Architecture of the Secoqc Quantum Key Distribution network

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Abstract

The European projet Secoqc (Secure Communication based on Quantum Cryptography) [1] aims at developing a global network for unconditionally secure key distribution. This paper specifies the requirements and presents the principles guiding the design of this network, and relevant to its architecture and protocols.

1 Introduction

The performance of Quantum Key Distribution (QKD) systems have notably progressed since the early experimental demonstrations. The current evolutions in QKD research [2, 3, 4, 5, 6] indicate that the pace of this progression is very likely to be maintained, if not increased, in the future years. In parallel to these improvements of QKD techniques, commercial products are also being developed [7], making QKD deployment a feasible alternative for securing real data networks.

Deployment of a real QKD network is however far from being straightforward. It requires development of a network architecture connecting multiple users that may possibly be very far away from each other. Considering the fact that the existing QKD links are only point-to-point, and intrinsically limited in distance, deployment of a practical QKD network structure is a nontrivial problem, which is the target of European FP6 integrated project Secoqc [1]. As a part of the Secoqc project, in this paper, we describe the proposed architecture for a QKD network. We also specify the

requirements relevant to the network design, protocols, and services. The objective of this specification is to define the major components and their main features.

The rest of this paper is organized as follows. In section 2, we start by a brief account on the interest and applicability of quantum key distribution to secure communications. In section 3, we expose the motivations for the development of QKD networks and provide a survey of the previous works on QKD networks. Some major design decisions of the Secoqc QKD network are discussed in this context as well. In Section 4, we specify the architectural view of the Secoqc QKD network, including the components and their connections that are essential for the design of network structure and protocols. Finally, in Section 5, we specify the services types provided by the QKD network and discuss the important requirements related to these services.

2 Application of QKD to Secure Communications

Distributing keys among a set of legitimate users while guaranteeing the secrecy of these keys with respect to any potential opponent is a central issue in cryptography, known as the "key distribution problem". There are essentially two methods currently in use to solve the key distribution problem over deployed secure communication systems: 1) public key cryptography and 2) secret couriers.

Public-key cryptography foundations rest on the difficulty of solving some mathematical problems for which no polynomial algorithms are known. The computing resources needed to solve these problems become totally unreachable when long enough keys are used. Public-key cryptographic systems thus rely on what is called computational security. Public-key cryptography is however not unconditionally secure; the problems on which it is based are not intractable; and in addition, their non-polynomial complexity has so far not been proven.

The secret courier method is known since the ancient times: a trusted courier travels between the different legitimate users to distribute the secret keys, hopefully without being intercepted or corrupted on his way by any potential opponent. Only practical security can be invoked in this case, which has to be backed by the enforcement of an appropriate set of security measures. Although secret couriers become costly and unpractical when implemented on large systems, this technique has remained in use in some highly-sensitive environments for which public-key cryptography is

thought to be inappropriate, such as government intelligence or defense. Quantum Key Distribution, invented in 1984 by Charles Bennett and Gilles Brassard [8] based on some earlier ideas of Stephen Wiesner [9], is an alternative solution for solving the key distribution problem. In contrast to public-key cryptography it has been proven to be unconditionally secure, i.e., secure against any attack, whatever time, computing power or any other resources that may be used [10, 11]. QKD security relies on the laws of quantum mechanics, and more specifically on the fact that it is impossible to gain information about non-orthogonal quantum states without perturbing these states [12]. This property can be used to establish a random key between two users, commonly called Alice and Bob, and guarantee that the key is perfectly secret to any third party eavesdropping on the line, commonly called Eve.

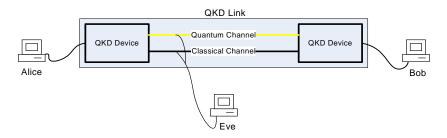


Figure 1: Structure of a QKD link as it is referred throughout this article

Without going in the details of the different implementations or protocols, we can describe the structure and the principle of operation of the basic practical QKD system: a QKD link. As depicted on Fig. 1, a QKD link is a point-to-point connection between two users, commonly called Alice and Bob, that want to share secret keys. The QKD link is constituted by the combination of a quantum channel and a classical channel. Alice generates a random stream of classical bits and encodes them into a sequence of non-orthogonal quantum states of light, sent over the quantum channel. Upon reception of those quantum states, Bob performs some appropriate measurements leading him to share some classical data correlated with Alice's bit stream. The classical channel is then used to test these correlations. If the correlations are high enough, this statistically implies that no significant eavesdropping has taken place on the quantum channel and thus that a perfectly secure symmetric key can be distilled from the correlated data

shared by Alice and Bob. In the opposite case, the key generation process has to be aborted and started again.

3 QKD networks

There are several fundamental limits regarding what can be achieved with standalone QKD links. QKD links can by definition only operate over point-to-point connections between two users, which greatly restricts the domain of applicability of quantum key distribution within secure communication networks. Furthermore, since all QKD links rely on the transmission of quantum information in order to guarantee security against online eavesdropping, they will always remain intrinsically limited in rate and distance, and cannot be deployed over any arbitrary network topology. To overcome those limitations, it seems important to study what can be achieved by networking QKD links in order to extend the extremely high security standard offered by QKD to the context of long distance communications between multiple users. The development of QKD network architectures appears from this perspective as a necessary step towards the effective integration of QKD into secure data networks.

What we will call a QKD network throughout this paper is an infrastructure composed of QKD links connecting multiple distant nodes. The essential functionality of the QKD network is to distribute unconditionally secure symmetric secret keys to any pair of legitimate users accessing the network. These first elements of definition are however fairly generic and can be refined. Indeed, even though we are at the infancy of the development of QKD networks, different models of QKD networks have already been proposed. The first QKD network demonstrator, the "DARPA Quantum network", has been deployed between Harvard University, Boston University and BBN in 2004 [14, 15].

It is convenient to characterize the different QKD network models by the functionality that is implemented within the nodes. We can, in this perspective, differentiate three main categories of network concepts, based on different "families" of node functionalities: 1) optical; 2) quantum; and 3) trusted relay.

"Optical QKD nodes" stands for nodes where some classical optical function, like beam splitting, switching, multiplexing, demultiplexing, and etc., is implemented on the quantum signals sent over the quantum channel. The interest of such optical networking functionalities is that they allow to go beyond 2-users QKD. One-to-many connectivity between QKD

devices was demonstrated over a passively switched optical networks, using the random splitting of single photons upon beam splitters [16]. Active optical switching can also be used to allow the selective connection of any two QKD nodes with a direct quantum channel. The BBN Darpa quantum network [14, 15] contains an active 2-by-2 optical switch in one node, that can be used to actively switch between two network topologies. Optical functions can thus be used to realize multi-user QKD and the corresponding nodes do not need to be trusted, since quantum signals are transmitted over an quantum channel with no interruption from one end user QKD device to the other one. Such QKD network model can however not be used to extend the distance over which keys can be distributed. Indeed, the extra amount of optical losses introduced in the nodes will in reality shorten the maximum span of quantum channels.

To be able to extend the distance on which key distribution can be performed, it is necessary to fight against the degradation of quantum signal along its propagation on the quantum channel. This process, known as decoherence [17], is typically quantum and can only be taken care of by the use of nodes which are able to perform some active transformations on the quantum signals sent over the quantum channel. We will call such nodes quantum nodes. Quantum nodes can be of different flavors, but all rely on entanglement, that can be used as a resource for secure key generation [21]. Indeed, as explained in [18], a network of distant quantum memories each of them able to store a share of a multipartite entangled states can be used for quantum cryptographic purposes. In this perspective, the main challenge of quantum nodes is to distribute entangled states over long distances. The most elaborated quantum nodes proposed so far are quantum repeaters [19]. They use entangled photon sources, quantum memories and purification of entanglement to obtain perfect entangled states, stored in nodes, over a quantum channel segment. Such segments are then chained and entanglement swapping used to obtain end-to-end perfect entanglement over an arbitrary long distance. Quantum repeaters however rely on elaborated quantum operations and on quantum memories that cannot be realized with current technologies. As discussed in [20], quantum nodes called quantum relays could also be used to extend the reach of QKD. Quantum relays are simpler to implement that quantum repeaters since the do they don't require quantum memories. Building quantum relays remains however technologically difficult and would not allow to extend QKD reach to arbitrary long distances.

Classical trusted relays can on the other hand be implemented with today's technologies since such nodes consist in classical memories, that we will call key stores, placed in secure locations. QKD networks based on trusted key relays follow a simple principle: local keys are generated over QKD links and then stored in nodes that are placed on both ends of each link. Global key distribution is performed over a QKD path, i.e. a one-dimensional chain of trusted relays connected by QKD links, establishing a connection between two end nodes, as shown on Fig. 2. Secret keys are forwarded, in a hop-by-hop fashion, along QKD paths. To ensure their secrecy, one-time-pad encryption and unconditionally secure authentication, both realized with a local QKD key, are performed. End-to-end information-theoretic security is thus obtained between the end nodes, provided that the intermediate nodes can be trusted. Classical trusted relays can be used to build a long-distance QKD network. They have been used in the BBN QKD network [14, 15] and will also be used to build the Secoqc QKD network [1].

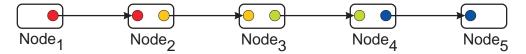


Figure 2: "Hop-by-hop" unconditionally secure message passing on a path made of trusted relay nodes connected by QKD links. Message decryption / re-encryption is done at each intermediate node, by using one-time-pad between the local key, distributed by QKD, K_{local} , and the secret message M resulting in the ciphered message $M \oplus K_{local}$. Different key association are symbolized by different colors. This figure is taken from [22]

The focus of the Secoqc project is on "long-range high security communications" based on quantum key distribution". As explained above, this imposes to rely on trusted nodes used as key relays. We have adopted this network model within the Secoqc project. An important choice is however the way the local keys are used to secure long-distance traffic. The main originality of the Secoqc project with respect to previous works on QKD networks relies in the fact that we have opted for a dedicated key distribution network infrastructure that we have called "network of secrets" [24]. The functionality of the network of secrets is solely to store, forward, and manage the secret key materials generated by QKD. Such key distribution network is characterized by dedicated link, network and transport layers and can be considered somehow independently of the quantum key generation processes and on the key requests arising from application.

The central design issue behind this concept is that the keys are stored and managed within key stores, placed in nodes, and not within QKD devices or within the machines running endpoint secure applications. This design choice allows to manage keys over a dedicated global network (the network of secrets) composed of key stores linked together with classical channels. The network of secrets is by essence a classical network but we will call it the "Secoqc QKD network" or "the QKD network" in the rest of this paper since we will always assume that the underlying key generation mechanism, responsible for filling the key stores, is quantum key distribution. We present the architecture of this QKD network in the next section.

4 Architecture of the Secoge QKD Network

In this section, we explain the proposed architecture of the Secoqc QKD network and its components. The purpose is to provide an abstract perspective which gives a clear picture of the components and the environment for designing the details of network protocols. We also discuss the expected functional and nonfunctional requirements of the QKD network.

4.1 QKD Network Structure

Many interesting network functionalities arise from the fact that the network graph of QKD links and QKD nodes may provide redundant paths between any two nodes. Within Secoqc, we have decided to focus on such topologies for our QKD network. Such redundant topologies are typically found in the core of communication networks. This is the reason why we are referring to Quantum Backbone (QBB) nodes for the central and multiply-connected nodes within our QKD network.

The architecture of the Secoqc QKD network is illustrated in Fig. 3: the QKD network is composed of a set of Quantum BackBone (QBB) nodes that are connected by QBB links in order to distribute unconditionally secure keys between any pair of application programs that are running on host computers. The whole structure constitutes a global key forwarding backbone network. In this network, the host computers are connected to different QBB nodes across the network. Alternatively, an application program can run on a host computer which is connected to a Quantum Access Node (QAN). QAN is a node with limited capabilities; it implements very little routing functionalities, but is more specialized in providing access interface to many client applications. As shown in Fig. 3, the QAN

is connected to a QBB node via a secure connection, e.g., a QKD link. The application programs that intend to have secure communications over a public network, such as the Internet, can use the QKD network for generation of unconditionally secure session keys. These session keys, can then be used for cryptographic purposes. It has to be emphasized that the QKD network will not carry the real data traffic among application programs. The sole responsibility of the QKD network is to share secret keys with unconditional security. The actual communications, as shown in Fig. 3, are performed on the existing public or private networks.

Upon the request of an application program, namely the master application program, the ingress QBB or QAN node, which is the access point for the master application program, examines the possibility of providing a path for the requested destination with the desired Quality of Service (QoS). The destination application program, namely the slave application program, obviously, must be connected to another QBB or QAN node, which is referred to by the egress QBB or QAN node. If the QKD network has enough resources, it will accept the request for path establishment. Otherwise, the request will be rejected. If the path is established successfully, upon the request of the master application program, the ingress QBB or QAN node generates a random session key and forwards it through the QKD network to the egress QBB/QAN node, which will deliver the key to the slave application program. In its way through the QKD network the session keys will be secured through hop-by-hop one-time-padding using the local keys. Local keys, that are information theoretically secure, are established via QBB links between adjacent QBB nodes. As shown in Fig. 3, QBB nodes are located inside private and secure networks (sites). Regarding that the local keys are unconditionally secure and that the QBB nodes are inside secure locations, we can conclude that the QKD network can be used for global distribution of unconditionally secure session keys. Note that the QBB links, which connect adjacent QBB nodes, are deployed over potentially unsecured locations; thus, they are vulnerable to different types of security threats. However, hop-by-hop one-time-padding assures security of session keys. Furthermore, redundant paths over the QKD network can be utilized by the routing and forwarding protocols to combat Denial of Service (DoS) attacks.

From the network point of view, QBB nodes are analogous to the routers in the traditional inter-networking infrastructures. We will discuss the main components of the network, i.e., the QBB links and the QBB nodes, with further details in the subsequent sections of this paper.

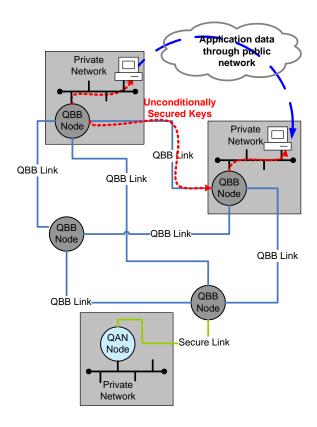


Figure 3: The structure of the Secoqc QKD network

4.2 QBB Links

The QBB links are special links, connecting QBB nodes together. As shown in Fig. 4, each QBB link consists of:

- 1. arbitrary number of quantum channels to send quantum bits;
- 2. a classical channel for signaling and forwarding of session keys.

Quantum channels are used to send quantum bits, and the classical channel is used for signalling and session key forwarding. There might be several quantum channels between two adjacent QBB nodes to improve the effective key generation rate. However, since an extra pair of quantum devices is required to establish a single quantum channel, the economical

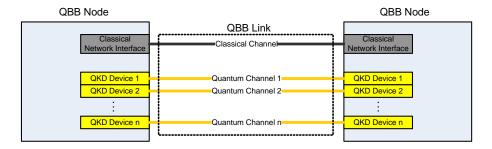


Figure 4: QBB link

factors might hinder establishment of multiple quantum channels. Referring to the classical notion of QKD link in Section 2, a QBB link is an extension of a QKD link, which allows to improve effective key generation rate. The importance of this parallel structure can be revealed if we consider the typical dependency between the length of a QKD link and the effective key generation rate as shown in Fig. 5. The vertical axis shows the effective key

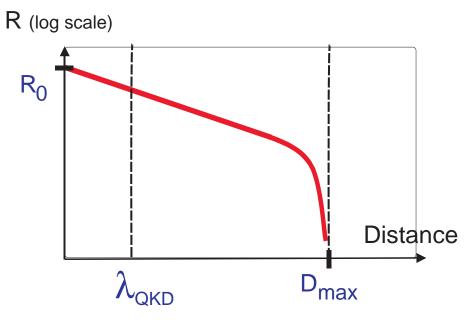


Figure 5: Typical profile of the Rate versus Distance curve for a single QKD link.

generation rate, and the the horizontal axis shows the distance between the QKD devices. Three essential parameters can be used to characterize the shape of this curve:

- 1. The secret bit rate at zero distance, R_0 . It is typically in the range 100 kbit/s to a few Mbit/s for current technologies.
- 2. The scaling parameter λ_{QKD} . As long as the signal to noise ration is high enough and therefore the error rate well below some security threshold, the logarithm of the secret bit rate scales linearly with distance: $R(l) = R_0 \, e^{-l/\lambda_{QKD}}$. The scaling parameter is platform and protocol dependent, but typically varies between 5 and 25 km for QBB candidates platforms [23]
- 3. The maximum distance D_{max} . This distance is also platform and protocol dependent and can vary from 20-30 km for short distance systems to 100-120 km for long-distance systems.

Stand-alone quantum channels are not sufficient to establish unconditionally secure local keys. Further signalling through a complementary classical channel is required to extract unconditionally secure keys from the raw key materials, derived from the measurements of quantum bits. In the Secoqc QKD network, the session keys are forwarded by the QBB nodes in their path to the destination over the classical channels. The classical channel is also used for other purposes, e.g., routing messages, network management messages, and etc. The classical channel is a virtual channel rather than a physical channel. That is, it could be either established over a public network through a TCP/IP socket or it could be a direct point-to-point link between two adjacent QBB nodes. The classical channels in the QKD network are not secure channels. Proper cryptographic algorithms must be used if the communication has to be secured using the local keys which are generated by the QKD devices. For example, if some routing messages have to be authenticated, a proper scheme must be implemented.

It is important to note that quantum channels are subject to a variety of security threats by adversaries. However, the responsibility of QKD protocols [8] is to generate local keys between QBB nodes while being able to detect eavesdropping. Two QKD devices will succeed to extract a secure key from the raw key materials obtained from measurements of quantum bits provided that the quantum bit error rate is below some security threshold [13]. If the raw key bits contain too many errors, security with respect to eavesdropping cannot be guaranteed, thus, the raw key bits are discarded.

Obviously, an adversary can interrupt the key stream between two nodes by measuring the quantum signals, introducing too many errors. One objective of the QKD network is thus to enhance resiliency of key distribution by providing redundant paths among QBB nodes. This implies that the network protocols should be able to detect possible attacks on the individual links and react to them by choosing proper forwarding paths between QBB nodes.

4.3 QBB Node

QBB nodes are the main elements of the QKD network. Similar to routers in a conventional network, they forward session keys across the QBB network. They can also serve as access points for key clients (i.e., application programs). Physically, QBB nodes are special computers with multiple QBB interface ports, enabling connection to multiple QBB links. Each QBB node can also have multiple QKD devices to create parallel QKD links on each individual QBB link. The QKD devices can operate over different types of quantum channels and rely on different technologies, provided that they comply with the QBB node's standard interface. There is also an interface for classical channel on each QBB port. The logical structure of the software components of a QBB node is shown in Fig. 6. The major software components are: 1) Multiple instances of Quantum Point-to-Point Protocol (Q3P) [24] modules which serve as the link layer modules for the QBB links; 2) a routing module which is responsible for collecting and maintaining the local routing information; and 3) a forwarding module for maintaining paths and making forwarding decisions. All other software modules such as node management, local connection management, random session key generator, security monitor and etc. reside inside the box denoted by "other modules". We do not elaborate on the other modules in this paper as they have no or little interaction with networking responsibilities of a QBB node.

Q3P module manages all link level communication issues between two adjacent QBB node. A Q3P module includes a submodule for managing the communications over a classical channel, including functionalities for 1) authentication; 2) encryption/decryption; 3) fragmentation/assembling; 4) flow control; 5) link level error control; 6) congestion control, if the classical channel is established through a public network; 6) connection management between two adjacent QBB nodes. Q3P module also includes a submodule which acts as an array of device drivers for the QKD device array. This module collects local keys from the QKD devices and deliv-

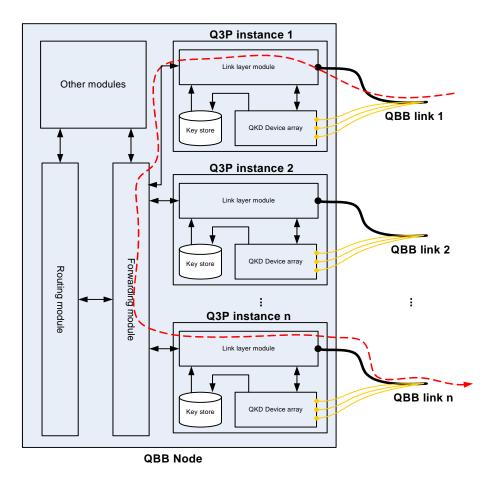


Figure 6: QBB node

ers them to a key store. Note that the QKD devices constantly generate local keys at their maximum key generation capacities. The QKD device drivers also allow the QKD devices to share a single classical channel as it is needed for key generation process inside the QKD devices. Another important submodule of a Q3P module is the key store. The main purpose of the key store is to compensate low key generation rate of QKD devices by accumulating a big database of ready to use local keys which will be used for local cryptographic operations between two adjacent QBB nodes that are connected by a QBB link. Having the key stores, QBB nodes can tolerate secret key traffic bursts by buffering keys which are generated at a

constant rate, but will be consumed with a random rate.

To function as a router, the QBB node incorporates modules for key forwarding and routing. The key forwarding module examines the destination address or the virtual circuit number of the incoming network key packets, performs necessary processing, and forwards them to the appropriate output buffer corresponding to a particular Q3P instance. An example of forwarding path inside a QBB node is illustrated by the dashed curve in Fig. 6. A scheduling scheme prioritizes departure of packets from the buffer to the destination Q3P instance according to the QoS requirements of the buffered key packets. Forwarding module also manages virtual circuits if necessary. This includes call admission control, and traffic policing. Forwarding module also creates and terminates virtual circuits inside a QBB node. In order to enable key packet forwarding, a QBB node includes a module for calculation and maintenance of routing information, e.g., routing tables.

5 Requirements of Services Provided by the Key Distribution Network Layer

In this section, we classify and specify the types of services that will be provided by the Secoqc QKD network. This will help selecting proper routing and forwarding scheme for the QKD network. Simply put, the QKD network should provide unconditionally secure and synchronized keys for the consuming application peers. A typical scenario can be explained by regarding the specified architecture in Section 4: an application program, running on a host computer which is connected to a QBB or QAN node, intends to open a secure connection to another application, running on another host which is also connected to another QBB or QAN node. An example could be an email client which is to setup an SSL connection to a mail server. Another example is when a security gateway attempts to establish a VPN connection through IPSec to another security gateway. Currently, these applications rely on a preset shared secret or certified public keys to generate session keys. However, they can be modified to send their request to a QBB/QAN node to establish a path through the QKD network to the other end point. The key request should contain information about:

- 1. the address of the destination node;
- 2. the port number of the destination application;

- 3. the QoS parameters such as key refreshment rate;
- 4. the key block length.

The ingress QBB node, which has received the request, tries to establish such a connection through QKD network by examining the local routing information and negotiation with the other QBB nodes that might participate in establishing the connection. If the path establishment is accomplished successfully, the ingress QBB node replies to the request of the initiating application with a positive message. In this case, the egress QBB node informs the other party by sending an appropriate message. Otherwise, if the path establishment fails due to insufficient available resources or other reasons, appropriate acknowledgment is sent out to the initiating application program. The failure acknowledgment message could offer the initiating application with the best available QoS. After path establishment process, the QKD network should maintain the connection, and forward secret key which will be generated by the ingress QBB node to the Egress QBB node reliably.

Regarding the aforementioned overview of the services of the QKD network, some of the functional requirements of the QKD network are:

- 1. creation and maintenance of proper routing information which will be distributed among QBB nodes;
- 2. establishment and maintenance of paths between Ingress and Egress QBB nodes;
- 3. forwarding of secret keys by OTP through specified paths;
- 4. coping with possible network and link level errors;
- 5. monitoring security of the established path.

In terms of QoS, the initial implementation of the QKD network will provide the following service types.

1. Best effort: for this type of service, a consuming application will be allowed to transmit session keys with an average rate, λ_k , and burst of σ_k . For this type of service, the QKD network do not provide any guarantee of QoS; the (λ_k, σ_k) pair only specifies the upper bounds on the request of the customer. In other words, a customer with this type of service may receive less than what specified by the upper bound. However, note that, regardless of the type of service, the QKD network provides a reliable session key transport.

2. Guaranteed key rate: for this type of service, the QKD network guarantees a certain rate of session keys. More specifically, the customer is allowed to ask for certain amount of keys within a certain period of time. For instance, a customer may sign a contract for 128 kbits of key materials every one second. Note that in this context, the QKD network can only give a statistical guarantee of service.

An important nonfunctional requirement of QKD network is load balancing by choosing proper paths which might not be the shortest paths. This is important as the QBB links have limited capacities. This also implies that the algorithms and schemes that heavily rely on encrypted or authenticated signalling messages will not be reasonable choices for the QKD network. Let's finally mention that QKD network routing and forwarding algorithms also should be resilient against link failure since such failures may be directly due to the detection of security threats by some security monitoring agents.

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