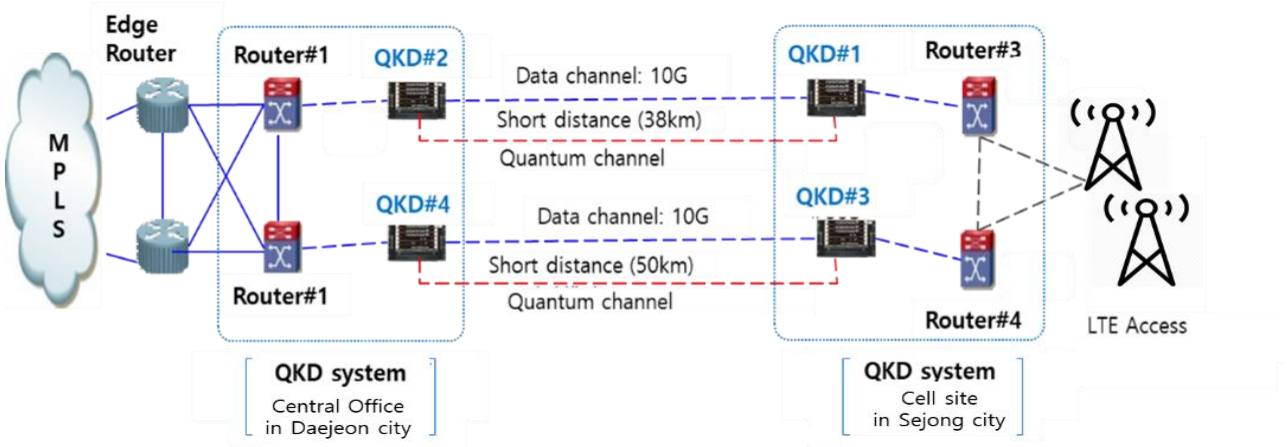


Figure 12-1 – QKD network deployment in LTE backhaul in Korea

In 2017, a trusted relay node was implemented for long distance QKDN and in 2019, the implementation and commercialization of QKD quantum cryptography for a total of 221 km of transmission line between Sungsu central office (Seoul area) and Dunsan central office (Daejeon area) of SK Telecom was accomplished. It was extended to the Taepyung central office in 2020 and this is the end-to-end distance of 380 km. Other main cities are targeted to be reached with QKD step by step.

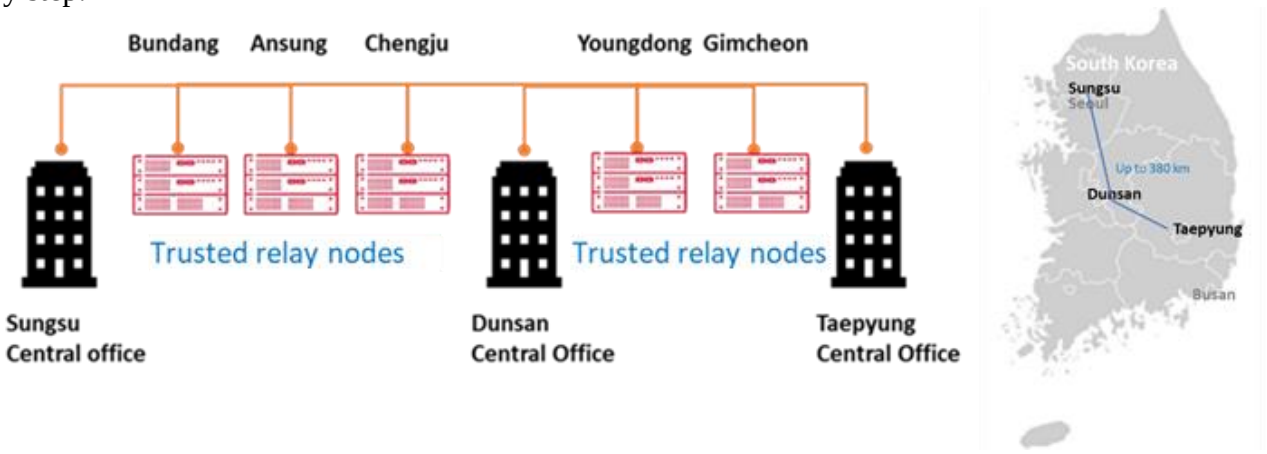


Figure 12-2 – Long distance QKD network deployment in LTE and 5G backbone in Korea

12.1.1.2 Problem statement

As applications in Internet of Things (smart cities, factories), vehicles and healthcare are expected to use 5G networks, the 5G network requires the highest level of security available when being designed and deployed. At present, SK Telecom's 5G/LTE backbone network between Sungsu through Daejeon to Taepyung takes charge of about 30% of SK Telecom's total data traffic. This data is

protected using the present cryptography which is expected to be vulnerable to quantum threats in the near future. So, it is critical for telecom operators to secure data traffic over their 5G/LTE backbone networks with QKD.

12.1.1.3 Solution

When deploying QKD over 5G/LTE backbone network between Sungsu through Daejeon to Taepyung, Trusted nodes have been deployed to extend the reach of the key exchange used by the encryptors at both ends and they are positioned in highly secure locations at SK Telecom's premises.

12.1.1.4 Benefits and impact

Before deploying QKD over the 5G/LTE backbone network, it was protected with TLS/IPsec (IKEv2) which is eventually expected to be broken by Shor's algorithm with quantum computing. However, by using QKD, SK Telecom can protect the data over 5G/LTE backbone from quantum attacks.

12.1.1.5 Economic considerations

SK Telecom deployed QKD nodes along the 5G/LTE backbone with trusted nodes in between which all use the dark fibre of SK Telecom's network.

12.1.1.6 Stakeholders (Actors)/Domains

UC-5-1-1 was developed for SK Telecom's internal use but it can be applied by any telecom operators who would like to protect their subscribers' critical data in their backbone network.

12.1.2 UC-5-1-2: Quantum secured inter-domain 5G service orchestrator

12.1.2.1 Use case description

In [b-Wang], it is reported that QKD technologies in combination with SDN and network function virtualization (NFV) can be applied to secure interconnections of distributed virtual network functions (VNFs) to achieve quantum secured inter-domain 5G service orchestration.

This was experimentally demonstrated via interconnecting four autonomous 5G islands simultaneously through the q-ROADM with eight optical channels using the 5GUK Exchange orchestration platform. The overall concept is as shown in Figure 12-3 [b-Wang].

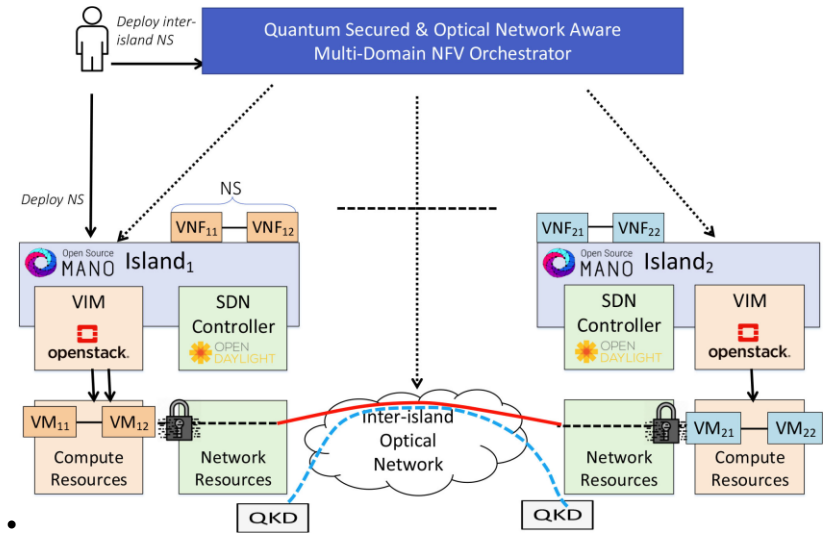


Figure 12-3 – Overall concept of QKD secured 5GUK Exchange scenario

12.1.3 UC-5-1-3: QKDN for 5G front-haul

12.1.3.1 Use case description

For 3G/4G networks, the base station (or known as eNodeB by 3GPP) is comprised of the base band unit (BBU) and the remote radio unit (RRU). The front-haul is referred to as the fibre connection between the BBU and RRU which features a high bandwidth, low latency and private CPRI interface.

For 5G, the base station (or known as gNodeB by 3GPP) functions are reallocated into three parts as RRU, distributed unit (DU) and central unit (CU), as shown in Figure 12-4.

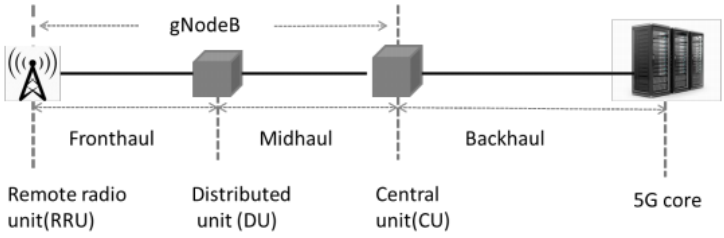


Figure 12-4 – 5G transport structure

The 5G RRU can handle certain physical layer functions of previous BBU locally, thus, the fronthaul transportation requirements can be relaxed to accommodate the surging 5G capacity. The next generation fronthaul interface (NGFI) is designed for the connection between RRU and DU, as a new decoupled open interface to support RRU and DU from different vendors.

The security guarantee for 5G fronthaul is an important issue which need to satisfy high bandwidth, low latency and high-level security at the same time.

QKD is a promising solution to secure 5G fronthaul which is mentioned in [b-Priem].

12.1.4 UC-5-1-4: QKDN for 5G mid-haul

12.1.4.1 Use case description

The mid-haul is a newly introduced concept in 5G to indicate the connection between the DU and CU.

SK Telecom (SKT) has showcased the application of QKD to the 5G mid-haul network to secure confidential data transmission from a smart factory to the cloud.

A customer of SKT, an auto parts manufacturer (Myunghwa Industry) based in Ansan, implemented a smart factory using IoT devices and robots which generates a large volume of confidential data such as design documents transmitted over the 5G network to reach the SKT Cloud. Therefore, the customer was looking for fast and secure access to the SK Telecom commercial 5G service to connect their new smart factory.

To best address this customer security need, SKT has secured the 5G network connectivity with the latest quantum safe technology using quantum cryptography. One 5G DU is located on the SKT's customer site in Ansan while the 5G CU is located at the central office of SKT Network in Sungsoo. Since the 5G DU to CU connectivity uses a fibre optic network, it was possible to combine QKD with the encryption on the 5G mid-haul network. The deployment is illustrated in Figure 12-5.

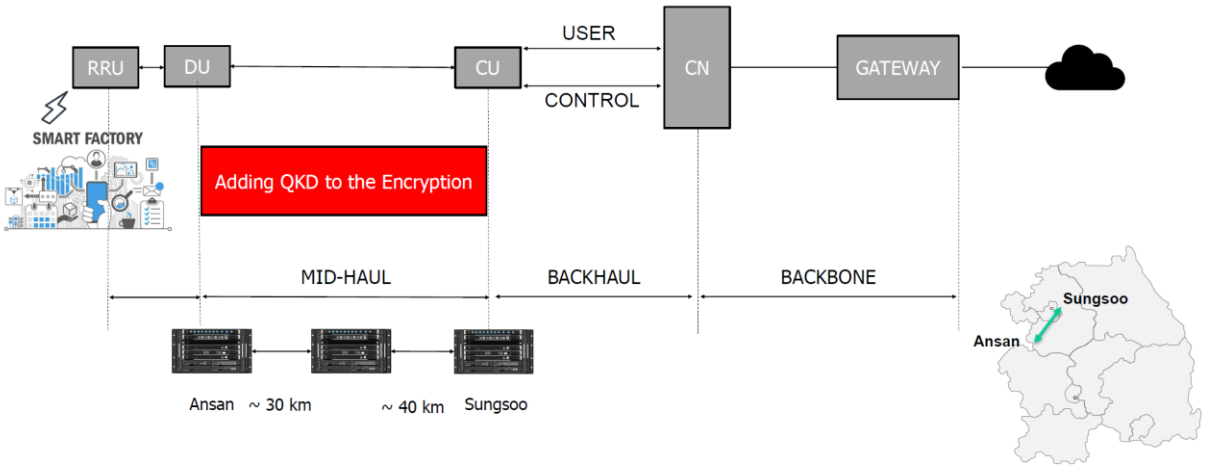


Figure 12-5 – 5G mid-haul QKD deployment for smart factory

This solution combines the latest technology available ensuring high-speed, stability and security for the customer data connectivity.

12.1.4.2 Problem statement

The smart factory in Ansan generates a large volume of confidential data transmitted over 5G mid-haul to reach the SKT Cloud in Sungsoo where it is processed and sent back to the machines and robots in the smart factory as input data. So, it is critical to protect this data over the 5G network for their intangible property.

12.1.4.3 Solution

SK Telecom deployed QKD nodes in point-to-point configuration for data transport as well as QKD key relay over the 5G mid-haul network between Ansan and Sungsoo in December 2018. Two QKD nodes are connected through a network point of presence defined as a hub for the encryption and QKD key relay.

12.1.4.4 Benefits and impact

By protecting data over SK Telecom's 5G mid-haul with QKD, SK Telecom can provide business partners of SKT Cloud with the highest level of security for their data in the near quantum era, in contrast to other cloud service providers.

12.1.4.5 Economic considerations

SK Telecom deployed QKD nodes at both ends and additional QKD nodes in between but, as a network operator, used its own dark fibre optic and 5G radio access network.

12.1.4.6 Stakeholders (Actors)/Domains

Any business partners who would like to protect their data from quantum attacks can achieve this goal by using SKT Cloud with QKD in SK Telecom's 5G network.

12.1.5 UC-5-1-5: Quantum security enhancement for universal AKA authentication protocol

12.1.5.1 Use case description

Authentication verifies whether a user has the right to access a system. In the traditional authentication mode, users present valid information such as passwords to the authentication party to verify that they have the right to access the system. Authentication includes user authentication and network authentication where:

- user authentication means that the network authenticates users to prevent unauthorized users from occupying network resources; and
- network authentication allows users to authenticate networks to prevent users from accessing illegal networks and obtaining key information.

The Authentication and Key Agreement (AKA) is a two-way authentication mechanism defined in [b-RFC4187]; its improved version AKA' is defined in [b-RFC5448]. Both mechanisms have been developed by IETF and adopted by 3GPP and are widely used wireless network authentication mechanisms.

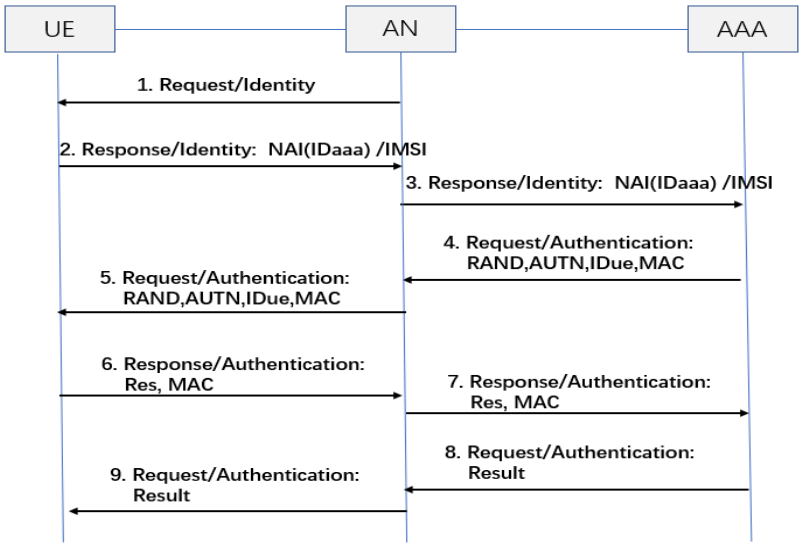


Figure 12-6 – AKA authentication protocol

12.1.5.2 Problem statement

AKA authentication is considered to be a relatively safe authentication system, but it still has some shortcomings:

- If the AKA process is implemented in plaintext transmission mode, in which the interactive data is not encrypted and protected, the user ID, IMSI and other sensitive information will be disclosed and there will be risk of middleman disguised identity attack.
- IMSI as unchangeable user information credentials should not be visible but be encrypted.
- Using a public key cryptosystem to protect data in the authentication process is not as good as using a pre-shared key symmetric encryption mechanism. The public key cryptosystem is also more difficult to operate and maintain.

12.1.5.3 Solution

The QKDN is used to realize the advantage of secure key distribution. The client UE and the authentication server AAA use QKDN to share keys. Symmetric encryption fully ensures the security of data. The QRNG can generate enough secure true random numbers for the client and authentication server to use in the AKA process.

In the protocol improvement, the privacy of IMSI is fully considered. The client only sends the hash value of IMSI and random number, R1. The random number, R2, generated by the authentication server is not only used to generate the authentication vector (AV) but also used with R1 generated by the client to be authentication factors of both parties. After the authentication succeeds, R1 and R2 can be used to generate new shared keys for both parties, see Figure 12-7.

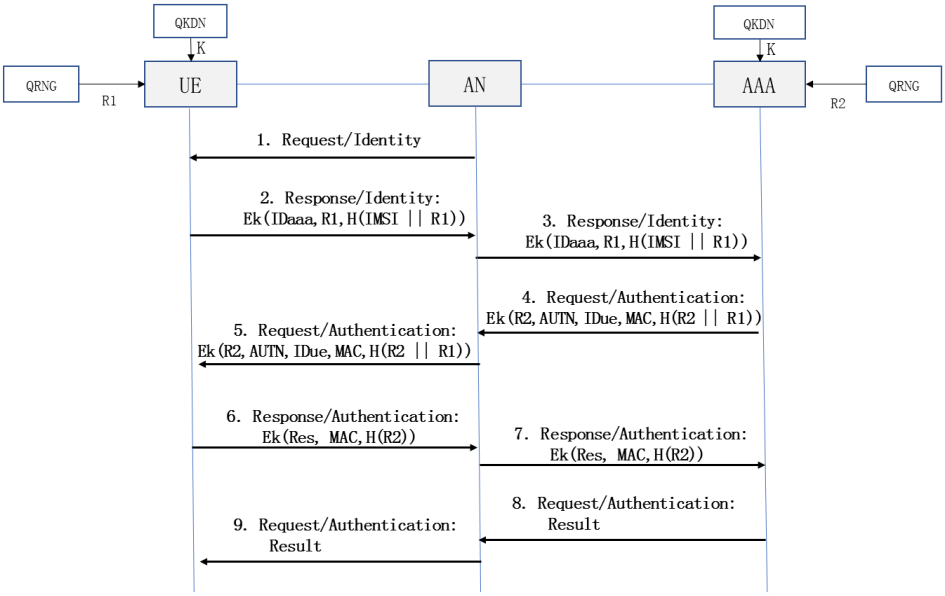


Figure 12-7 – AKA authentication protocol improved by quantum security

12.1.5.4 Benefits and impact

The quantum security enhanced AKA authentication protocol can realize two-way authentication, nondisclosure of identity information of both authentication parties and multi-factor authentication. With the symmetric encryption method, it can protect the interactive data with confidentiality, integrity and authenticity. The protocol can resist attacks such as man-in-the-middle, forged identity, dictionary and replay attacks. The use of QRNG also ensures the true randomness of the generated random numbers.

12.1.5.5 Economic considerations

The keys can be pre-shared between the UE and AAA via mobile media eliminating the need to deploy the QKD module for users and reducing the cost.

12.1.5.6 Stakeholders (Actors)/Domains

Telecom operators and QKD service providers.

12.1.6 UC-5-1-6: Secondary authentication protocol in 5G based on quantum security

12.1.6.1 Use case description

Network slices have been introduced in 5G to meet the differentiated needs of different industries. To prevent unauthorized users from accessing the industry's network slices, 5G proposes secondary authentication for user access. The secondary authentication refers to the authentication between the end user and the data network outside the ISP's domain so that legitimate users can have secure access to the data network. According to [b-3GPP TS 33.501], the secondary authentication process applies between the user terminal, UE and the AAA server of the external data network (DN). The authentication protocol is based on the EAP framework defined in [b-RFC3748] and can be customized.

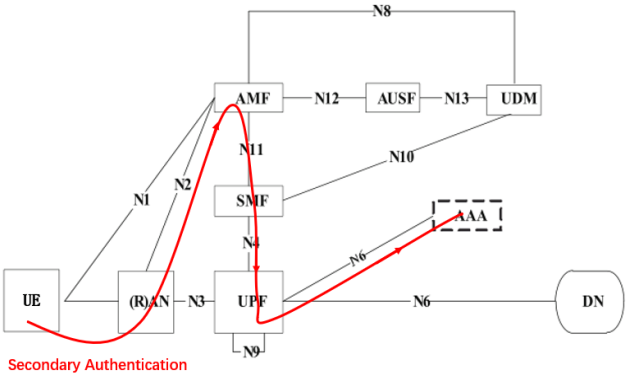


Figure 12-8 – Secondary authentication protocol in 5G

UC-5-1-6 describes two newly designed schemes quantum secure symmetrical encryption (EAP_QSSE) and quantum secure symmetrical encryption and hash-function (EAP_QSSEH) based on quantum security. Both authentication parties use quantum random numbers as authentication factors and QKDN to share keys, for two-way authentication of UE and AAA, to achieve lightweight and fast 5G network secondary authentication in a symmetrical encryption authentication manner.

Figure 12-9 – Secondary authentication protocol based on quantum security

12.1.6.2 Problem statement

Network development has entered the 5G era. As an enabling technology of ICT, 5G has greatly promoted the rapid development of networking and intelligence in various industries resulting in the acceleration of industrial upgrading. Applications in vertical industries will be one of the most important development directions for 5G networks in the future and there is also a diverse demand for 5G networks including security issues for 5G network device access.

5G provides different access modes and network service modes for different scenarios and supports different service delivery modes in which there are obvious differences in security requirements. For example, for the simultaneous access of resource-constrained massive IoT devices, the security authentication process requires limited computing resources; however, for the ultra-high reliable and low-latency applications such as Internet of Vehicles and tele-healthcare, the access authentication process needs to be efficient and fast.

12.1.6.3 Solution

Under the premise of secure authentication, both authentication parties use quantum random numbers as authentication factors and QKDN to share keys, for two-way authentication of UE and AAA, to achieve lightweight and fast 5G network secondary authentication in a symmetrical encryption authentication manner.

12.1.6.4 Benefits and impact

The EAP_QSSE secondary authentication protocol has the characteristics of lightweight and fast implementation. It can realize two-way authentication, non-disclosure of identity information of both authentication parties and multi-factor authentication. The EAP_QSSE protocol protects information with confidentiality, forward security and truly random numbers. It also has the function of key negotiation and can resist attacks such as man-in-the-middle, forged identity, dictionary and replay attacks.

The EAP_QSSEH can further introduce secure hash function on the basis of the EAP_QSSE to ensure the integrity of the message. It further ensures the security of the information shared by both authentication parties since they only exchange the hash values of ciphertext of the shared information rather than the ciphertext.

12.1.6.5 Economic considerations

The keys can be pre-shared between the UE and QKDN via a mobile device which is more cost-effective without deploying QKD modules for the users.

12.1.6.6 Stakeholders (Actors)/ Domains

Telecom operators and QKD service providers.

12.2 UC-5-2: QKD in SDN/NFV based network

12.2.1 UC-5-2-1: Secure SDN and NFV control and management plane

12.2.1.1 Use case description

The implementation of UC-5-2-1 involves the creation of QKD keys that are combined with the usual keys in the protocols used so that the security is incremental: to break into the system, the old protocols have to be broken but also the new QKD layer.

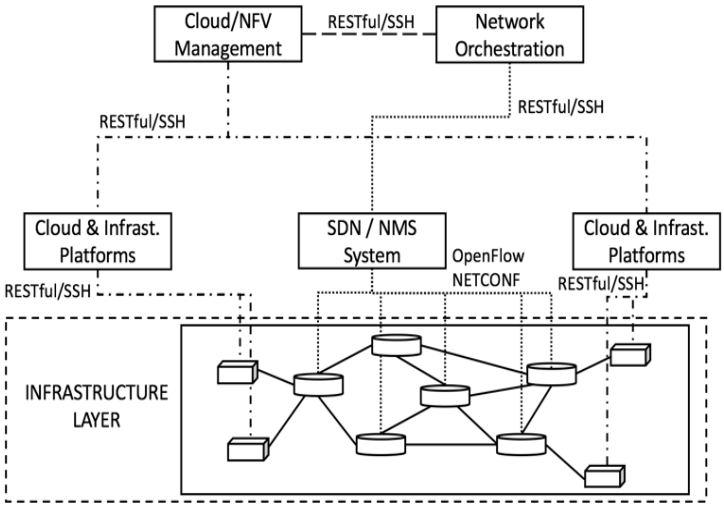


Figure 12-10 – Abstract view of a control plane architecture including cloud/NFV and network orchestration and SDN control plane to secure by QKD

A diagrammatic description of the testbed used to implement UC-5-2-1 in 2018 is depicted in Figure 12-11 with only two transponders and up to 17 classical co-propagating channels were used together with the quantum channel.

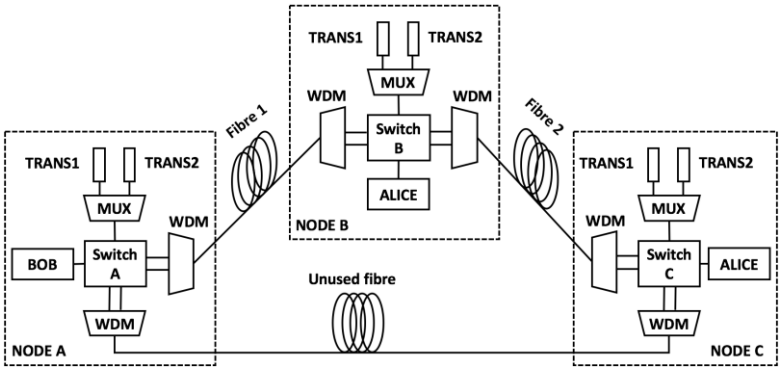


Figure 12-11 – Diagrammatic description of the testbed used to implement the use-case in 2018

12.2.1.2 Problem statement

Integrating SDN and NFV technologies can affect networks by introducing new threats that were not present before as the configuration of the network elements and the images of VNFs must be transferred from central offices, network controllers and orchestration platforms. This is a key problem since a compromised control and management plane would affect the entire infrastructure and services.

12.2.1.3 Solution

To tackle this issue, QKD can be seen as an additional security layer that runs in parallel (or also integrated) to the transport network. QKD can help to mitigate such threats; securing the communications in the control and management plane.

12.2.1.4 Benefits and impact

The adoption of SDN and NFV technologies brings many benefits to networks such as the reduction of the complexity and cost of operating the entire infrastructure or the reduction of vendor lock-in in the systems layer (e.g., NMSs).

12.2.1.5 Economic considerations

Due to the flexibility of the SDN paradigm, an additional layer of QKD can be introduced without disturbing the classical infrastructure in the production nodes of the network. Moreover, this service can be implemented on fibre structures which are already installed and optimize their use.

12.2.1.6 Stakeholder (Actors)/Domains

Typical vertical applications of UC-5-2-1 are for network security and self-healed network management.

12.2.2 UC-5-2-2: Quantum encryption for end-to-end services

12.2.2.1 Use case description

UC-5-2-2 combines QKD systems to secure end-to-end (E2E) services e.g., transport tunnels, VPNs between remote premises. Protocols like patch computation element protocol (PCEP) and multiprotocol label switching (MPLS) are used and modified to use QKD.

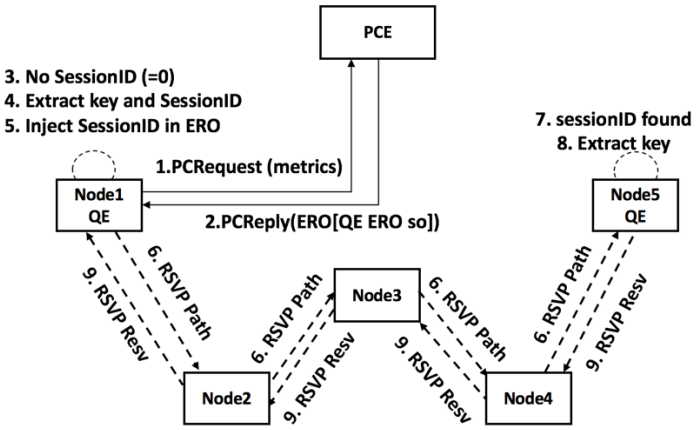


Figure 12-12 – MPLS/PCEP workflow for setting up a quantum encryption service

Figure 12-13 illustrates a logical scheme describing the network used for the E2E quantum encryption service via IPsec. The left part shows the DC management and data networks, with a QKD domain (Bob) and a virtual router connected to a PCE while the right part shows the local network connecting another virtual router to the remote PCE and another QKD domain (Alice). The intermediate area exposes the packet/optical network.

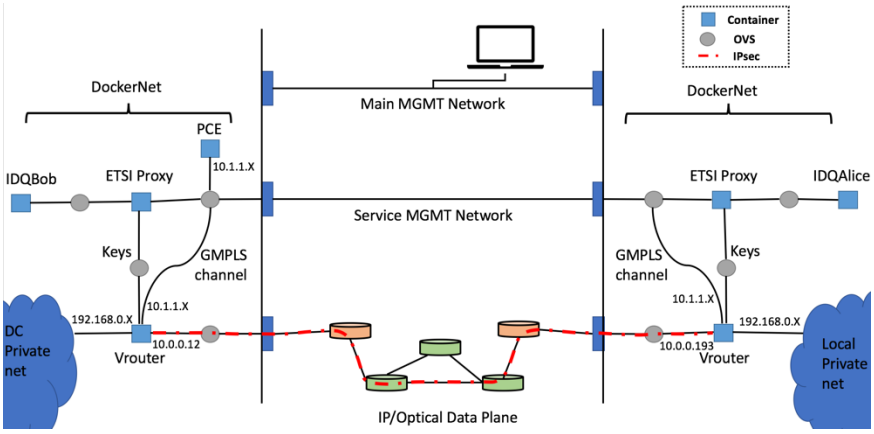


Figure 12-13 – Logical scheme describing the network used for the E2E quantum encryption service via IPsec

12.2.2.2 Problem statement

One of the most demanded capabilities is an increase on the security standards of network services as big corporations have to transfer data securely between their headquarters and data centres. These services rely on underlying security protocols that are at risk of future attacks, more so when speaking about data meant to have everlasting security. Also, depending on the service being deployed, the security can be implemented at different layers e.g., IPsec, MACsec, optical transport network (OTN).

12.2.2.3 Solution

QKD can be seen as a measure to provide such future-proof security if it is appropriately used by other security systems e.g., HSMs, VNFs, network cards, etc. and automated via management systems.

12.2.2.4 Benefits and impact

As SDN and NFV technologies are being progressively adopted in transport networks, they also open the market for new capabilities and services to be provided by the operators. SDN allows new technologies and solutions to be integrated in the network at a faster pace.

12.2.2.5 Economic considerations

Due to the flexibility of SDN paradigm, the additional layer of QKD can be introduced without disturbing the classical infrastructure in the production nodes of the network. Moreover, this service can be implemented on fibre structures which are already installed and optimize their use.

12.2.2.6 Stakeholders (Actors)/Domains

Typical vertical applications of UC-5-2-2 are for network security, enterprise VPNs for business to business (B2B) communications and 5G networks.

12.2.3 UC-5-2-3: Quantum security for service chaining

12.2.3.1 Use case description

A proof-of-transit technique has been developed to verify if a packet has traversed all the nodes within a path. QKD is used to provide order to the proof of transit as well as security enhancement. Figure 12-14 illustrates a representation of an ordered proof of transit scheme in a network. The input and output nodes are connected by a chain of nodes that each packet must travel.

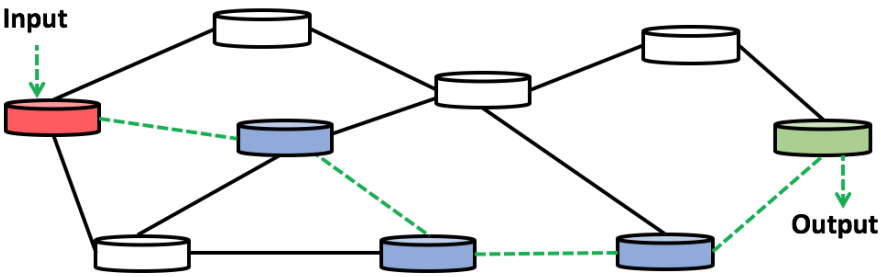


Figure 12-14 – Representation of an ordered proof of transit (OPoT) scheme in a network

Figure 12-15 illustrates the setup for the ordered proof of transit to secure service chaining as it was used in the Madrid quantum network [b-Aguado-3]. Two logical layers are shown: the QKD layer (lower part) and the data, OPoT layer (upper part).

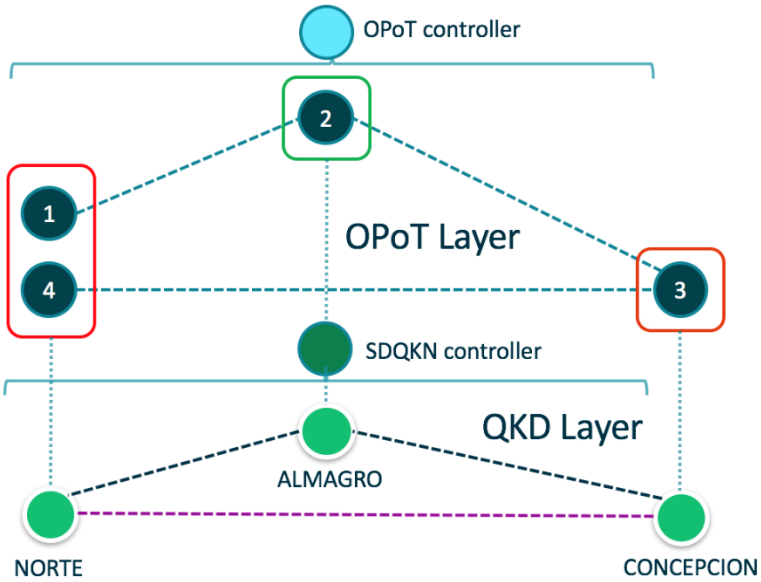


Figure 12-15 – OPoT-DEM: setup for the ordered proof of transit to secure service chaining as was used in the Madrid quantum network

12.2.3.2 Problem statement

The changing behaviour of current network services is forcing operators to evolve from traditional/legacy, non-scalable and rigid networks towards new flexible architectural solutions. The lead on this evolution comes from multiple sources with NFV being one of the most radical and popular trends. It relies on computing virtualization concepts to encapsulate network elements functionalities, or VNFs, in virtual machines or instances which are placed in commodity data centres or cloud computing infrastructure. However, the flexibility brought by these new networking trends also carry associated vulnerabilities and implications. For instance, in a virtualized environment, several functions might be deployed in distributed locations for composing a service function chain (SFC). Both control and data communications must be appropriately secured as any attempt to compromise a virtual function or its behaviour can compromise the entire infrastructure.

A wide-spread concern about virtualized network elements is related to traffic attestation. Any network device deployed in a production network must be capable of assessing if a specific traffic flow passes through it and is correctly forwarded. If a node cannot guarantee this capability, it will not be accepted for production deployment.

By progressively replacing physical network functions (PNFs) with VNFs, this task becomes harder. As traffic traverses multiple intermediate nodes (possibly out of the control of the VNF operator), it could eventually bypass a critical node within the SFC e.g. a firewall.

12.2.3.3 Solution

QKD is used to exchange information between elements within the chain, providing order and an extra layer of security. Having, also, the continuous flow of keys provided by QKD and the speed of symmetric encryption also reduces the overhead and higher flows can be managed.

12.2.3.4 Benefits and impact

This trend allows network resources to be dynamically allocated per-user/service and on demand, thus, permitting a new degree of flexibility in network management, reducing the time-to-market of new network functions, installation time of new services and cost of scaling and operating a network.

12.2.3.5 Economic considerations

Due to the flexibility of SDN paradigm, the additional layer of QKD can be introduced without disturbing the classical infrastructure in the production nodes of the network. Moreover, this service can be implemented on fibre structures which are already installed and optimize their use.

12.2.3.6 Stakeholders (Actors)/ Domains

Typical vertical applications of UC-5-2-3 are for network security and attestation, QKD as a cloud service, critical infra-structure protection, QKD for B2B and 5G networks.

12.3 UC-5-3: QKD in blockchain network

12.3.1 UC-5-3-1: Quantum-secured blockchain

12.3.1.1 Use case description

[b-Kiktenko] proposes a quantum-safe blockchain solution based on QKD.

12.3.1.2 Problem statement

It is well known that blockchain faces a severe security threat from quantum computing as its security is based on public key exchange algorithm, e.g., ECC.

12.3.1.3 Solution

The main idea is to replace the proof of work (PoW) based consensus mechanism with the Byzantine algorithm which does not need public key exchange for authentication. Instead, it relies on QKD to realize information-theoretically secure authentication for pairwise nodes within the blockchain network.

12.3.1.4 Benefits and impact

Due to the abandonment of the public key algorithm in this use case, the blockchain network can be considered as "quantum-safe blockchain".

12.3.1.5 Stakeholders (Actors)/Domains

Blockchain service providers.

12.3.2 UC-5-3-2: Quantum vault for blockchain

12.3.2.1 Use case description

In [b-Huttner], ID Quantique and its partners propose a quantum vault solution to utilize QKD and QRNG to enhance the security of blockchain.

12.3.2.2 Problem statement

The major pain point of blockchain technology is considered to be the secure storage of private keys. The vault is a traditional popular solution used to manage blockchain private keys based on HSM.

12.3.2.3 Solution

The quantum vault solution uses QRNG to produce true random number as secret key seeds and uses the Shamir key sharing algorithm to split the keys into multiple elements and then uses QKD to securely distribute the key elements to distributed distant key storage nodes. The solution is illustrated in Figure 12-16.

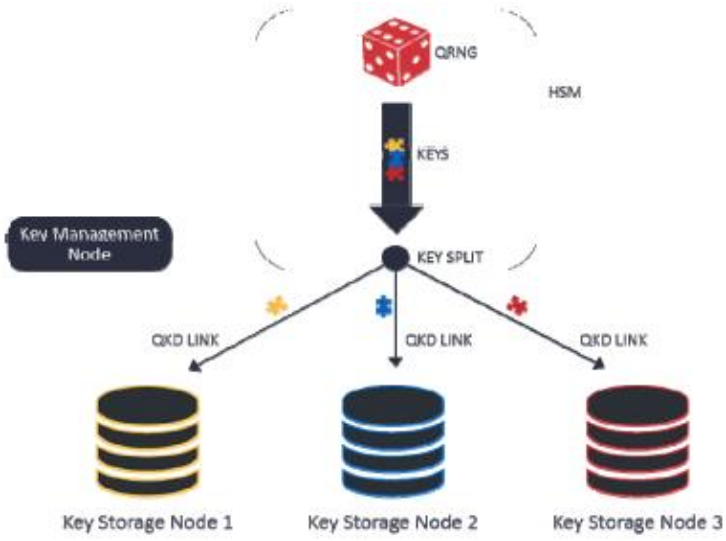


Figure 12-16 – QKD in a quantum-secured blockchain vault

12.3.2.4 Benefits and impact

UC-5-3-2 enhances the security of blockchain by using QKD to securely distribute its private key segments to the distributed key storage nodes.

12.3.2.5 Stakeholders (Actors)/Domains

Blockchain service providers

12.4 UC-5-4: QKD in TSN network

12.4.1 Use case description

The time-sensitive networking (TSN) is one widely applied communication standard developed by IEEE to meet stringent latency and timing requirements of the industrial environment.

Ensuring cybersecurity is also an important requirement in life-critical control systems for which industrial TSN will provide communication. While private key exchange which requires manually pre-sharing keys and public key exchange which requires more computing resources are discouraged for the TSN targeted scenario, QKD can be one possible solution for TSN, as manifested in [b-Avnu].

12.4.2 Stakeholders (Actors)/ Domains

Industrial manufacturers

12.5 UC-5-5: QKD in SCION

12.5.1 Use case description

Despite the fast advancement of internet-based services, the architecture and core protocol have remained mostly the same for decades since the internet's inception. However, to accommodate the ever increasing and diverse data services more efficiently and securely, a new architecture is necessary and several efforts have been made for a next-generation internet architecture. QKD can play an important role in a new internet architecture to enhance the security, which is one of the main concerns that today's internet is facing.

One example use case introduced here is the QKD integration with Scalable, Control and Isolation on Next-Generation Networks (SCION) which is a research project led by researchers at ETH Zurich. SCION aims to offer a communication infrastructure that remains highly available even in the presence of adversaries.

Some typical vertical applications of QKD in SCION include for high-availability communication such as financial networks and industrial control systems used for power distribution. Governments can also use this architecture for critical communication infrastructure such as law enforcement communication.

Achievable security levels: A network is considered secure if it can achieve the desired properties even in the presence of an active adversary. One such prominent property is availability, i.e., the control-, data-, management-, and configuration-planes should be protected such that an adversary cannot disrupt basic communication connectivity.

12.5.2 Problem statement

Since all the E2E symmetric keys are driven from the local secret key in SCION architecture, managing the local secret is critical. As security is one of the main concerns, security enhancements can be added to the SCION architecture by integrating QKD with SCION and using QKD in the making of the local key.

12.5.3 Solution

As the first integration model for a QKD-equipped SCION architecture, QKD is applied to the DRKey setup protocol (one of the SCION extension protocols) which enables network entities to derive symmetric cryptographic keys on the fly from the local secret key.

In DRKey setup protocols, an autonomous system (AS) uses one local secret key to derive a symmetric key for another AS or end host on the fly using an efficient key generation function, pseudorandom function (PRF).

The main advantage of this approach is that the authentication process is extremely efficient. A router can efficiently derive a key for any AS and use it to authenticate packets to this AS. Moreover, it does not need coordination within an AS. If all routers within an AS share a secret SCMP key, each of them can locally and efficiently re-create the SCMP key using the DRKey protocol for any destination AS without any additional communication and without storing any per-AS state.

Assumptions made are:

– **Initial PKI Infrastructure**: it is assumed that each entity has a public/private key pair (K_i^+, K_i^-), and that the public keys are correctly distributed to all other parties.

Figure 12-17 illustrates a high-level overview of the SCION-QKD integration model, which consists of two main components in addition to the server and client:

1) SCION certificate service (CS) which initiates the DRKey protocols, and
2) QKD that ensures the secure key distribution amongst ASes.

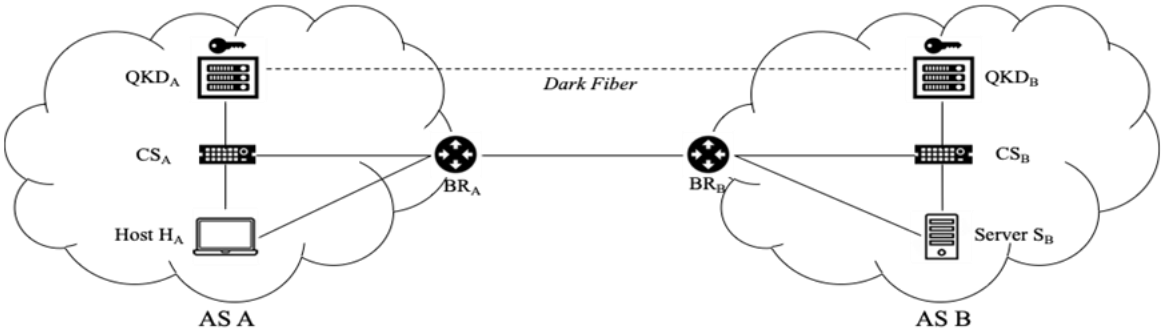
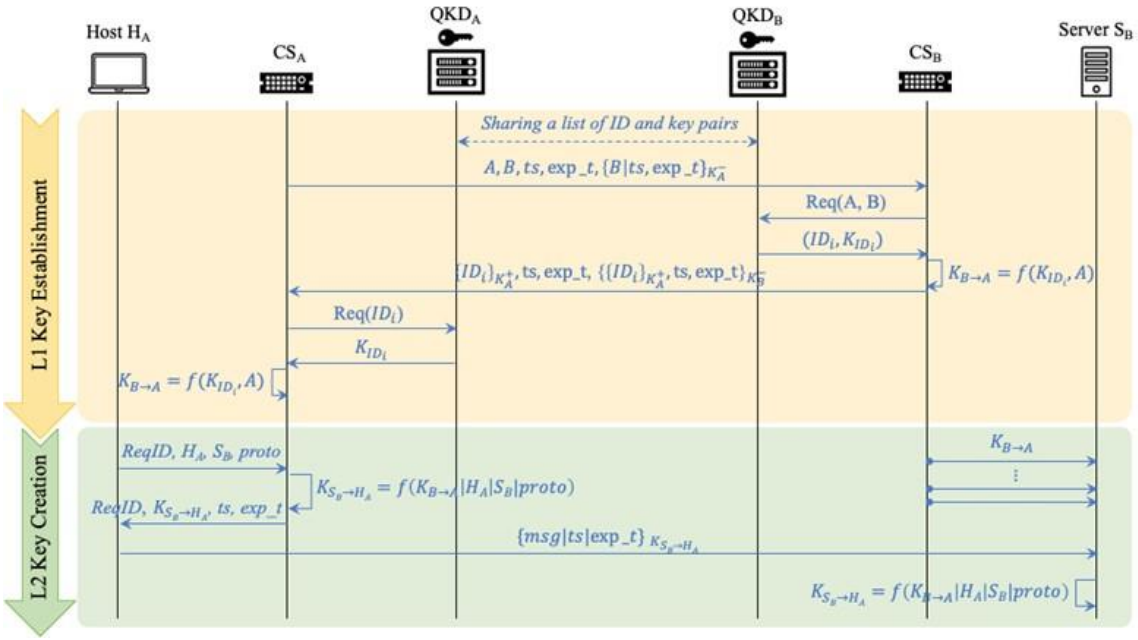


Figure 12-17 – High-level overview of the SCION-QKD integration model

In this integrated model, DRKey distribution process is illustrated in Figure 12-18.



Notations:

– KB → A: Symmetric key shared between AS B and AS A

– KB:SB → A:HA: Symmetric key shared between Server SB in AS B and Host HA in AS A

Figure 12-18 – DRKey distribution process

The detailed steps of the LI and L2 DRKey distribution process are as follows:

1) Local CS (CS_A) initiates the L1 Key establishment protocol to the remote CS (CS_B).
2) With the help of QKDs, CS_B generates a symmetric key ($K_{B \rightarrow A}$) and delivers it to CS_A.
3) CS_B also frequently shares the newly generated L1 keys with all the entities within the AS (e.g., S_B).
4) A local client (H_A) requests an L2 Key from CS_A for communication with S_B.
5) CS_A creates a new symmetric key (L2 Key: $K_{B:SB \rightarrow A:HA}$) using $K_{B \rightarrow A}$ and replies it to H_A.
6) H_A starts communication using $K_{B:SB \rightarrow A:HA.}$
7) S_B also creates $K_{B:SB->A:HA}$ by itself upon packet arrival, and verifies the validity of the packets.

This architecture can be deployed to ISPs' or any end users' (e.g., business or university) network.

Some specific functional requirements include:

- **Latency guarantees**: due to the complexity of inter-domain networks and interactions between high numbers of flows, latency guarantees are very challenging to achieve even in non-adversarial contexts. The key distribution latency for an end-to-end key sharing should be minimal.
- **Global time synchronization**: time-synchronization within a few seconds is required among all entities in the network (i.e., hosts, certificate services, QKDs).

Some standards relevant to UC-5-5 include [b-ETSI GS NGP 001] and [b-ETSI GS NGP 005].

12.5.4 Benefits and impact

QKD can be integrated into the candidate of the next internet architecture, i.e., SCION which is one research project that aims to realize this to add the advanced security measures. QKD keys can be used for local secret keys to drive all the E2E symmetric keys and, in turn, the security enhancements can be added to the SCION architecture as follows:

- **Security in key exchange**: to exchange a first-level key, the certificate services of corresponding ASes need to perform a key-exchange protocol via a secure channel, e.g., using TLS. With QKD, only the key ID is exchanged instead of the key, eliminating threats of on-path adversaries.
- **Key-fetching performance**: to be able to derive second-level keys without additional delay, an AS needs to keep the frequently contacted AS's first-level key proactively. For ASes that are not contacted regularly, on-demand key exchange is required. The QKD-based instant key establishment can reduce the additional delay.
- **Management scalability**: today's Internet consists of more than 71 K active ASes, which is expected to increase. Since QKD supports an instant key establishment, ASes do not need to perform AS-to-AS key establishment, increasing key-management scalability.

12.5.5 Economic considerations

SCION architecture needs border routers capable of encapsulating and decapsulating SCION traffic. SCION AS also needs to deploy certificate, beacon, name and path servers. QKDN supports per-AS key distribution and, assuming that the SCION architecture will exist in an integrated QKDN, an extra cost will be added for QKDN integration.

12.5.6 Stakeholders (Actors)/ Domains

UC-5-5 can be deployed by ISPs and/or B2B users (e.g., enterprises, universities etc).

13 UCC6: QKD applied in different vertical sectors

QKD can be applied in various vertical economic sectors that require high level and long-term security which may include, but are not limited to, the following:

- Finance
- Government and public sectors
- Healthcare, e.g., to secure genome data
- Telecom networks, e.g., to secure 5G network
- Industry networks
- Other critical infrastructures

13.1 UC-6-1: QKDN for smart factory

13.1.1 Use case description

Hyundai Robotics manufactures industrial robots, applies them to overseas industrial facilities and remotely operates through various ICT infrastructure such as IoT devices, leased line and servers. In this process, a malicious hacking threat on optical cable of leased line may cause production disruption due to confidential leaks.

To prevent such problems, a commercial QKDN for the smart factory has been installed to protect corporate information and to enhance security. This network applies QKD to leased line between Hyundai Robotics and KT Corp. office in Daegu, see Figure 13-1 for an illustration.

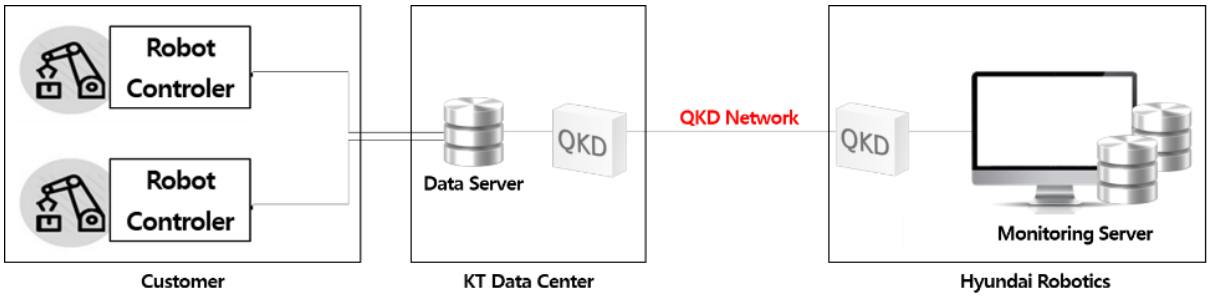


Figure 13-1 – QKDN for smart factory

13.1.2 Problem statement

The main concern for global manufacturing industries is how to support secure remote management and administration since the relative data is related to their know-how and is business sensitive. Existing remote communication between the data centre and customer side is based on legacy telecommunication technologies, such as leased-line, VPN, e-MTC, etc. These communication methods are open to malicious hacking threats to the optical cable, mobile/satellite communication.

13.1.3 Solution

Monitoring and control data requiring the highest security is stored in the data centre of the KT Corp. office; one of KT's business model is the co-located cloud service. The leased line based on optical cable provides connectivity between the KT office and Hyundai Robotics' control centre. A set of QKD systems is installed in both sites (trusted node – secured by each site's own security policy) and supports the QKD-based security (quantum cryptography) for the optical cable.

13.1.4 Benefits and impact

The effort of global manufacturing industries to manage and administrate their products in remote locations through telecommunication technologies should take the security into account. Highly secured communication technology can remove this kind of threat from business/corporate

management strategy. This solution can also be applied to secure mobile and satellite communication-based leased line on wireless and very long distance leased line service.

13.1.5 Economic considerations

Monitoring and managing a manufacturer's products 24/7 in remote locations requires the expense of their human experts working together in/next to the locations. Highly secure communication technology like QKD can eliminate the required human resource and, thus, the expense.

13.1.6 Stakeholders (Actors)/ Domains

Telecom operators and Industrial manufacturers.

13.2 UC-6-2: QKDN for social safety

13.2.1 Use case description

Local governments operate drone-based surveillance system for public safety. In particular, since it is necessary to be careful about information leakage in areas adjacent to military camps, QKD networks are applied to drone communication.

Korea (Rep. of) is deploying a commercial QKDN for social safety and this network applied QKD for drone communication between two adjacent local governments in Gangwon-do, see Figure 13-2.

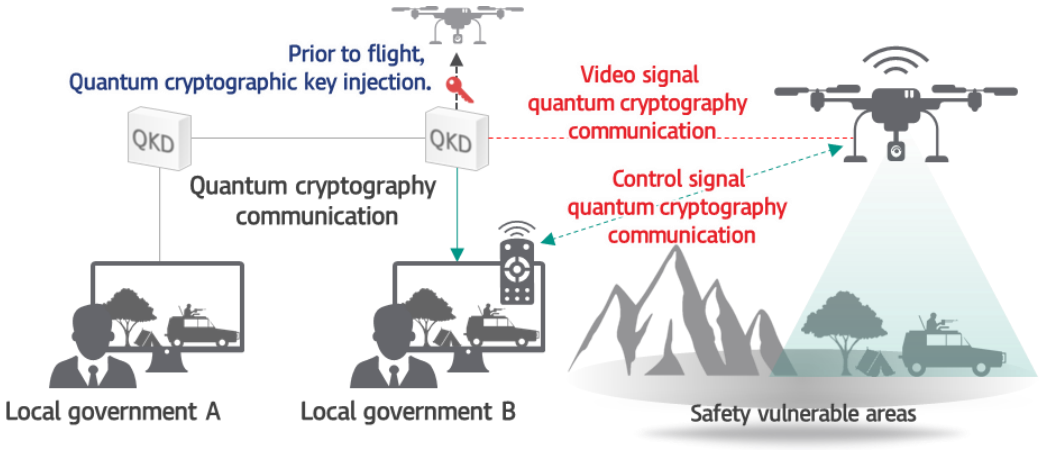


Figure 13-2 – QKDN for social safety

By injecting the quantum encryption key supplied from QKD into the drone, not only is the drone control signal protected, but also the video signal from the drone is encrypted and protected to improve security.

13.2.2 Problem statement

Video data captured from a flying drone requires the highest security to be delivered to the local government. The wireless communication provides connectivity between the drone and the local government's monitoring centre. A set of QKD systems is installed at both ends of the leased-line and supports the QKD-based security (quantum cryptography) into the optical cable. However, the drone is located out of side of QKD connectivity.

13.2.3 Solution

The QKD key generated from QKD systems is injected into the drone prior to it leaving and flying from its mooring position. Then, the drone can communicate the data through quantum encrypted format.

13.2.4 Benefits and impact

Wireless QKD technologies have not been commercially implemented yet as it is challenging for mobile objects such as drones, airplanes, vehicles, etc. QKD key injection in a trusted node/location can compensate this weakness. Before fully wireless QKD technology is realized, this approach could be tentatively acceptable for the security of mobile objects.

13.2.5 Economic considerations

QKD implementation for mobile objects may require a higher expense than QKD for fixed objects. A pre-injection approach can achieve QKD secured communication more cost-efficiently for mobile objects.

13.2.6 Stakeholders (Actors)/ Domains

Telecom operators and local government

13.3 UC-6-3: QKDN for medical centre

13.3.1 Use case description

In St. Mary's Hospital, a large medical institution in Korea (Rep. of)., the central medical data server manages the medical data of branches located in various regions and the branches share medical data such as patient information and medical records through the central medical data server. In this sharing process, there is a possibility that medical information, which is personally sensitive information, may be leaked by hacking.

To prevent such threats, a commercial QKDN has been applied between medical data servers to encrypt medical data and improve security. This network applied QKD to leased line between St. Mary's Hospitals and their data centre in Seoul, see Figure 13-3.

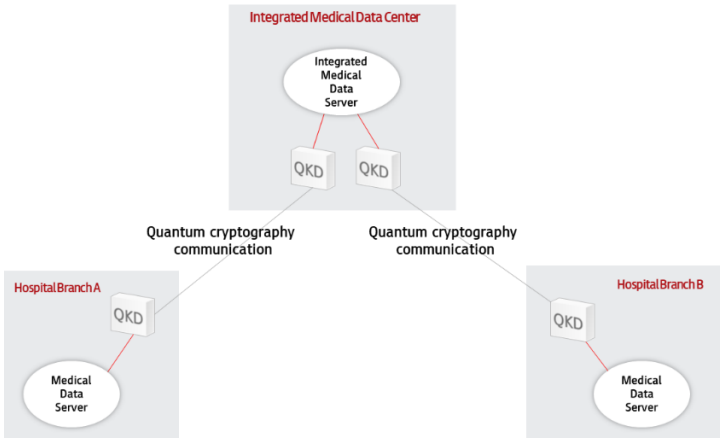


Figure 13-3 – QKDN for medical centre

13.3.2 Problem statement

A main concern for the smart medical industry is on how to support secure remote management and administration between data services and medical centres since the relative data is related to patient privacy. Existing remote communication between the data centre and customer side is based on legacy telecommunication technologies, such as leased-line, VPN, MPLS, etc. These communication methods are open to malicious hacking threats on optical cable, mobile/satellite communication.

13.3.3 Solution

Privacy-sensitive data, such as patient information and medical records, require the highest security when shared between branches of medical centres and their data centres. The leased-line based on optical cable provides the connectivity between them and a set of QKD systems is installed in multiple

sites (trusted node – secured by each site's own security policy) which support the QKD-based security (quantum cryptography) for the optical cable.

13.3.4 Benefits and impact

The medical industry's effort to manage and administer their data in remote data servers through telecommunication technologies should take the security into account. Highly secure communication technology can eliminate this kind of threat from business/corporate management strategy. This solution can also be applied to secure mobile and satellite communication-based leased line on wireless and very long distance leased line service.

13.3.5 Economic considerations

Sharing data stored in a remote data server requires the expense of a dedicated and closed communication network. Highly secure communication technology like QKD can be implemented in a public network environment and eliminate the expense.

13.3.6 Stakeholders (Actors)/ Domains

Telecom operators and medical centres.

13.4 UC-6-4: QKDN for secure mVoIP

13.4.1 Use case description

For mVoIP, there are threats of hacking such as voice terminal wiretapping, voice network wiretapping, and session hijacking attack. To prevent such threats, a commercial QKDN for secure mVoIP was deployed in Korea (Rep. of). This network applies QKD to VoIP communication between two smart phones, see Figure 13-4.

The KSA key is received from the QKDN and injected into the secure communication devices and the mVoIP voice call data is encrypted through the devices.

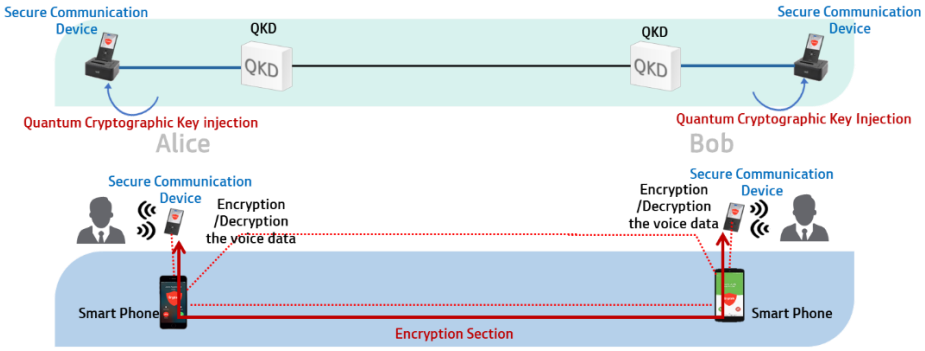


Figure 13-4 – QKDN for secure mVoIP

13.4.2 Problem statement

Voice data requires the highest security when exchanged between smart phones and wireless communication provides connectivity between them.

A set of QKD systems is installed at both ends of the leased-line which supports the QKD-based security (quantum cryptography) into the optical cable, but the smart phones are located outside of QKD connectivity.

13.4.3 Solution

The QKD key generated from the QKD systems is injected into smart phones from charging stations, then, the smart phone can communicate the voice data in a quantum encrypted format.

13.4.4 Benefits and impact

Wireless and portable QKD technologies have not been commercially implemented yet as it is challenging for mobile objects such as smart phone, drones, airplanes, vehicles, etc. QKD key injection in trusted nodes/locations can compensate this weakness. Before fully wireless QKD technology is realized, this approach could be considered as tentatively acceptable for the security of mobile objects.

13.4.5 Economic considerations

QKD implementation for mobile objects may require a higher expense than QKD for fixed objects. A pre-injection approach can achieve QKD secured communication more cost-efficiently.

13.4.6 Stakeholders (Actors)/ Domains

Telecom operators and secure communication service providers.

14 Key findings and suggestions

14.1 Findings from the investigation of QKDN use cases

As one novel and valuable means to implement key distribution function, which is one of the fundamental cryptography primitives, QKDN has a variety of application scenarios in the ICT world as identified in this report.

Although there are a lot of potential use cases, the maturity levels of the identified use cases are still quite different and limited by the maturity of supporting technologies. For example, the QKD key rate is still at Kbit/s level for 100 km distance which cannot support OTP encryption for most services. Thus, QKD combined with AES is popularly applied. QKD for most consumer market applications still face great obstacles due to the high equipment cost, large device size and lack of mobility support.

At present, the application development of QKDN is still at an early stage and requires great effort to promote potential use cases from laboratory or testbed demonstrations to real commercial markets. In this process, standardization will play an important role to stimulate the flourishing of QKDN applications.

14.2 Considerations and suggestions for standardization on QKDN in ITU-T

Current standardization work mostly focuses on the QKDN itself.

For the service layer, it only defines the interface for any application to request and receive keys from the QKDN. What is still absent in standardization concerns how to integrate QKD within certain applications, e.g., certain TCP/IP protocols, cryptographic algorithms.

Service layer standardization is also important to promote QKDN applications, ensure E2E application-level interoperability and facilitate commercial adoption by potential customers. Thus, it is suggested for:

- ITU-T Study Group 11 to study the telecom signalling and protocols to integrate the capabilities of QKDN
- ITU-T Study Group 13 to further study how to integrate QKDN with various future network forms
- ITU-T Study Group 15 to study the application of QKDN in transport networks
- ITU-T Study Group 17 to further study the standardization issues on how to integrate QKDN into various security applications

Appendix I

Overview of QKDN use cases

This Appendix provides an overview of the QKDN use cases considered by the Focus Group on Quantum Information Technology for Networks.

I.1 UCC1: QKD combined with other cryptographic primitives

I.1.1 QKD combined with secret sharing

Use case ID	UC-1-1
Contributor	Thomas Länger; *Austrian Institute of Technology (AIT)*
Short description	This use case describes a distributed cloud archive for long term storage of digital data with advanced security and privacy guarantees. QKD links, as well as other technical and other cryptographic means ensure that the data can securely be transported to the involved cloud providers, and remains integrity protected, as well as confidentiality protected against the storage providers, other tenants of the involved storage clouds, as well as other non-entitled third parties.

I.1.2 QKD combined with SMC

Use case ID	UC-1-2
Contributors	Armando Pinto; *University of Aveiro* Vicente Martín; *UPM – Universidad Politécnica de Madrid*
Short description	This use case describes quantum enabled private recognition of composite signals in proteins and genome. It consists of a service which enables quantum secure multiparty computation to perform private recognition of composite signals. The generation and distribution of quantum oblivious keys are the basis of this novel service. The quantum oblivious keys are generated from the raw keys of a QKD system. This use case is based on use cases UC-5-2-1 and UC-5-2-2.
References	[b-Lemus] and [b-Pinto]

I.1.3 Hybrid QKD and PQC for encrypted communications

Use case ID	UC-1-3
Contributors	Zhangchao Ma; *CAS Quantum Network Co., Ltd.*
Short description	Quantum-safe cryptography is urgently needed to protect systems with high security requirements, as data today can be saved and decrypted later by quantum computers. Both QKD and PQC present opportunities and obstacles. QKD can provide provably-random keys and information theoretic secure distribution of those keys. However, to deploy a QKD system in the real-world, the technology must overcome the transmission distance problem as well as restrictions of point-to-point links, high manufacturing and maintenance cost, and lack of scalability. PQC, on the other hand, is similar to classical cryptography that is algorithm-based. However, deploying a new cryptosystem incurs potentially high cost, with the time and energy consumed by cryptographic computations. In addition, PQC in principle still faces the risk of potential attacks by future mathematical breakthroughs. QKD and PQC can be integrated in the hybrid quantum-safe scheme to enhance data transfer security.
References	[b-Leilei]

I.2 UCC2: QKD integrated with various TCP/IP protocols

I.2.1 QKD integrated in data link layer

Use case ID	UC-2-1
Short description	On the data link layer, QKD may be used as a part of the Point-to-Point Protocol (PPP) protocol. The encryption functionality in PPP is the Encryption Control Protocol (ECP - RFC 1968) which allows the use of encryption in PPP frames. QKD may be used as a key exchange protocol for PPP. QKD may also be used to provide keys for the IEEE 802.1 MACsec layer 2 protocol. As QKD is today mainly implemented as point-to-point link involving two endpoints connected by a quantum channel, it is reasonable to combine a QKD link with a link encryptor to form a QKD link encryptor. Key management is integrated in the link encryptor. For example, this solution may securely bridge two Fast Ethernet networks.
References	Section 6.2 of [b-ETSI GS QKD 002]

I.2.2 QKD integrated in network layer

Use case ID	UC-2-2
Short description	QKD may be used by a modified IKE protocol to provide the shared secret for IPsec payload encryption. The shared secret provided by QKD may either be used in a conventional block or stream cipher for One-Time-Pad payload encryption in a high security context.
References	Section 6.2 of [b-ETSI GS QKD 002]

I.2.3 QKD integrated in transport layer

Use case ID	UC-2-3
Short description	Transport Layer Security (TLS) and its predecessor Secure Sockets Layer (SSL) are layer 4 protocols, which provide end-to-end security for network communication services. A session key, usually established with public key exchange, is used e.g. to secure the transmission of credit card information in e-commerce transactions. In a scenario involving QKD, the session key may be replaced by a QKD key, or the QKD keys may immediately be used for One-Time-Pad encryption of transmission data. QKD keys may also be used for message authentication, replacing Hash-based Message Authentication Codes (HMACs) as used in TLS, or the pseudo-random functions of standard SSL.
References	Section 6.3 of [b-ETSI GS QKD 002]

I.2.4 QKD integrated in application layer

Use case ID	UC-2-4
Short description	Above the transport layer, QKD systems may be integrated in layer 7, the application layer of the OSI model. This may be useful for applications using pre-shared keys for user authentication or for the acquisition or certain rights, or as encryption keys for payload transmission between instances of the application.
References	Section 6.4 of [b-ETSI GS QKD 002]

I.3 UCC3: QKD implemented in various network topologies

I.3.1 QKDN as metropolitan access network

Use case ID	UC-3-1
Contributor	Thomas Länger; *Austrian Institute of Technology (AIT)*
Short description	This use case describes a general-purpose high security communications network between several branches and offices within an area of about 100km in diameter (metropolitan area). The single network nodes are interconnected with dedicated optical point to point links for classical digital communication and quantum key distribution. The network uses a dedicated optical infrastructure, which is completely separated from the internet.

I.3.2 QKDN as inter-city backbone network

Use case ID	UC-3-2
Contributor	*CAS Quantum Network Co., Ltd.*
Short description	In September 2017, the 2000 km Beijing-Shanghai backbone QKD network was put into operation. The backbone network consists of 32 physical nodes linearly connected by QKD links and has 135 links in total. Two to eight multiple QKD links lie between adjacent nodes. The backbone network is designed to function as a high bandwidth channel that feeds quantum keys between metropolitan and QKD networks located in different cities. The backbone network has been connected to four metropolitan QKD networks already established in Beijing, Shanghai, Jian and Hefei.
References	[b-Zhang-1] and [b-Zhang-2]

I.3.3 QKDN as free-space satellite-ground or inter-satellite network

Use case ID	UC-3-3
Contributor	*Beijing University of Posts and Telecommunications, China; CAS Quantum Network Co., Ltd, China; Ministry of Industry and Information Technology (MIIT), China; SpeQtral*
Short description	This use case describes a high security general-purpose long-haul network based on multi-layer satellites around the world. By using satellite as relay, long-distance QKD can be realized within the global metropolises.

I.4 UCC4: QKD with different user device categories

I.4.1 Wireless user device with offline QKD-keys

Use case ID	UC-4-1
Contributors	Zhangchao Ma; *CAS Quantum Network Co., Ltd.*
Short description	This use case describes QKD-key embedded secure mobile communication. To extend QKD service to the mobile terminals is envisioned with high value, but the current physical layer limitations still restrict the direct application of QKD via the air interface between mobile user equipment and base stations. In this use case, the proposed solution is to pre-install the QKD-key pool into the mobile user and network side to enhance security of mobile communication which is achievable with existing QKD techniques.

I.4.2 Wireless user device with integrated QKD module

Use case ID	UC-4-2
Contributors	Zhangchao Ma; *CAS Quantum Network Co., Ltd.*
Short description	As QKD module being miniaturized into chip-scale, it is possible to be integrated into mobile devices to perform wireless QKD service. This use case describes a successful demonstration, by the University of Bristol in the United Kingdom, of the QKD chip transmitter integrated on the credit card, and the QKD receiver in the ATM rack to achieve the free-space quantum key distribution.
References	[b-Sibson]

I.5 UCC5: QKD integrated in various network forms

I.5.1 QKD in 4G/5G networks

I.5.1.1 QKDN for LTE backhaul and 5G backbone

Use case ID	UC-5-1-1
Contributors	Mingeun Yoon and Dong-Hi Sim; *SK Telecom*
Short description	This use case describes a network applying QKD to LTE backhaul between Sejong central office and one of SK Telecom's DU site at Daejeon. A trusted relay node was implemented for long distance QKD networks in 2017. Implementation and commercialization of QKD quantum cryptography for a total of 221km of transmission line between Sungsu central office (Seoul area) and Dunsan central office (Daejeon area) of SK Telecom was accomplished in 2019. It will be extended to Taepyung central office and this will make the end to end distance 380km. Other main cities will be reached with QKD step by step.
References	[b-XSTR-SEC-QKD]

I.5.1.2 Quantum secured inter-domain 5G service orchestrator

Use case ID	UC-5-1-2
Contributors	
Short description	This use case describes QKD technologies in combination with SDN and NFV and their application in securing interconnections of distributed VNFs to achieve quantum secured inter-domain 5G service orchestration. And it was experimentally demonstrated via interconnecting four autonomous 5G islands simultaneously through the q-ROADM with eight optical channels using the 5GUK Exchange orchestration platform.
References	[b-Wang]

I.5.1.3 QKDN for 5G front-haul

Use case ID	UC-5-1-3
Short description	The security guarantee for 5G fronthaul is an important issue which need to satisfy high bandwidth, low latency and high-level security at the same time. QKD is a promising solution to secure 5G fronthaul and this use case describes the application of QKD to secure the 5G fronthaul.
References	[b-Priem]

I.5.1.4 QKDN for 5G mid-haul

Use case ID	UC-5-1-4
Contributors	Mingeun Yoon and Dong-Hi Sim; *SK Telecom*
Short description	The mid-haul is one newly introduced concept in 5G to indicate the connection between DU (Distributed Unit) and CU (Centralized Unit). SK Telecom has showcased the application of QKD to the 5G mid-haul network, in order to secure the confidential data transmission from a smart factory to the cloud. This use case describes how SKT has secured the 5G network connectivity with the latest quantum safe technology using quantum cryptography to best address a customer's security need. This solution combines the latest technology available ensuring high-speed, stability and security for the customer data connectivity.
References	[b-Priem]

I.5.1.5 Quantum security enhancement for universal AKA authentication protocol

Use case ID	UC-5-1-5
Contributors	Chunli Ma, Yong Zhao and Hongyu Wu; *QuantumCTek Co., Ltd.*
Short description	QKDN is used to realize the advantage of secure key distribution. The client UE and the authentication server AAA use QKDN to share keys. Symmetric encryption fully ensures the security of data. The quantum random number generator (QRNG) can generate enough secure true random numbers for the client and authentication server to use in AKA process.
References	[b-RFC4187] and [b-RFC5448]

I.5.1.6 Secondary authentication protocol in 5G based on quantum security

Use case ID	UC-5-1-6
Contributors	Chunli Ma, Yong Zhao and Hongyu Wu; *QuantumCTek Co., Ltd.*
Short description	This use case describes two newly designed schemes EAP_QSSE (Quantum Secure Symmetrical Encryption) and EAP_QSSEH (Quantum Secure Symmetrical Encryption and Hash-function) based on quantum security. Both authentication parties use quantum random numbers as authentication factors, and quantum key distribution network (QKDN) to share keys, for two-way authentication of UE and AAA, to achieve lightweight and fast 5G network secondary authentication in a symmetrical encryption authentication manner.
References	[b-3GPP TS 33.501] and [b-RFC3748]

I.5.2 QKD in SDN/NFV based network

I.5.2.1 Secure SDN and NFV Control and Management Plane

Use case ID	UC-5-2-1
Contributors	Vicente Martín; *UPM – Universidad Politécnica de Madrid*
Short description	The adoption of SDN and NFV technologies brings many benefits to the network, like the reduction of the complexity and costs of operating the entire infrastructure or the reduction of vendor's block-in in the systems layer (e.g., NMSs). However, the network can be affected by some threats that were not present before, as the configuration of the network elements and the images of VNFs must be transferred from central offices, network controllers and orchestration platforms. To tackle this issue, QKD can be seen as an additional security layer that runs in parallel (or also integrated) to the transport network. QKD can help to mitigate such threats, securing the communications in the control and management plane.
References	[b-Aguado-1]

I.5.2.2 Quantum encryption for end-to-end services

Use case ID	UC-5-2-2
Contributors	Vicente Martín; *UPM – Universidad Politécnica de Madrid*
Short description	As SDN and NFV technologies are being progressively adopted in transport networks, they also open the market for new capabilities and services to be provided by the operators. SDN allows new technologies and solutions to be integrated in the network at a faster pace. One of the most demanded capabilities is an increase on the security standards of network services, as big corporations have to transfer data between their secure headquarters and data centres. These services (usually enterprise VPNs for business to business -B2B- communications) rely in underlying security protocols that are at risk of future attacks, more when speaking about data meant to have everlasting security. Also, depending on the service being deployed, the security can be implemented at different layers (e.g., IPsec, MACsec, Optical Transport Network - OTN). Quantum key distribution can be seen as a measure to provide such future-proof security, if it is appropriately used by other security systems (e.g., HSMs, VNFs, network cards, etc.) and automated via management systems. This use-case combines QKD systems to secure end-to-end (E2E) services (e.g., transport tunnels, VPNs) between remote premises. Protocols like PCEP (Patch Computation element Protocol) and MPLS (Multiprotocol Label Switching) are used and modified to use QKD.
References	[b-Aguado-2]

I.5.2.3 Quantum security for service chaining

Use case ID	UC-5-2-3
Contributors	Vicente Martín; *UPM – Universidad Politécnica de Madrid*
Short description	The changing behaviour of current network services is forcing operators to evolve from traditional/legacy, non-scalable and rigid networks towards new flexible architectural solutions. The lead on this evolution comes from multiple sources, being Network Functions Virtualization (NFV) one of the most radical and popular trends. But the flexibility brought by these new networking trends carry associated vulnerabilities and implications. For instance, in a virtualized environment, several functions might be deployed in distributed locations for composing a service function chain (SFC). Both control and data communications must be appropriately secured, as any attempt to compromise a virtual function or its behaviour can compromise the entire infrastructure. A wide-spread concern about virtualized network elements is related to traffic attestation. Any network device deployed in a production network must be capable of assessing if a specific traffic flow passes through it and is correctly forwarded. If a node cannot guarantee this capability, it won't be accepted for production deployment. By progressively changing physical network functions (PNFs) by virtual network functions (VNFs), this task becomes harder. As the traffic traverses multiple intermediate nodes (possibly, out of the control of the VNF operator), it could eventually bypass a critical node within the SFC (e.g. a firewall). In order to mitigate this issue, a proof-of-transit technique has been developed to verify if a packet has traversed all the nodes within a path. QKD is used to provide order to the proof of transit as well as a security enhancement. Having also the continuous flow of keys provided by QKD and the speed of symmetric encryption also reduces the overhead and higher flows can be managed.
References	[b-Aguado-3]

I.5.3 QKD in blockchain network

I.5.3.1 Quantum-secured blockchain

Use case ID	UC-5-3-1
Short description	It is well known that blockchain encounters severe security threat from quantum computing as its security is based on public key exchange algorithm, e.g., ECC. This use case describes a one quantum-safe blockchain solution based on QKD proposed by authors from RQC. The main idea is to replace the PoW based consensus mechanism with the Byzantine algorithm based one. For the new consensus mechanism, it does not need public key exchange for authentication, but it relies on QKD to realize information-theoretically secure authentication for pairwise nodes within the blockchain network. Due to the abandon of public key algorithm, it can be considered as quantum-safe blockchain.
References	[b-Kiktenko]

I.5.3.2 Quantum vault for blockchain

Use case ID	UC-5-3-2
Short description	ID Quantique and its partners have proposed one quantum vault solution to utilize QKD and QRNG to enhance the security of blockchain. It is considered that the major pain point of blockchain technology is the secure storage of private keys. the vault is the traditional popular solution for managing blockchain private keys which is based HSM. Hereby the quantum vault solution utilizes QRNG to produce true random number as secret key seeds and uses Shamir key sharing algorithm to split the keys into multiple elements, and then use QKD to securely distribute the key elements to distributed distant key storage nodes.
References	[b-Huttner]

I.5.4 QKD in TSN network

Use case ID	UC-5-4
Short description	The Time-sensitive Networking (TSN) is one widely applied communication standard developed by IEEE to meet the stringent latency and timing requirements of industrial environment. Ensuring cybersecurity is also an important requirement in life-critical control systems for which industrial TSN will provide communication. While private key exchange which requires manually pre-sharing keys and public key exchange which requires more computing resources are discouraged for the TSN targeted scenario, QKD can be one possible solution for TSN.
References	[b-Avnu]

I.5.5 QKD in SCION

Use case ID	UC-5-5
Contributors	Mingeun Yoon and Dong-hi Sim; *SK Telecom* Jonghoon Kwon; *ETH Zürich*
Short description	Despite the fast advancement of internet-based services, the architecture and core protocol have remained mostly the same for decades since the internet's inception. However, to accommodate ever increasing and diverse data services more efficiently and securely, a new architecture is necessary, and several efforts have been made for a next-generation internet architecture. QKD can play an important role in a new internet architecture for enhancing the security which is one of the main the concern that today's internet is facing. One example use case introduced here is the QKD integration with SCION (Scalable, Control and Isolation on Next-Generation Networks) which is a research project lead by researchers at ETH Zurich. SCION aims to offer a communication infrastructure that remains highly available even in the presence of adversaries.
References	[b-ETSI GS NGP 001] and [b-ETSI GS NGP 005]

I.6 QKD applied in different vertical sectors

I.6.1 QKDN for smart factory

Use case ID	UC-6-1
Contributors	Miryeong Park, Chun Seok Yoon and Hyungsoo Kim; *KT Corp.*
Short description	A commercial QKD network for smart factory is being deployed in Korea. This network applied QKD to leased line between Hyundai Robotics and KT office in Daegu. Hyundai Robotics manufactures industrial robots, applies them to overseas industrial facilities, and remotely operates through various ICT infrastructure such as IoT device, leased line and servers. In this process, a malicious hacking threat on optical cable of leased line may cause production disruption due to confidential leaks. To prevent such problems, the QKD network is installed to protect corporate information and to enhance security.

I.6.2 QKDN for social safety

Use case ID	UC-6-2
Contributors	Miryeong Park, Chun Seok Yoon and Hyungsoo Kim; *KT Corp.*
Short description	A commercial QKD network for social safety is being deployed in Korea. This network applied QKD to drone communication between two adjacent local governments in Gangwon-do. Local governments operate drone-based surveillance system for public safety. In particular, since it is necessary to be careful about information leakage in areas adjacent to military camps, QKD networks are applied to drone communication. By injecting the quantum encryption key supplied from QKD into the drone, not only the drone control signal is protected, but also the video signal from the drone is encrypted and protected to improve security.

I.6.3 QKDN for medical centre

Use case ID	UC-6-3
Contributors	Miryeong Park, Chun Seok Yoon and Hyungsoo Kim; *KT Corp.*
Short description	A commercial QKD network for medical centre was deployed in Korea. This network applied QKD to leased line between St. Mary's Hospitals and their data centre in Seoul. In St. Mary's Hospital, a large medical institution, the central medical data server manages the medical data of branches located in various regions, and the branches share medical data such as patient information, medical records through the central medical data server. In this sharing process, there is a possibility that medical information, which is personally sensitive information, may be leaked by hacking. To prevent such threats, a QKD network is applied between medical data servers to encrypt medical data and improve security.

I.6.4 QKDN for secure mVoIP

Use case ID	UC-6-4
Contributors	Miryeong Park, Chun Seok Yoon and Hyungsoo Kim; *KT Corp.*
Short description	A commercial QKD network for secure mVoIP was deployed in Korea. This network applied QKD to VoIP communication between two smart phones. In mVoIP, there are threats of hacking such as voice terminal wiretapping, voice network wiretapping, and session hijacking attack. The KSA key is received from QKDN and injected into the secure communication devices. The mVoIP voice call data is encrypted through the devices.

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