The Status of Quantum-Based Long-Term Secure Communication over the Internet

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Abstract. Sensitive digital data, such as health information or governmental archives, are often stored for decades or centuries. The processing of such data calls for long-term security. Secure channels on the Internet require robust key establishment methods. Currently used key distribution protocols are either vulnerable to future attacks based on Shor’s algorithm, or vulnerable in principle due to their reliance on computational problems. Quantum-based key distribution protocols are information-theoretically secure and offer long-term security. However, significant obstacles to their real-world use remain. This paper, which results from a multidisciplinary project involving computer scientists and physicists, systematizes knowledge about obstacles to and strategies for the realization of long-term secure Internet communication from quantum-based key distribution. We discuss performance and security particulars, consider the specific challenges arising from multi-user network settings, and identify key challenges for actual deployment.

Keywords: Quantum cryptography; Confidentiality; Long-term security; Quantum key distribution; Information-theoretic security.

1 Introduction

The basis for exchanging a vast amount of information in today’s world is the Internet — a network that spans the earth and allows any two parties to communicate with each other. If sensitive information is about to be transmitted (e.g., medical records or governmental documents), secure connections must be established to protect confidentiality, integrity, and authenticity. The most common method for establishing such a secure connection is to use the Transport Layer Security (TLS) protocol \cite{21}, which combines a key distribution protocol with a channel protocol. First, the key distribution protocol is run to establish
a common secret key unknown to a potential eavesdropper tapping the communication. Then, the obtained key is used in the channel protocol to encrypt and authenticate the transmitted data, protecting its confidentiality and integrity.

Currently, the most commonly used key distribution protocol is based on the Diffie–Hellman key exchange [22]. Diffie–Hellman key exchange provides so called computational security. Its security is based on the assumption that computing discrete logarithms in certain groups is computationally infeasible (i.e., it would take a prohibitively long time for the computation to finish). However, it has been shown that quantum computers can efficiently compute such discrete logarithms [67] and, therefore, Diffie–Hellman key exchange is rendered insecure once quantum computers are available. Recently, alternative key distribution protocols based on lattice cryptography have been proposed (e.g., [3,9]) that are conjectured secure against quantum computers. However, in principle, these protocols are potentially still vulnerable to computational attacks as their security is based on a computational problem. Such computationally secure key distribution protocols achieve security only for a limited period of time, i.e., as long as attackers do not have sufficient computational power to break the security and obtain the exchanged secret keys.

An alternative to computational security is information-theoretic security. Information-theoretically secure components are not vulnerable to computational attacks (e.g., brute force attacks) and therefore provide long-term security against them. Channels providing long-term confidentiality require information-theoretically secure key distribution and encryption. The integrity demands for such a channel are usually only temporary (computational), that is, it is sufficient to guarantee integrity while the data is in transit. While substantial effort has been made to define, understand, and construct computationally secure channels (originating, e.g., from [6]), a thorough understanding of how to construct information-theoretically secure channels achieving standard security goals of confidentiality and integrity as well as replay and reordering protection is still lacking. For information-theoretic encryption, one-time pad (OTP) encryption [66] is an optimal solution. We remark, however, that any information-theoretically secure encryption scheme requires the secret key to be of the same length as the encrypted data. There exist several candidates for information-theoretically secure key distribution. A naive approach is to distribute keys using a trusted courier that physically delivers a generated key stored on a hard drive. This approach, however, suffers from obvious disadvantages with regards to practicability because it requires hours of traveling by the courier, which is far too long for most practical applications. Other approaches for information-theoretically secure key distribution are protocols in the bounded storage model [49] or the noisy channel model [77]. However, it is currently unclear how these models can be realized in practice [12]. Currently, the most promising approach for information-theoretically secure key distribution is Quantum Key Distribution (QKD). The security of QKD is based on the laws of quantum physics and its feasibility has already been demonstrated in many field tests [16,25,55,61]. However, there are still several challenges in order to realize
QKD-based long-term secure communication on the Internet. The performance and security of implementations of QKD protocols is still an issue. Furthermore, techniques need to be developed that allow using QKD-based secure channels in distributed networks with many users.

In this work, we first discuss the current state of quantum-based key distribution protocols with regards to performance and security (Sec. 2). We then discuss the current state of enabling QKD in multi-user networks (Sec. 3). Finally, we summarize the challenges yet to be addressed in order to realize QKD-based long-term secure communication on the Internet (Sec. 4).

2 Quantum-based Key Distribution

We now describe the state of the art for QKD. We first explain relevant concepts of quantum physics, then we categorize and summarize prominent QKD protocols. Next, we compare the performance of the protocols, and finally we discuss security models and attacks on protocol implementations.

2.1 Quantum Physics Background

QKD protocols rely on fundamental laws of quantum physics: the typical change of state of a quantum object after a measurement and the impossibility to copy a quantum state without disturbing the state of the original particle. Security of QKD protocols relies on the fact that a potential eavesdropper reveals himself by the process of his attack. Eavesdropping introduces inevitable errors to the exchanged quantum states that can later be detected by the communicating parties.

At the core of every QKD protocol lies the exchange of quantum states. In contrast to modern optical communication systems, where classical bits are encoded as an absent (0) or present (1) “classical” laser pulse in a certain time interval, QKD uses qubits — quantum objects, that can carry more than one bit of classical information at a time and exhibit a behavior that cannot be described within classical physics. Very different physical systems can serve as qubits: single photons, weak laser pulses, Fock states and squeezed states of light, half-spin quantum systems as trapped atoms and ions, or Rydberg atoms coupled to a cavity [10]. Quantum information can be encoded using different types of observables, i.e., physically measurable properties of qubits. For example, information can be encoded using polarization, phase, creation time of single photons, or quadrature, phase and amplitude of multi-photon coherent laser states [10,64].

2.2 Common Functionality

We now sketch the functionality that is common to all QKD protocols discussed later. These protocols comprise a raw key distribution phase and a post-processing phase.
Raw key distribution. The first part of every QKD protocol establishes a raw secret key by transmission of qubits over a special quantum channel. Ideally, such a channel should not alter the encoded information due to interaction of qubits with the transport medium (e.g. a change of polarization in a glass fiber). Distortions must be kept low in order to fulfill the requirements for a successful key distribution, because disturbances of the qubit states may have also been caused by an attacker.

During the raw key distribution phase, the communicating partners exchange qubits over the quantum channel. Upon receiving a qubit, the recipient performs a measurement on some observable of the qubit and decodes a classical bit from its result according to a procedure determined by the chosen QKD protocol. Afterwards, the communicating partners consult about their measurements using a classical authenticated channel. This procedure is specific to each QKD protocol and the result is a raw secret key. If they deduce that an attacker might have disturbed the quantum information too severely, the key distribution has to be started over.

Post-processing. After the raw key distribution phase, each of the communicating partners has obtained an individual raw key. Perfectly correlated keys are very improbable, so error correction (e.g. low density parity check [26], cascade [11], or polar codes [37]) has to be performed. Afterwards, privacy amplification is applied to generate the final key from the error-corrected raw key. This ensures security even against an eavesdropper that may have observed a small number of bits undetected during the raw key exchange or the error correction. The resulting secret key can then be used as a key for OTP or Advanced Encryption Standard (AES) encryption.

As described above, QKD requires an authenticated classical channel between the communicating partners. Such an authenticated channel can be established using a short pre-shared secret or by relying on a typical TLS connection. Recently, it was proposed to realize authenticated channels based on laws of quantum physics [29,54]. We remark that the authenticated channel used in a QKD protocol needs to remain secure only while the QKD protocol is executed.

2.3 Protocol Families

There are many different ways QKD protocols are implemented. For our analysis, we categorize them by the way information is prepared (prepare-and-measure or entanglement based) and by the type of variables (discrete variables (DV), continuous variables (CV), or distributed phase reference (DPR)).

Classification by information preparation method. We describe categories for QKD protocols based on how the quantum states are prepared.

Prepare-and-measure. In prepare-and-measure protocols (Fig. 1a), a sender Alice actively prepares an information carrier, encodes information within it and
sends it to one or more recipients. Prominent representatives of this protocol category are the protocol developed by Bennett and Brassard (BB84) \cite{bb84} or derived protocols, such as \cite{bb84,Brassard93}.

**Entanglement-based.** Entanglement-based protocols (Fig. 1b) involve a source producing entangled particles — multiple quantum objects that can be described by a correlated quantum state violating local realism \cite{bell}. A measurement on some observable of one of the objects instantly affects the state of the other object. This can be observed by Bell tests \cite{bell} — a procedure allowing the verification of the useful entanglement \cite{bell} of the initial particles. The qubits are detected by the communicating parties, and, because of the non-classical correlations between these particles, Alice and Bob can share a (quantum) secret without direct exchange of information. A prominent representative of this protocol category is the E91 protocol, developed by Ekert \cite{ekert91}.

![Alice Bob](a) ![Alice Bob Source Bob](b)

**Fig. 1.** (a) Prepare-and-measure protocol (e.g. BB84 \cite{bb84}), (b) Entanglement-based protocol (e.g. E91 \cite{ekert91}). Solid line denotes the quantum channel, dashed line stands for the authenticated classical channel. Arrows denote the direction of information flow.

**Classification by the type of variables.** QKD protocols can also be classified by the type of variables used for the information carriers.

**Discrete variables.** For the protocols with discrete variables (DV), the values of the information carrying observables are discrete. Most commonly, qubits are transmitted using single photons or weak laser pulses. In principal, half-spin particles (e.g. electrons) can also be used, but the transmission of such particles is problematic. The information can be encoded, for example, in time, polarization, spin, or phase. The source can be implemented as a prepare-and-measure system or as an entanglement-based system. DV protocols require expensive and inefficient single-photon source and detector devices. Prominent representatives of this protocol category are \cite{bb84,Brassard93,ekert91,bb84,Brassard93}.

**Continuous variables.** Continuous variable (CV) protocols are an alternative to DV protocols that, instead of qubits (e.g. single photons and weak laser pulses), use many particle states (e.g. squeezed or coherent states of light). Hereby no discrete variables are detected — zeros and ones — but the observation of the continuous spectrum of the quadrature components of light is performed, e.g., by
homodyning techniques [20]. Detection of quantum states is also performed differently in CV protocols compared to DV protocols. Here, standard components for quantum communication are used. For instance, homodyne or heterodyne detection schemes [20] (In homodyne schemes, the signal and a local oscillator have identical frequencies. In heterodyne schemes, these frequencies differ) are employed. This is much faster and more efficient than the detection of single photons. Most of these protocols can be implemented both as prepare-and-measure as well as entanglement-based schemes. Prominent representatives of this protocol category are [30,57].

Distributed phase reference. A third family of QKD protocols — distributed phase reference (DPR) protocols — uses discrete variables for encoding of information, but at the same time the security is guaranteed by observing the coherence of subsequent pulses. Bits may be encoded in a sequence of pairs of pulses [69] or in the phase of subsequent pulses [36]. The two approaches may also be combined into a two dimensional QKD protocol [4], where several bits can be encoded by two subsequent pulses. DPR protocols require similar devices as DV protocols, namely, single photon sources and detectors. Prominent representatives of this protocol category are [4,36,69].

2.4 Existing Protocols

In the following, we briefly summarize the functionality of a few prominent QKD protocols and assign them to the categories presented above.

BB84. The first QKD protocol was proposed by Bennett and Brassard in 1984 (BB84) [7]. This protocol is a prepare-and-measure protocol, belongs to the DV protocol family, and uses discrete states of photons for information encoding. The information can be carried by polarization or by the phase of single photons.

The BB84 protocol with polarization encoding works as follows (see Fig. 2): Alice chooses randomly one bit — 0 or 1, and one of two polarization bases: rectilinear, denoted as $\boxplus$, or $\pm 45^\circ$, denoted as $\boxtimes$. Then, Alice encodes that bit within the chosen basis and sends it to Bob. Bob also chooses a basis randomly and independently from Alice, in which he detects the photon. Statistically, in half of all cases his choice does not correspond to the basis chosen by Alice. If Bob chooses a wrong basis, he can measure the correct bit with a probability of 50%, so an error rate of 25% is introduced. To get rid of these errors Alice and Bob exchange publicly over an authenticated classical channel information about their chosen bases and dismiss all of the events detected in the wrong bases. This procedure is called key sifting. Afterwards, parts of the sifted key are exchanged between Alice and Bob, compared, and their quantum bit error rate (QBER) is estimated. If the QBER does not exceed 20% [17], a secure connection can be established using two-way error correction and privacy amplification. For this, post-processing algorithms are used as described in Sec. 2.2 and a secret key is distilled.
Another milestone in DV QKD protocols is the protocol proposed by Ekert in 1991 (E91) [23]. It was the first entanglement-based protocol that does not require the source to be a part of either Alice’s or Bob’s setup. A source of entangled photons distributes distinct photons of a qubit pair to the different communicating partners Alice and Bob. Then, Alice and Bob choose a detection basis randomly and independently, perform measurements, and obtain a raw key. With a random subset of this raw key, they test for a violation of Bell’s inequalities. If the test succeeds, Alice and Bob start key sifting, error correction, and privacy amplification procedures as in BB84. Otherwise, they have to start the key distribution over again.

In Fig. 3 the CV protocol implemented by Grosshans and Grangier is shown [30]. Here, a single-mode coherent state produced by a laser at the wavelength of 1550 nm is modulated in one of its quadratures $p$ or $q$ by using a random, Gaussian distributed modulation. Then the signal is transmitted over a noisy channel to Bob, who measures only one of the quadratures using homodyne techniques. Therefore, a local oscillator (e.g. laser light) has to be implemented locally by Bob or transmitted over the quantum channel from Alice. The choice of the quadrature is performed by the addition of the phase $\phi \in \{0, \pi/2\}$ randomly to the local oscillator. Information reconciliation and error correction are performed after the detection.

2.5 Performance

The aforementioned QKD protocols can be run over free space or via glass fibers. Depending on the communication medium, different secret key generation rates and effective distances are observed. Typical key rates for DV protocols are up to several kbit s$^{-1}$ on the distance of several 10 km and up to several bit s$^{-1}$ over approximately 100 km distance (cf. Tab. 1) via fiber cables. Recently, DV-based quantum key distribution via satellite has been demonstrated over a distance of 1203 km at a key rate of 1 kbit s$^{-1}$ [43]. For CV protocols the key rate is comparable — up to 10 kbit s$^{-1}$ for channels of a few km and up to 150 km effective distance. In Tab. 1 performance measures for fiber based QKD protocols are listed. For all QKD protocols, the key rate decreases exponentially with the distance.
Fig. 3. Schematic of a CV protocol, as in [30] with homodyne detection. AFG is an Arbitrary Function Generator.

communication distance due to noise and losses in the quantum channel. It has been proven that the maximal key rate depends solely on these losses [72, 60]. Lost information is assumed to be gained by a potential attacker in the case of prepare-and-measure protocols, resulting in a failed protocol execution. In the case of entanglement-based protocols, this reduces the violation of the Bell inequality, ultimately leading to a failed Bell test and protocol execution.

Table 1. Performance of different protocols. PaM: prepare-and-measure protocols, EB: entanglement-based protocols.

| Protocol       | Type | Source | Key rate at 100 km | Max. dist. |
|----------------|------|--------|--------------------|------------|
| Yin [78] (2016)| DV   | EB     | 2 kbit s\(^{-1}\) | 404 km     |
| Korzh [41] (2015)| DPR | PaM    | 10 kbit s\(^{-1}\) | 307 km     |
| Wang [75] (2012)| DPR | PaM    | 20 kbit s\(^{-1}\) | 260 km     |
| Stucki [70] (2009)| DPR | PaM    | 6 kbit s\(^{-1}\)  | 250 km     |
| Liu [13] (2010)  | DV   | PaM    | 15 bit s\(^{-1}\) (200 km) | 200 km     |
| Huang [35] (2016)| CV  | PaM    | 500 bit s\(^{-1}\) | 100 km     |
| Honjo [34] (2007)| DV  | EB     | 0.50 bit s\(^{-1}\) | 100 km     |
| Jouguet [38] (2013)| CV  | EB     | 200 bit s\(^{-1}\) (80 km) | 80 km      |

Besides the key rate and distance, the compatibility of the system with the existing communication infrastructure is important. For example, DV QKD protocols require quite expensive single photon detectors, single- or entangled-photon sources and precise time measuring devices. Simultaneously, the typical distribution distances and rates for the secret key distribution allow for use only in
metropolitan network areas. Imperfections in the single-photon sources make photon number splitting attacks possible (see Sec. 2.6).

CV protocols are a more recent class of protocols that offer higher secret key rates and lower costs for implementation, because neither single photon sources nor single photon detectors are required. Standard components for optical communication can be used. A recent experiment showed that CV protocols can be applied even in a geostationary satellite for standard optical communication achieving much longer communication distances [31]. However, the security of CV protocols against side-channel attacks is not as well understood as for DV protocols [20,42] (cf. Sec. 2.6).

DPR protocols currently achieve the best performance results (Fig. 1). Furthermore, multi-dimensional QKD schemes, such as DPR protocols, allow to transmit more than one bit of classical information in a single qubit [4].

2.6 Security

A QKD protocol is considered secure if, after the protocol execution, the communication partners Alice and Bob know a common secret key and an eavesdropper Eve has not obtained any information about the key. We now summarize work analyzing the security of QKD protocols and discuss theoretical and practical attacks on implementations of QKD.

Security models and proofs. When analyzing the security of a QKD protocol the goal is to show security against a powerful attacker, Eve, that potentially possesses perfect technology. For example, Eve may be able to extract and store qubits for an arbitrary duration and perform any quantum operation or measurement on them. However, according to fundamental quantum physical laws, Eve can neither clone nor measure the state of the system perfectly and resend a new particle without leaving a trace. In addition, usually the existence of an authenticated classical channel between the communication partners or a short pre-shared key is assumed. This is necessary to guarantee data integrity and authenticity, so that Eve cannot perform an impersonation attack or change the classical data sent. We stress that the authenticated channel does not need to provide any confidentiality guarantees.

An attack on a QKD system is called individual if Eve measures each qubit separately. In a collective attack, Eve still interacts with each qubit separately, but she may measure all the auxiliary systems used for the interactions jointly. If Eve is allowed to attack several sent qubits simultaneously, the attack is called coherent. Renner et al. [58] prove the security of a wide range of QKD protocols against coherent attacks.

QKD security proofs rely on information theory and do not depend on computational hardness assumptions. This fundamental difference in comparison to currently used key distribution methods guarantees the long-term security of QKD. However, idealized assumptions in QKD security proofs lead to incomplete security models. For realistic security guarantees about actual implementations,
more assumptions regarding hardware and software are required. Indeed, attacks exploiting imperfect devices and insecure software may be possible, as we describe below.

Depending on protocol families, proven security guarantees against theoretical attacks vary. While some DV protocols have been shown to be unconditionally secure [45, 68], similar proofs for CV and DPR protocols are still missing. An overview of security proofs for CV protocols is given by Diamanti, Kogias, Laudenbach and others [20, 40, 42]. A security analysis of DPR protocols is provided by Moroder et al. [51].

As an example, we discuss the security of BB84 against an intercept-resend attack, which is a special case of an individual attack. In this attack, Eve chooses a basis randomly and detects the state of particles. She has a probability of 50% to choose a wrong basis. Afterwards, she prepares a replacement for the detected qubit and sends it to Bob. In that way, she induces a 25% QBER in Bob’s key. However, as shown by Shor and Preskill, Alice and Bob know the key distribution session might have been compromised [68] if the QBER exceeds 11%. Other strategies, for example, detection of not every qubit or detection using an intermediate basis are disadvantageous for Eve, since she obtains less information about the secret key. In the case of entanglement-based protocols, during the measurement of qubits, Eve destroys the nonclassical correlations between the particles, so a Bell test during the key processing fails. In summary, security proofs for QKD protocols show that an attacker reveals himself when trying to eavesdrop on the quantum states sent over the network. This is what makes QKD so powerful in comparison to classical key distribution.

**Attacks on implementations.** Even for protocols that have been proven unconditionally secure, side-channels and non-perfect setups can lead to weaknesses. Every single implementation then requires a special treatment. As for classical cryptography, the developers of QKD systems search for any kind of weakness in their implementation. Security proofs have to be adapted and side-channels must to be analyzed.

For example, the creation of tailored single photons is non-trivial. In most cases, there is a non-negligible probability for pulses with a photon number larger than 1. Thus, if there is more than one photon in a weak laser pulse, Eve can pick some photons with a beam splitter and gain information without being noticed. This type of attack is called a photon number splitting attack. As a countermeasure, protocols have been modified: decoy states have been added to BB84 [47] and new protocols, such as SARG04, have been developed [63].

Hijacking a quantum channel by a trojan horse attack, information about Alice’s and Bob’s setups can be extracted [28] or even manipulated [38]. For example, if Eve obtains information about Alice’s choice of bases in real-time, she can perform a successful intercept-resend attack as she is no longer limited to guessing the bases randomly.

Another possibility is bright illumination of Bob’s detectors via the quantum channel. This can allow the attacker to control the measurement results of Bob.
Lydersen et al. describe how an attacker could successfully obtain the complete secret key and remain unnoticed [48].

Crucially, all these attacks must be performed physically and during the actual key distribution. This is a fundamental difference to classical key distribution protocols, whose security might be broken by attacks that were unknown at the time of the distribution.

**Device-independent QKD.** Device-Independent QKD is an approach aiming to dispense with the assumption of trust in the own setup hardware [50]. Hereby, the security of the whole QKD system should be evaluated by a quantum-correlation test, i.e., a Bell test, similar to the E91 protocol [74]. Since purely device-independent protocols are hard to realize, measurement-device-independent QKD protocols have been developed [46, 73, 78].

3 Quantum-based Key Distribution in Multi-User Networks

So far, we have discussed QKD in a setting where two communicating partners are connected directly by a dedicated quantum channel. However, in reality dedicated communication channels usually do not exist between every two communicating partners. Instead, communicating partners are connected via hubs through which the communication is routed. To realize long-term secure communication using QKD technology, hubs need to be developed that are compatible with QKD. In the following, we first describe how the Internet is organized using hubs and thereby identify requirements for QKD protocols that should be used in such networks. Then, we discuss two approaches for realizing QKD hubs which allow for using QKD in a hub-based network.

3.1 Network Characteristics of the Internet

The Internet consists of an extensive number of different types of devices that potentially communicate with each other. These devices may be small (e.g. mobile phones, wearables) or large (e.g. desktop computers). Communication should be possible between any two devices and the devices should be able to join and leave the network dynamically. Distances between the devices may be very long (e.g. several thousand of kilometers) and many services run on the Internet require low latency (e.g. less than a second) and high transfer rates (e.g. several megabits per second). These properties are achieved on the Internet by using a multi-layer network topology consisting of local area networks, metropolitan area networks, and wide area networks. The different network layers are connected via hubs (Fig. [4]). Messages exchanged between clients are routed through these hubs. Secure end-to-end communication is usually achieved by establishing a TLS connection between any two end points.
3.2 Trusted Node-based Hubs

Network hubs for QKD can be realized using trusted nodes. In this approach, key material is not directly exchanged between the communicating partners but relayed over the trusted nodes. Here, each of the communicating partners, Alice and Bob, are connected to a trusted node in close distance and the trusted nodes are also connected (Fig. 5). In order for Alice and Bob to establish a secure connection, they exchange keys with their trusted nodes, and the trusted nodes also exchange keys between themselves. Then, an end user key for Alice and Bob is computed from the key material generated on the communication path. This method for key distribution in distributed networks only provides security as long as none of the trusted nodes on the communication path is compromised [24].

On the positive side, such hubs allow to extend the distance limitations imposed by QKD protocols. Assuming there exist sufficiently many trusted nodes between the communicating parties, keys can be relayed several times and QKD distance limitations only account for each key relay individually. On the negative side, we have seen that trusted node-based hubs do not support end-to-end security because the quantum states are destroyed in each hub.

The feasibility of building a trusted node based QKD network has been shown in several field tests: DARPA network in 2005 [25], in Austria in 2008 [55], in Japan in 2011 [61] and China [76]. Currently, a 2000 km long link connecting Beijing to Jinan, Hefei and Shanghai is being installed [19].

3.3 Quantum Hubs

An alternative approach for building QKD networks is to use quantum hubs [32]. Here, the quantum information carriers are routed from Alice to Bob directly
without any detection or optical-electrical-optical conversions in between. One can either use active optical switches [18,15] or wavelength division multiplexing (WDM) to address different recipients. Recently, several experiments showing entanglement distribution via WDM in glass fiber at telecommunication wavelengths have been reported [27,14].

A novel approach for such all-optical network is an extension of entanglement-based DV protocols. Such a quantum hub works for entanglement based protocols (e.g. E91 or BBM92) and is depicted in Fig. 6. The photons are created in the quantum hub at distinct wavelengths and then distributed to different end users by using standard wavelength division multiplexing techniques. Such quantum hubs allow for real end-to-end security.

Quantum hubs have similar distance limitations as the corresponding QKD protocols. To overcome the distance limitations, quantum repeaters (QR) have been proposed in 1998 as a device that allows to distribute entangled particles over arbitrarily long distances [13]. The desired distance is divided into shorter intervals as in Fig. 7. Within every interval entanglement is shared in a standard way by creating entangled particles $A - A'$ and $B - B'$ and distributing them
to the interval ends, where photons $A'$ and $B$ are measured jointly, e.g., by a Bell measurement, such that the remaining pair of particles $A$ and $B'$ becomes entangled. This procedure is known as entanglement swapping. Since the timing is a crucial factor in this process, the photons have to be stored in a quantum memory, where the quantum objects can be stored for a long time without distortion of their states. Various architectures of quantum repeaters have been suggested and various elementary parts of it have been implemented \cite{2,33,59,60} and analyzed \cite{1,52}. However, an integrated setup has not yet been finished.

\begin{center}
\includegraphics[width=0.3\textwidth]{repeaters.png}
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**Fig. 7.** Schematic structure of a quantum repeater.

4 Challenges & Outlook

We summarized the current state of realizing long-term secure communication on the Internet on the basis of quantum technology. To achieve this goal, practical quantum-based key distribution protocols that can also be used in a multi-user network setting are required. We have discussed the functionality, performance, and security of the most prominent candidates for quantum-based key distribution protocols. They currently allow for data rates of approximately $20 \text{ kbit s}^{-1}$ over a distance of 100 km. A maximum communication distance of 404 km can be achieved at a data rate of $10^{-4} \text{ bit s}^{-1}$. Quantum-based key distribution in multi-user networks is currently realized using relay nodes, which must be trusted to not compromise the confidentiality of the transmitted data. Furthermore, we discuss an approach for realizing quantum hubs that allow for quantum-based key distribution in multi-user networks without trusted nodes. We also briefly summarize work on quantum repeaters that would allow to remove the distance limitations of current QKD technology.

In view of the current state of QKD technology, we identify the following open challenges for realizing QKD-based long-term secure communication on the Internet:

- The data rate of QKD protocols needs to be further improved so that comparable data rates as in classical communication can be achieved.
- Candidate QKD protocols need to be identified that allow for a secure implementation resistant to known theoretical and practical attacks.
Secure connection protocols (e.g., TLS) need to be re-designed to support QKD-based information-theoretically secure key distribution. Understanding is furthermore needed in how to combine information-theoretic confidentiality with integrity and message-ordering protection in a channel protocol, taking into account real-world aspects like message fragmentation or bi-directional communication.

The proposed approaches for realizing quantum hubs need to be implemented and their practicality has to be shown.

The practicality of quantum repeaters needs to be shown in implementations and it must be shown how they can be combined with quantum hubs in order to allow for QKD in a wide area multi-user network like the Internet.

Progress towards a wider deployment of QKD was made this year, in the shape of initial experiments performing QKD communication or preparing it with satellites [31,71]. These initiatives suggest the possibility of a satellite-based free-space network, where satellites are trusted nodes and out of reach for attackers. Alternatively, drones could be used to create such a network [62]. For the future, it is envisioned that quantum channels are combined to realize the so called quantum Internet [39]. Such an Internet infrastructure would constitute a significant advancement in quantum information processing allowing for novel applications, such as quantum secret sharing [53] and distributed quantum computation, which so far have only been explored theoretically.

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