In principle, quantum key distribution (QKD) offers information-theoretic security based on the laws of physics. In practice, however, the imperfections of realistic QKD devices might introduce deviations from the idealized models used in the security analysis. Can quantum code-breakers successfully hack real QKD systems by exploiting the side channels? Can quantum code-makers design innovative counter-measures to foil quantum code-breakers? This article reviews theoretical and experimental progress in the practical security aspects of quantum code-making and quantum code-breaking. After numerous efforts, researchers have extensively understood and managed the practical imperfections, and the recent advances, such as the measurement-device-independent QKD protocol, have closed the critical side channels in the physical implementations, enabling secure QKD with realistic devices.

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Bob with the private key can decrypt the cipher text to recover the plain text efficiently. The security of public key cryptography is based on computational assumptions. Given the public key, there is no efficient known algorithm for Eve to work out the private key or to recover the plain text, from the cipher text. For instance, the security of the best-known public key crypto-system, RSA (Rivest et al., 1978), is based on the presumed hardness of factoring large integers. Unfortunately, public key cryptography is vulnerable to unanticipated advances in hardware and software. Moreover, in 1994 Peter Shor then at AT&T invented an efficient quantum algorithm for factoring (Shor, 1997). For this reason, if a large scale quantum computer is ever constructed, much of conventional cryptography will fall apart!

After more than two decades of intense theoretical and experimental efforts, primitive small scale quantum computers have already been built. Several big companies and a number of labs and start-ups are racing to build the world’s first practical quantum computer. For instance, Google’s Quantum Artificial Intelligence Laboratory plans to commercialize quantum computers within five years (Mohseni et al., 2017); IBM Q has already put its 16 qubit quantum processor online for client use1; Chinese Academy of Sciences and Alibaba have established the Quantum Computing Laboratory to advance the research of quantum computing2; Other companies, such as Intel, Microsoft, Rigetti, IonQ and so forth, have also joined the international race to build a quantum computer. Moreover, China is building the National Laboratory for Quantum Information Science to support the revolutionary research in quantum information; The European Commission is planning to launch the flagship initiative on quantum technologies3; USA has already launched the National Quantum Initiative Act in 20184. All in all, the risk of successful construction of a quantum computer in the next decade could no longer be ignored.

Note that some data such as our DNA data and health data need to kept secret from decades. This is called long-term security. However, cryptographic standards could take many years to change. Since an eavesdropper intercepting encrypted data sent in 2019 may save them for decades and wait for the future successful construction of a quantum computer and retro-actively crack an encryption scheme, cryptographic standards need to consider potential future technological advances in the next few decades. For instance, Canadian Census Data are supposed to be kept for secret for 92 years5. Hence, the 2019

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1 IBM Q: https://www.research.ibm.com/ibm-q
2 CAS-Alibaba: http://quantumcomputer.ac.cn/index.html
3 https://ec.europa.eu/digital-single-market/en/news/quantum-europe-2017-towards-quantum-technology-flagship
4 https://www.congress.gov/bill/115th-congress/house-bill/6227
5 http://www12.statcan.ca/English/census01/Info/chief.cfm
Census data should be kept secret until 2111. To ensure such security, we need to predict the future technology in the next century. As a comparison, the first general-purpose electronic computer, ENIAC, was formally dedicated in 1946, which was less than 92 years ago. This meant that general-purpose electronic computers did not even exist 92 years ago. Therefore, if history is any guide, we think that it is not realistic for one to predict with any confidence what types of technology would exist 92 years from now.

In 2015, the US National Security Agency (NSA) announced plan to plan for transition to quantum-safe crypto-systems. For instance, the US National Institute of Standards and Technology (NIST) has made a call for quantum-safe candidate algorithm nominations, which was due November 30, 2017\textsuperscript{6}. Over the next few years, those candidate algorithms will be evaluated.

Broadly speaking, there are two approaches to a quantum-safe encryption scheme. The first approach is to use conventional cryptography and to develop alternative public-key encryption schemes such as hash-based or code-based encryption schemes that known quantum attacks such as Shor’s algorithm (Shor, 1997) do not apply. Such an approach is called post-quantum cryptography and it has the advantages of being compatible with existing crypto infrastructure and having high key rates and being available over long distances. Recently, Google has performed a test deployment of a post-quantum crypto algorithm in Transport Layer Security (TLS)\textsuperscript{7}. One drawback of post-quantum algorithms is that those conventional algorithms are only shown to be secure against known quantum attacks. There is always a possibility that some smart conventional or quantum physicist or computer scientist might one day come up with clever algorithms for breaking them efficiently. As said, this would lead to a retroactive security breach in future for data transmitted today with potentially disastrous consequences.

The second approach is to use quantum cryptography (Bennett and Brassard, 1984; Ekert, 1991), particularly quantum key distribution (QKD). It has the advantage of promising information-theoretical security based on the fundamental laws of quantum physics, i.e., the security is independent of all future advances of algorithm or computational power.

Note however that quantum cryptography can not replicate all the functionalities of public key cryptography. In future, quantum cryptography is likely to be combined with the post-quantum cryptography to form the infrastructure of quantum-safe encryption scheme. For instance, the post-quantum cryptography can be used to perform the initial authentication. This authentication is only required in a short time, and once it is done, the generated QKD key will be secure forever.

\section*{B. Quantum key distribution (QKD)}

The main goal of QKD is to achieve security based on the laws of physics (Bennett and Brassard, 1984; Ekert, 1991). The quantum no-cloning theorem dictates that an unknown quantum state cannot be cloned reliably (D.Dieks, 1982; Wootters and Zurek, 1982). Now, if Alice distributes a key via quantum (e.g., single-photon) signals, then since there is only a single copy of the key to begin with, there is no way for Eve to clone the quantum state reliably to produce two copies of the same quantum state. Therefore, if Eve tries to eavesdrop in QKD, she will unavoidably introduce disturbance to the quantum signals, which will then be detected by the users, Alice and Bob. Alice and Bob can then simply discard such a key and try the key distribution process again.

Note that an important advantage of QKD is that, since the communication is quantum, once a QKD session is over, there is no classical transcript for Eve to keep. Therefore, an eavesdropper has to break a QKD session real-time or it will be secure forever. This is very different from conventional key distribution schemes.

\subsection*{1. BB84 protocol}

The best-known QKD scheme is the Bennett-Brassard-1984 (BB84) protocol (Bennett and Brassard, 1984). The BB84 protocol allows two users, Alice and Bob, who share a quantum channel (e.g., an optical fiber or free-space) and an authenticated conventional classical channel to generate a secure key, in the presence of an eavesdropper with unlimited quantum computing power. In the BB84 protocol, a sequence of single photons are sent by Alice to Bob through a quantum channel. A schematic diagram of the BB84 protocol is illustrated in Fig. 1. The steps of the protocol are as follows.

1. For each signal, Alice randomly chooses one of the four polarization states, namely, vertical, horizontal, 45-degree and 135-degree, and encodes it in the polarization of a single photon and then sends the photon through a quantum channel to Bob.

2. For each signal, Bob chooses one of the two bases, rectilinear and diagonal, and performs a measurement on the polarization of a received photon. Bob publicly announces his basis choice through an authenticated conventional channel. Similarly, Alice publicly announces her basis choice via an authenticated conventional channel.

\begin{itemize}
 \item[1.] For each signal, Alice randomly chooses one of the four polarization states, namely, vertical, horizontal, 45-degree and 135-degree, and encodes it in the polarization of a single photon and then sends the photon through a quantum channel to Bob.
 \item[2.] For each signal, Bob chooses one of the two bases, rectilinear and diagonal, and performs a measurement on the polarization of a received photon. Bob publicly announces his basis choice through an authenticated conventional channel. Similarly, Alice publicly announces her basis choice via an authenticated conventional channel.
\end{itemize}

\textsuperscript{6} https://csrc.nist.gov/Projects/Post-Quantum-Cryptography
\textsuperscript{7} https://security.googleblog.com/2016/07/experimenting-with-post-quantum
3. Alice and Bob discard the polarization data that have been sent and received in different bases. They keep only those polarization data that have been sent and received in the same basis. This remaining data forms the sifted key. Alice and Bob can choose a random sample of their polarization data and compare them to compute the quantum bit error rate (QBER).

4. If the computed QBER is too high, then they abort. Otherwise, they proceed with classical post-processing to produce a secret key.\(^8\)

2. Intuition of security

The quantum no-cloning theorem guarantees that Eve cannot copy the unknown quantum state sent by Alice reliably (Dieks, 1982; Wootters and Zurek, 1982). Furthermore, a key feature in quantum mechanics is the complementarity between the two conjugate bases, rectilinear or diagonal. Since the two measurements corresponding to the two bases do not commute with each other, there is no way to measure the two observables simultaneously without disturbing the state. Therefore, Eve who tries to eavesdrop and extract information on the polarization data will inevitably introduce disturbance to the state. On the other hand, with their authenticated classical channel, Bob has a fundamental advantage over Eve in that he can compare his basis choice with Alice and determine the QBER for data that are transmitted and received in the same basis.

What happens if Eve attacks the quantum channel? A simple example of an eavesdropping strategy is an intercept-resend attack. In this attack, for each photon sent from Alice, Eve performs a measurement in a randomly chosen basis and re-sends a new photon to Bob according to her measurement result. Let us focus on those cases when Alice and Bob happen to use the same basis since they will throw away other cases. If Eve happens to use the correct basis (50%), then both she and Bob will decode Alice’s bit value correctly. No error is introduced by Eve. On the other hand, if Eve uses the wrong basis (50%), then both she and Bob will have random measurement results. This suggests that if Alice and Bob compare a subset of the sifted key, they will see a significant amount of errors. Here, for these bits, the photons will be passed on to Bob in the wrong basis, so regardless of Eve’s measurement result, Bob will have a 50% probability of measuring the opposite of Alice’s bit value. In other words, Eve’s attack will introduce 50% QBER for half of the total bits, and thus a total of 25% QBER. This example illustrates the basic principle behind QKD: Eve can only gain information at the cost of introducing errors, which will expose her existence.

3. Overview of recent development

On the theoretical side, the first security proof of QKD was based on the uncertainty principle by Mayers (Mayers, 2001). Mayers’s proof was put into a conceptually simple framework based on entanglement distillation by Lo and Chau (Lo and Chau, 1999), building on the earlier work on quantum privacy amplification (Deutsch et al., 1996) and entanglement distillation (Bennett et al., 1996). Later on, Shor and Preskill employed the idea of the Calderbank-Shor-Steane (CSS) quantum error correcting code (Calderbank and Shor, 1996; Steane, 1996) to simplify the entanglement-based proof to a prepare-and-measure protocol (Shor and Preskill, 2000). See also (Biham et al., 2000; Devetak and Winter, 2005; Koashi, 2009) for security proofs of QKD.

Rather interestingly, the rigorous definition of secure keys was presented afterwards in 2000s (Ben-Or et al., 2005; Renner and König, 2005), where the composable security definition in classical cryptography (Canetti, 2001; Canetti and Krawczyk, 2002) was introduced to quantum cryptography (Ben-Or et al., 2005; Ben-Or and Mayers, 2004). In the mean time, device imperfections in practical systems were investigated in security analyses (Inamori et al., 2007; Lütkenhaus, 2000), and the remarkable framework of the security analysis for realistic devices was established by Gottesman-Lo-Lütkenhaus-Preskill (GLLP) (Gottesman et al., 2004). A further development was the security proof for the consideration...
of finite-key effects in a more rigorous manner (Renner, 2008; Renner and König, 2005; Tomamichel et al., 2012).

On the experimental side, after more than two decades of efforts (Gisin et al., 2002; Lo et al., 2014), QKD has experienced from the first laboratory demonstration performed in 1992 over 32.5-cm free space (Bennett et al., 1992a) to the recent landmark accomplishment of quantum satellite QKD experiment over 1200 km (Liao et al., 2017a) among China and 7600 km (Liao et al., 2018) between China and Austria. Note that this is a seven order of magnitude of improvement in terms of the distance of QKD. There are also on-going efforts on satellite-based quantum communications by Europe, USA, Canada, Japan, and Singapore (Joshi et al., 2018). Researchers have pushed QKD to a secret key rate of more than 10 Mbits/s (Islam et al., 2017; Yuan et al., 2018). Commercial QKD systems are currently available on the market, and a number of field-test QKD networks have been conducted in USA (Elliott et al., 2005), Europe (Peep et al., 2009; Stucki et al., 2011), Japan (Sasaki et al., 2011), and China (Chen et al., 2009, 2010; Wang et al., 2010).

Recently, China has successfully completed the 2000-km-long fiber-optic trunk link between Beijing to Shanghai (Chen et al., 2019). UK has launched the Quantum Communications Hub project aiming to build quantum networks in England\(^9\), US is deploying their first dark fiber quantum network connecting Washington DC to Boston over 800-km\(^10\). Several countries, e.g., European Telecommunications Standards Institute (ETSI)\(^11\), International Organization for Standardization (ISO) and International Telecommunication Union (ITU), have put great efforts to address standardisation issues in QKD.

Overall, QKD is already mature for several real-life applications (Qiu, 2014). For instance, QKD was used to encrypt security communications in 2007 Swiss elections and 2010 World Cup. In China, QKD is being widely used to ensure long-term security for numerous users in government, financial and energy industry, including People’s Bank of China, China Banking Regulatory Commission and so forth. Fig. 2 shows a schematic diagram of the space-ground integrated quantum network (Chen et al., 2019), constructed already in China, which spans more than 2,000 km coverage area.

**C. Focus of this review**

In the Code Book by Simon Singh (Singh, 2000), the author boldly proclaimed that quantum cryptography achieves the Holy Grail of cryptography by offering unconditional security. Therefore, quantum cryptography presents the final stage of evolution of cryptography. After quantum cryptography, cryptography will stop to evolve. Is this really true?

In principle, QKD promises unconditional security based on the laws of physics. In practice, however, the realistic QKD devices display imperfections, which might seldom conform to idealized theoretical models used in the security analysis by theorists. And the deviations might be vulnerable by some special attacks, i.e. the quantum hacking. For this reason, an arms race has been going on in quantum cryptography among quantum code-makers and quantum code-breakers. The main goal is to assess the deviations between the system and the ideal, thus establishing the practical security for real QKD systems.

Table I summarizes the quantum hacking strategies developed from 2000 to the present. Right after the QKD security proofs with ideal devices have been presented, a well-known hacking strategy was proposed — photon number splitting (PNS) attack (Brassard et al., 2000; Lütkenhaus, 2000) targeting on practical QKD source. The source device imperfection severely undermines the performance of a QKD system, typically below 30-km fiber (Gottesman et al., 2004; Lütkenhaus, 2000; Ma, 2006). In order to close this side channel for a QKD source, the decoy state method has been proposed by quantum code-makers to make QKD practical with standard weak coherent pulses (WCPs) that are generated by attenuated lasers (Hwang, 2003; Lo et al., 2005; Wang, 2005). Decoy-state QKD presents dramatic performance improvement over the conventional security proofs (Gottesman et al., 2004), and it has become a standard technique in current QKD experiments. Table II provides a list of decoy-state QKD experiments.

After the decoy-state method, however, various quantum hacking attacks have been performed by quantum code-breakers against other components in practical QKD systems (see Table I). To counter those attacks, a few important concepts have been proposed by quantum code-makers. One particularly practical counter-measure against quantum hacking is measurement-device-independent quantum key distribution (MDI-QKD) (Lo et al., 2012). MDI-QKD completely removes all security loopholes in the detection system and allows a QKD network to be secure with untrusted relays. It is practical with current technology. Table III summarizes the MDI-QKD experiments after its invention. In addition, we note other important developments of QKD protocols and implementations (see Table IV), and new quantum cryptographic protocols (see Table V) which have recently been proposed and demonstrated by quantum code-makers.

Note that the side channels are common problems to any cryptosystems, i.e., not only to quantum cryptog-

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9 https://www.quantumcommshub.net/about-us/

10 https://techcrunch.com/2018/10/25/new-plans-aim-to-deploy-the-first-u-s-quantum-network-from-boston-to-washington-dc/

11 http://www.etsi.org/technologies-clusters/technologies/quantum-key-distribution
FIG. 2 (Color online) Schematic diagram of the space-ground integrated quantum network in China (Chen et al., 2019), consisting of four quantum metropolitan area networks in the cities of Beijing, Jinan, Shanghai, Hefei, a backbone network over 2,000 km, and ground-satellite links. There are three types of nodes in the network: user nodes, all-pass optical switches, and trusted relays. Each metropolitan network consists of all the three types of nodes, and the backbone network is connected by trusted relays. The satellite is connected to a ground satellite station near Beijing, which is further connected to the backbone network. [Figure adopted from the QCrypt-2018 talk by Yu-Ao Chen*].

* http://2018.qcrypt.net/scientific-program/

raphy but also to modern cryptographic systems. For instance, the power consumption of the CPU performing encryption and decryption, and the timing of the signals are common side channels, which can threaten implementations of both quantum and modern (non-quantum) cryptographic systems (Brumley and Boneh, 2005; Kocher et al., 1999). Therefore, closing the side channels are essentially required in all cryptographic technologies. It is only through painstaking battle-testing that the security of a practical crypto-system could be established with confidence. The arms race between code-makers and code-breakers will continue in cryptographic systems.

Nonetheless, since QKD is working on the physical layer of security, compared to modern cryptography, QKD provides a more accurate description of physical reality of a cryptographic system. More importantly, QKD has the fundamental advantage of promising information-theoretical security, which is independent of all future advances of computational power. The recent advances, such as MDI-QKD, have closed the critical side channels in the physical implementations, enabling secure QKD with realistic devices. Therefore, we believe that QKD does represent an important chapter in the history of code-making. We hope that QKD will play an important role in the quantum-safe encryption infrastructure for real applications, and it will bring us one step closer to the dream of information-theoretical security.

D. Outline of this review

This review will focus mainly on the practical security of realistic QKD systems. We will begin with a discussion of security analysis in Section II and the basic implementation of QKD in Section III. In Section IV, we will review various quantum hacking attacks against QKD implementations. In Section V, we review the security of a practical QKD source. Particularly, we will focus on the decoy-state protocol which is a standard method for secure QKD with attenuated lasers. In Section VI, we turn to detector security. We will primarily review the measurement-device-independent quantum key distribution (MDI-QKD) protocol and how it automatically foils all attacks on the detection system. Section VII contains a review of other quantum cryptographic protocols. In Section VIII, we present some concluding remarks.

For those readers who want to learn further basics of
QKD, we refer to the two earlier reviews published in Review of Modern Physics, one by Gisin et al. that introduces the basic experimental elements and systems (Gisin et al., 2002) and the other one by Scarani et al. that discusses the basic security analysis tools of various QKD protocols (Scarani et al., 2009). A brief overview of the implementation security of QKD can be found in a survey article in (Lo et al., 2014) and an ETSI white paper by Lucamarini et al. 12. A short overview of the practical challenges associated with QKD can be found in (Diamanti et al., 2016). Moreover, the entropy uncertainty relation, an important tool to analyze the security of QKD, can be seen in (Coles et al., 2017), and the quantum random number generator, a basic element in a practical QKD system, can be found in (Herrero-Collantes and Garcia-Escartin, 2017; Ma et al., 2016b). A review on various techniques of single-photon detectors can be seen in (Hadfield, 2009; Zhang et al., 2015). Furthermore, we may not cover too much on some important topics, but we refer the readers to other review articles on the topics of continuous-variable QKD (CV-QKD) (Diamanti and Leverrier, 2015; Weedbrook et al., 2012), quantum repeaters (Kimble, 2008; Pan et al., 2012; Sangouard et al., 2011), Bell nonlocality and device-independent protocols (Brunner et al., 2014), and blind quantum computing (Fitzsimons, 2017). These related review articles are summarized in Table VI.

12 https://www.etsi.org/images/files/ETSIWhitePapers/
# TABLE I List of quantum hacking strategies.

| Attack                        | Source/Detection | Target component | Manner       | Year |
|-------------------------------|------------------|------------------|--------------|------|
| Photon-number-splitting       | Source WCP       | (multi-photons)  | Theory       | 2000 |
| Detector fluorescence         | Detection        | Detector         | Theory       | 2001 |
| Faked-state                   | Detection        | Detector         | Theory       | 2005 |
| Trojan horse                  | Source Detector  | Backreflection    | Theory       | 2006 |
| Time shift                    | Detection        | Detector         | Experiment*  | 2007 |
| Time side-channel             | Detection        | Timing information| Experiment   | 2007 |
| Phase remapping               | Source Detector  | Detector         | Experiment   | 2007 |
| Trojan horse                  | Source Detector  | Backreflection    | Experiments  | 2011 |
| Faraday mirror                | Source Detector  | Faraday mirror   | Theory       | 2011 |
| Wavelength                    | Detection        | Beam-splitter    | Experiment   | 2011 |
| Dead-time                     | Detection        | Detector         | Experiment   | 2011 |
| Channel calibration           | Detection        | Detector         | Experiment*  | 2011 |
| Intensity                     | Source Intensity | Modulator        | Experiment   | 2012 |
| Phase information             | Source Phase     | Randomization    | Experiment   | 2012 |
| Memory attacks                | Detection        | Classical memory | Theory       | 2013 |
| Local oscillator**            | Source Detector  | Local oscillator | Experiment   | 2013 |
| Trojan horse                  | Source Detector  | Backreflection    | Experiment   | 2014 |
| Laser damage                  | Source Detector  | Detector         | Experiment   | 2014 |
| Laser seeding                 | Source Detector  | Laser phase/intensity | Experiment | 2015 |
| Detector saturation**         | Detection Homodyne detector | Experiment | 2016 |
| Covert channels               | Detection        | Classical memory | Theory       | 2017 |
| Pattern effect                | Source Intensity | Modulator        | Experiment   | 2018 |

* Demonstration on commercial QKD system
** Continuous-variable QKD

# TABLE II List of decoy-state QKD experiments and their performance.

| Reference                        | Repetition rate | Encoding | Channel       | Maximal distance | Key rate (bps) | Year   |
|----------------------------------|-----------------|----------|---------------|------------------|----------------|--------|
| (Zhao et al., 2006a,b)           | 5MHz            | Phase    | Fiber         | 60km             | 422.5          | 2006   |
| (Peng et al., 2007)              | 2.5MHz          | Polarisation | Fiber         | 102km            | 8.1            | 2007   |
| (Rosenberg et al., 2007)         | 2.5MHz          | Phase    | Fiber         | 107km            | 14.5           | 2007   |
| (Schmitt-Manderbach et al., 2007)| 10MHz           | Polarisation | Free-space    | 144km            | 12.8*          | 2007   |
| (Yuan et al., 2007)              | 7.1MHz          | Phase    | Fiber         | 25.3km           | 5.5k           | 2007   |
| (Zhen-Qiang et al., 2008)        | 1MHz            | Phase    | Fiber         | 123.6km          | 1.0            | 2008   |
| (Wang et al., 2008)**            | 0.65MHz         | Phase    | Fiber         | 25km             | 0.9            | 2008   |
| (Dixon et al., 2008)             | 1GHz            | Phase    | Fiber         | 100.8km          | 10.1k          | 2008   |
| (Peev et al., 2009)              | 7MHz            | Phase    | Fiber network | 33km             | 3.1k           | 2009   |
| (Rosenberg et al., 2009)         | 10MHz           | Phase    | Fiber         | 135km            | 0.2            | 2009   |
| (Yuan et al., 2009)              | 1.036GHz        | Phase    | Fiber         | 100Km            | 10.1k          | 2009   |
| (Chen et al., 2009)              | 4MHz            | Phase    | Fiber network | 20km             | 1.5k           | 2009   |
| (Liu et al., 2010)               | 320MHz          | Polarisation | Fiber         | 200km            | 15.0           | 2010   |
| (Chen et al., 2010)              | 320MHz          | Polarisation | Fiber network | 130km            | 0.2k           | 2010   |
| (Sasaki et al., 2011)            | 1GHz            | Phase    | Fiber network | 45km             | 304.0k         | 2011   |
| (Wang et al., 2013)              | 100MHz          | Polarisation | Free space   | 96km             | 48.0           | 2013   |
| (Fröhlich et al., 2013)          | 125MHz          | Phase    | Fiber network | 19.9km           | 43.1k          | 2013   |
| (Lucamarini et al., 2013)        | 1GHz            | Phase    | Fiber         | 80km             | 120.0k         | 2013   |
| (Fröhlich et al., 2017)          | 1GHz            | Phase    | Fiber         | 240km†           | 8.4            | 2017   |
| (Liao et al., 2017a)             | 100MHz          | Polarisation | Free space   | 1200km           | 1.1k           | 2017   |
| (Boaron et al., 2018)            | 2.5GHz          | Time-bin | Fiber         | 421km†           | 6.5            | 2018   |

* Asymptotic key rate
** Heralded single-photon source
† Low-loss fiber of 0.18 dB/km
TABLE III List of MDI-QKD experiments and their performance.

| Reference | Clock rate | Encoding | Distance/loss | Key rate (bps) | Year | Notes |
|-----------|------------|----------|--------------|---------------|------|-------|
| (Rubenok et al., 2013) | 2MHz | Time-bin | 81.6km | 0.24\* | 2013 | Field-installed fiber |
| (Liu et al., 2013) | 1MHz | Time-bin | 50km | 0.12 | 2013 | First complete demonstration |
| (Ferreira da Silva et al., 2013) | 1MHz | Polariation | 17km | 1.94\* | 2013 | Multiplexed synchronization |
| (Tang et al., 2014b) | 0.5MHz | Polariation | 10km | 4.7 x 10^{-3} | 2014 | Active phase randomization |
| (Tang et al., 2014a) | 75MHz | Time-bin | 200km | 0.02 | 2014 | Fully automatic system |
| (Tang et al., 2015) | 75MHz | Time-bin | 30km | 16.9 | 2015 | Field-installed fiber |
| (Wang et al., 2015a) | 1MHz | Time-bin | 20km | 8.3\* | 2015 | Phase reference free |
| (Valivarthi et al., 2015) | 250MHz | Time-bin | 60dB | \sim 5 \times 10^{-2} | 2015 | Test in various configurations |
| (Pirandola et al., 2015) | 10.5MHz | Phase | 4dB | 0.1 | 2015 | Continuous variable |
| (Tang et al., 2016b) | 75MHz | Time-bin | 55km | 16.5 | 2016 | First fiber network |
| (Yin et al., 2016a) | 75MHz | Time-bin | 404km | 2.3 \times 10^{-4} | 2016 | Longest distance |
| (Comandar et al., 2016) | 1GHz | Polariation | 102km | 2.2 \times 10^{3} | 2016 | Highest repetition rate |
| (Kaneda et al., 2017) | 1MHz | Time-bin | 14dB | 0.85 | 2017 | Heralded single-photon source |
| (Wang et al., 2017a) | 1MHz | Time-bin | 20km | 6.3 \times 10^{-3} | 2017 | Stable against polarization change |
| (Valivarthi et al., 2017) | 20MHz | Time-bin | 80km | 100 | 2017 | Cost-effective implementation |
| (Liu et al., 2018a) | 50MHz | Time-bin | 160km | 2.6\* | 2018 | Phase reference free |
| (Liu et al., 2018b) | 75MHz | Time-bin | 100km | 14.5 | 2018 | Asymmetric channels |

\* Asymptotic key rate
\‡ No random state/decoy modulation

TABLE IV List of recent developments of other QKD protocols and implementations.

| Protocol | Manner | Notes |
|----------|--------|-------|
| Round-robin differential-phase-shift (RR-DPS) (Sasaki et al., 2014) | Theory | Initial proposal |
| RR-DPS (Guan et al., 2015) | Experiment | Passive |
| RR-DPS (Li et al., 2016; Takesue et al., 2015; Wang et al., 2015c) | Experiment | Active |
| High-dimension (Lee et al., 2014; Mower et al., 2013) | Experiment | Dispersive optics |
| High-dimension (Zheng et al., 2014b; Zhong et al., 2015) | Experiment | Franson interferometer |
| High-dimension (Mirhosseini et al., 2015; Sit et al., 2017) | Experiment | Structured photons |
| Device-independent (Gisin et al., 2010) | Theory | Qubit amplifier |
| Device-independent (Braunstein and Pirandola, 2012) | Theory | Entanglement swapping |
| Device-independent (Vazirani and Vidick, 2014) | Theory | General-attack proof |
| Device-independent (Miller and Shi, 2016) | Theory | Robust against noise |
| Device-independent (Arnon-Friedman et al., 2018) | Theory | Tight general-attack proof |
| Quantum access network (Fröhlich et al., 2013) | Experiment | Common receiver |
| Coherent-one-way (Korzh et al., 2015) | Experiment | Long-distance |
| Chip-based (Sibson et al., 2017a) | Experiment | Indium phosphide (InP) |
| Chip-based (Ma et al., 2016a; Sibson et al., 2017b) | Experiment | Silicon Photonics |
| Chip-based (Bunandar et al., 2018; Cai et al., 2017; Ding et al., 2017) | Experiment | Silicon Photonics |
| Loss-tolerant (Tamaki et al., 2014, 2016) | Theory | Imperfect source |
| Loss-tolerant (Tang et al., 2016a; Xu et al., 2015b) | Experiment | Imperfect source |
| Local local-oscillator (Huang et al., 2015a; Qi et al., 2015; Soh et al., 2015) | Experiment | CV-QKD |
| CV-QKD security proof (Furrer et al., 2012) | Theory | General-attack proof for squeezed state |
| CV-QKD security proof (Leverrier, 2015, 2017; Leverrier et al., 2013) | Theory | General-attack proof for coherent state |
### TABLE V List of recent developments of other quantum cryptographic protocols beyond QKD.

| Protocol                                      | Theory/Experiment | Notes                      |
|-----------------------------------------------|-------------------|----------------------------|
| Noisy quantum storage (Damgård et al., 2008; Konig et al., 2012; Wehner et al., 2008) | Theory            | Unconditional security     |
| Oblivious transfer (Erven et al., 2014)      | Experiment        | Noisy-storage model        |
| Bit commitment (Ng et al., 2012)             | Experiment        | Noisy-storage model        |
| Bit commitment (Kent, 2012)                  | Theory            | Relativistic assumption    |
| Bit commitment (Liu et al., 2014; Lunghi et al., 2013) | Experiment | Relativistic assumption    |
| Bit commitment (Chakraborty et al., 2015; Lunghi et al., 2015; Verbanis et al., 2016) | Experiment | Long commitment time       |
| Digital signature (Clarke et al., 2012)      | Experiment        | First demonstration        |
| Digital signature (Collins et al., 2014; Dunjko et al., 2014) | Experiment | No quantum memory          |
| Digital signature (Donaldson et al., 2016; Yin et al., 2017a) | Experiment | Insecure channel           |
| Coin flipping (Berlin et al., 2011; Pappa et al., 2014) | Experiment | Loss tolerance             |
| Data locking (Fawzi et al., 2013; Lloyd, 2013; Lupo et al., 2014) | Theory            | Loss tolerance             |
| Data locking (Liu et al., 2016; Lum et al., 2016) | Experiment | Loss tolerance             |
| Blind quantum computing (Barz et al., 2012; Broadbent et al., 2009) | Theory,Experiment | No quantum memory          |
| Blind quantum computing (Huang et al., 2017; Reichardt et al., 2013) | Theory,Experiment | Classical clients          |

### TABLE VI List of related reviews to QKD

| Reference                                | Subject                                      |
|------------------------------------------|----------------------------------------------|
| (Gisin et al., 2002)                     | Experimental basics of QKD                   |
| (Scarani et al., 2009)                   | Theoretical basics of QKD                    |
| (Diamanti et al., 2016; Lo et al., 2014) | Practical challenges of QKD                 |
| (Hadfield, 2009; Zhang et al., 2015)     | Single-photon detector                       |
| (Herrero-Collantes and García-Escartin, 2017; Ma et al., 2016b) | Quantum random number generator             |
| (Coles et al., 2017)                     | Entropy uncertainty relation                 |
| (Diamanti and Leverrier, 2015; Weedbrook et al., 2012) | Continuous-variable QKD                     |
| (Kimble, 2008; Sangouard et al., 2011)   | Quantum repeaters                            |
| (Brunner et al., 2014)                   | Bell nonlocality                             |
| (Fitzsimons, 2017)                       | Blind quantum computing                      |
II. SECURITY ANALYSIS

A. Security definition

In order to give a security proof of QKD, one needs to define a secure key first. Ideally, a secure key satisfies two requirements. First, the key bit strings possessed by the legitimate users, Alice and Bob, need to be identical. Second, from the view of anyone other than Alice and Bob, the key bit string should be uniformly distributed.

Here, we follow the definition from Ben-Or et al.’s work (Ben-Or et al., 2005). See also (Renner and König, 2005) for the definition. Define $k_A$ and $k_B$ to be the key bit strings obtained by Alice and Bob, respectively. They have the same length, $m$. For an ideal key set, $\{k_A, k_B\}$, the joint probability distribution satisfies,

$$\text{Prob}(k_A, k_B) = \begin{cases} 2^{-m}, & k_A = k_B; \\ 0, & k_A \neq k_B. \end{cases}$$

To express it in quantum language, the ideal key state shared by Alice and Bob is

$$\rho_{\text{ideal}} = 2^{-m} \sum_{k} |k,k\rangle_{A,B} \langle k,k| \otimes \rho_E,$$

where systems $A, B$ are keys held by Alice and Bob, and system $E$ is held by Eve. Note that Eve’s system $\rho_E$ is independent of the key $k$.

Due to practical issues, such as the finite data size and non-ideal error correction, Alice and Bob cannot generate an ideal key via QKD system. In reality, it is reasonable to allow the key to have a small failure probability. That is, Alice and Bob can generate a key very close to an ideal one. In probability theory, the total variation distance is widely employed to characterize how close two probability distributions are,

$$\epsilon = \frac{1}{2} \sum_{x} |P(x) - P_{\text{ideal}}(x)|,$$

where $x$ is the key bit string, the summation takes over the entire key space, $P(x)$ and $P_{\text{ideal}}(x)$ are the probability distributions of keys from a realistic and ideal experiment, respectively. This distance, $\epsilon$, can be interpreted as the probability to distinguish the real experiment and the ideal one.

The failure probability can also be written in a quantum manner by generalizing the variational distance to the trace distance (Renner and König, 2005),

$$\epsilon = \frac{1}{2} ||\rho_{\text{key}} - \rho_{\text{ideal}}||_1,$$

where $\rho_{\text{key}}$ is the practical state shared by Alice, Bob, and Eve after the final key measurement, and $\rho_{\text{ideal}}$ is defined in Eq. (2). In this case, both Alice and Bob’s systems are classical, while Eve’s system in general stays in quantum. Then, the joint state, $\rho_{\text{key}}$, is a classical-classical-quantum (c-c-q) state. The trace distance of two density matrices, $\rho$ and $\sigma$, is defined by,

$$\frac{1}{2} ||\rho - \sigma||_1 = \frac{1}{2} \sum_{i} |\lambda_{i}|,$$

where the $\lambda_{i}$ are eigenvalues of $\rho - \sigma$. If the same measurements are applied to $\rho$ and $\sigma$, the variational distance between the two outcome probability distributions is upper-bounded by their trace distance. A key state is $\epsilon$-close to the ideal key state if the underlying c-c-q state satisfies Eq. (4). It turns out that the security definition from the trace-distance measure owns a composability security property (Ben-Or et al., 2005).

**Definition 1.** A QKD protocol is $\epsilon$-secure if the generated c-c-q state $\rho_{\text{key}}$ is $\epsilon$-close to the ideal key state $\rho_{\text{ideal}}$ given in Eq. (2) with the trace distance definition.

Note that if a key state is $\epsilon$-close to the ideal key state, then the guessing probability for Eve on the final key is bounded by $\epsilon$. Here, we want to emphasize that one should not interpret the security parameter used in Definition 1 as the guessing probability. In fact, the statement, a key is $\epsilon$-close to the ideal key, is much stronger than the statement, Eve’s guessing probability on a key is bounded by $\epsilon$. Let us show a simple counter example. Denote $l = \log \epsilon$ and $l < m$. We consider a $m$-bit key $k_{\text{bad}}$, which concatenate a uniformly distributed $l$-bit string with $m - l$ bit of 0’s. Obviously, this key $k_{\text{bad}}$ does not satisfies the trace-distance (statistical distance in this case since everything is classical here) $\epsilon$-security definition used in Eq. (4), because the statistical distance between $k_{\text{bad}}$ and $k_{\text{ideal}}$ is close to 1 when $m \gg l$. However, the guessing probability of Eve on the key $k_{\text{bad}}$ is bounded by $\epsilon$. Clearly, the guessing probability alone is not a proper security parameter definition. This is a common mistake for those who are confused about the security foundation of (quantum) cryptography, see for example (Yuen, 2016).

In the Lo-Chau security proof (Lo and Chan, 1999), the joint quantum state shared by Alice and Bob before the final key measurement is one of the Bell states,

$$|\Phi^\pm\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$$

$$|\Psi^\pm\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle).$$

To see how security of QKD is related to entanglement, consider the case where Alice and Bob share $m$-pairs of perfect EPR pairs $|\Phi^+\rangle^m$. It is not hard to verify that if both of them perform the local $Z$ measurement, $M_{zz}$, on their halves of $m$ pairs, they will share the ideal key state $\rho_{\text{ideal}}$ in Eq. (2). In other words, the amount of distillable entanglement from quantum transmission would give a lower bound on the key generation rate.
The main idea of the Lo-Chau security proof is that Alice and Bob can apply quantum error correction to distill entanglement, after which, Alice and Bob share a quantum state $\rho_{AB}$, which ideally should be EPR pairs with the form of $|\Phi^+\rangle^\otimes m$. In reality, when the data size is finite, the entanglement distillation might fail with a small probability, $\epsilon_f$, which can be understood as the failure probability of quantum error correction,

$$\langle \Phi^+| \rho_{AB} |\Phi^+\rangle^\otimes m \geq 1 - \epsilon_f. \quad (7)$$

After considering Eve’s system $E$, one can show that, see Appendix A in (Fung et al., 2010),

$$F(\rho_{ABE}, (|\Phi^+\rangle \langle \Phi^+|)^\otimes m \otimes \rho_E) \geq 1 - \epsilon_f. \quad (8)$$

Then after the local $Z$-measurement on system $A$ and $B$, $M_{zz}$, for key generation, the trace distance of key state $\rho_{key}$ to $\rho_{ideal}$ is bounded by

$$\frac{1}{2}||\rho_{key} - \rho_{ideal}||_1$$

$$= \frac{1}{2}||M_{zz}(\rho_{ABE}) - M_{zz}(|\Phi^+\rangle \langle \Phi^+|)^\otimes m \otimes \rho_E||_1$$

$$\leq \frac{1}{2}||\rho_{ABE} - (|\Phi^+\rangle \langle \Phi^+|)^\otimes m \otimes \rho_E||_1$$

$$\leq \sqrt{1 - F(\rho_{ABE}, |\Phi^+\rangle \langle \Phi^+|)^\otimes m \otimes \rho_E)}$$

$$\leq \sqrt{\epsilon_f(2 - \epsilon_f)}. \quad (9)$$

Note that fidelity is widely used for security parameter quantification in QKD security proofs (Koashi, 2009; Lo and Chau, 1999; Shor and Preskill, 2000). In order to make the security parameter composable, one can simply apply Eq. (9).

### B. Security proof

From Sec. II.A, one can see that the main job for a security analysis is to make sure that Alice and Bob eventually share (almost perfect) EPR pairs before they make the final $ZZ$ measurement to obtain secure key bits. The procedure to extract perfect EPR pairs from imperfect ones is called entanglement distillation. The main idea of the Lo-Chau security proof lies on quantum error correction (Lo and Chau, 1999), which proved the security of an entanglement-based QKD protocol. Let us recap the Bennett-Brassard-Mermin-1992 (BBM92) (Bennett et al., 1992c) protocol, an entanglement version of BB84 in box 1. For the simplicity of description, we assume Alice and Bob own quantum memories, which will be removed shortly in the Shor-Preskill security proof (Shor and Preskill, 2000).

**Box 1: BBM92 protocol**

(1) Alice prepares an EPR pair, $|\Phi^+\rangle$, stores one half of it locally, and sends the other half to Bob.

(2) Upon receiving a qubit, Bob stores the half of the EPR pair in quantum memories. If the qubit lost in the channel or the quantum storage fails, they discard the pair.

(3) Repeat the above two steps many times until Alice and Bob store $N$ pairs of qubits.

(4) With the help of pre-shared perfect EPR pairs, Alice and Bob apply a quantum error correcting code to correct all the errors in $N$ EPR pairs.

(5) After a random hashing test, Alice and Bob share almost perfect EPR pairs. They return the EPR pairs cost in the previous step and measure the rest in the local $Z$ basis to obtain the final key.

The (quantum) random hashing test happens in the two conjugate bases separately. In each basis, Alice and Bob can compare the parities of the qubits. Comparison of each parity will cost Alice and Bob an EPR pair. Once they agree on enough number of parities, the states are stabilized by the operations, $X \otimes X$ and $Z \otimes Z$, with a small failure probability. This step comes from the error verification in classical error correction. There are a few notes on this scheme.

1. This scheme is source-independent. In the first step, the state preparation can be done by Eve. Then, Eve prepares qubits pairs (designed to be EPR pairs) and sends to Alice and Bob. The rest steps, 4 and 5, are the same.

2. After quantum transmission, Alice and Bob share $N$ EPR pairs. Due to channel disturbance or Eve’s interference, these $N$ EPR pairs are in general imperfect and might be entangled with each other and Eve’s system. Here, we consider the most general coherent attacks.

3. In a security proof, it is crucial to evaluate the number of EPR pairs cost in Step 4.

When Alice and Bob both measure in the local $Z$ basis, an error occurs when the outcomes are different. We call it a **bit error**. Similarly, when they both measure in the $X$ basis, a **phase error** occurs when the outcomes are different. Denote the bit and phase error rates to be $e_b$ and $e_p$, respectively,

$$e_b = \frac{\# \text{ of bit errors}}{N}$$

$$e_p = \frac{\# \text{ of phase errors}}{N}. \quad (10)$$
Since we are considering the most general coherent attack, the errors are in general not independent but correlated. Note that bit and phase errors can be defined in any two complementary bases in qubit case. For quantum signals measured in a particular basis, where the bit error is defined, the phase error denotes the hypothetical error if these signals were measured in its complementary basis. For higher dimension cases, such definitions would be slightly trickier with more than one types of phase errors.

In order to distill perfect EPR pairs from imperfect ones with errors defined in Eq. (10), Alice and Bob can employ quantum error correction. Entanglement distillation can be done in two steps via bit and phase error correction. In bit error correction, Alice hashes her qubits in the Z basis by apply Control-NOT (C-NOT) to ancillary perfect EPR pairs, as shown in Figure 3. Alice sends the measurement results of ancillary qubits to Bob, which serves as error syndrome in error correction. In the finite data size limit, the number of perfect EPR pairs cost in this procedure is given by the Shannon entropy, \( NH(e_b) \). By applying Hadamard gates, one can switch between bit and phase spaces. Then, similarly, the phase error correction will cost additional \( NH(e_p) \) EPR pairs. Finally, the net rate of EPR pairs generated is given by (Shor and Preskill, 2000),

\[
\rho \geq 1 - H(e_b) - H(e_p),
\]

where \( H(e) = -e \log e - (1 - e) \log(1 - e) \) is the binary Shannon entropy function.

![Figure 3](image)

**Fig. 3** Illustration of bit error correction. By adding Hadamard gates, the circuit can also be used for phase error correction.

In general, such quantum error correction based entanglement distillation procedure requires quantum memory and quantum computer, which is the essence of the Lo-Chau security proof (Lo and Chau, 1999). In order to remove this quantum memory or quantum computer requirement, one can move the final measurement ahead of the two error correction steps. The bit error correction becomes classical error correction, and the phase error correction becomes privacy amplification (Shor and Preskill, 2000). There are a few steps for this permutation of operations to work.

1. Quantum bit and phase error correction operations commute, as shown in Fig. 3. The key point here is that Alice and Bob use EPR pairs as ancillary qubits.
2. The Z-basis measurement on the ancillary EPR qubits commutes with all the operations for error correction. This is straightforward to see since there are only two possible operations on ancillary qubits, \( I \) and \( X \) (from C-NOT), both of which commute with the Z measurement.
3. The Z-basis measurement on the Alice and Bob qubits commutes with the bit error correction. This is also straightforward since the Z \( \otimes \) Z measurement with C-NOT. After moving the Z measurement ahead, C-NOT operation becomes regular exclusive-OR (XOR) on the two outcome bits.
4. The Z-basis measurement on the Alice and Bob qubits commutes with the phase error correction. This relies on the usage of EPR pair ancillary states.
5. In phase error correction, after locating the errors, phase error correction does not affect the values of final key measurement in the Z basis. Thus, no "correction" operation is needed. Of course, the EPR pairs are still cost here.
6. Then, all the quantum operations become classical bit operations, essentially, hashing.
7. In order to perform privacy amplification, one still needs to estimate the phase error rate \( e_p \). Now, let us focus on the case that the key bits are measured in the Z basis. The phase error rate can be estimated by measuring the key bits in the X basis. Of course, in order for this estimation to work, one needs to make sure the sampling is fair, which raises the following critical assumptions in security proof.

After considering the permutation of quantum error correction and measurement, Alice and Bob can directly measure the EPR pairs once they receive them. Suppose Alice prepares the original EPR pairs, measures halves of the pairs, and send the rest halves to Bob. Conditioned on Alice’s measurement outcomes, the states sent from Alice and Bob are pure. It is equivalent for Alice to prepare these states directly and send to Bob. Now, the entanglement-based protocol is reduced to a prepare-and-measure one.
Reduction from quantum bit error correction to classical error correction is easy to understand. Let us take Fig. 3 for example. The Alice and Bob needs to compare the ancillary qubit measurement results. Since the final $Z$ measurement commutes with C-NOT operation. One can measure all the qubits in the $Z$ basis first and XOR the bit values of all the measurement outcomes of the control qubits to the target qubits. The CNOT links shown in Fig. 3 can be understood as a hashing matrix. That is, it is equivalent to construct a matrix and multiply with the raw bit string. Of course, such error correction is linear. In general, any error correcting code can be applied, once bit and phase error correction can be decoupled.

Reduction from quantum phase error correction to privacy amplification is trickier. In general, after Hadamard gates, C-NOT operation does not commute $Z$ measurement any more. In fact, those two operations become anti-commute. In this case, Alice and Bob can design phase error correcting code such that it commutes with the $Z$ measurement. Again, let us take the linear code as an example. Certain number of parity bits need to be exchanged for error correction. Assuming universal hashing, Alice sends $N \langle e_p \rangle$ bits to Bob and Bob corrects the phase errors. Note that final key measurement must commute with this hashing. Then, they can use the null space the hashing matrix as for the final key space. This can also be understood as random number extraction. Alice and Bob use phase error rate to estimate the randomness in the key and apply universal hashing to extract out true randomness.

In quantum error correction, we assume Alice and Bob to use ancillary EPR pairs. As shown in Fig. 3, with EPR pairs, bit and phase two error correction operations commute with each other. That is, one can decouple these two error correction steps (Lo, 2003). In the Shor-Preskill security proof (Shor and Preskill, 2000), no ancillary EPR pairs are employed. Instead, the CSS quantum error correcting code (Calderbank and Shor, 1996; Steane, 1996) is used to decouple these two steps.

The infinite data size limit ($N \to \infty$) is used for the key-rate formula Eq. (11). When the data size is finite, the error correction efficiency may not reach to the Shannon limit. Depending on the data size, normally a factor is applied. It turns out that the privacy amplification is very efficient (Fung et al., 2010) in terms of finite data size effect, once the parameters are estimated. Another approach to dealing with the finite-size problem is by employing the smooth min-entropy (Renner, 2008; Renner and König, 2005; Tomamichel et al., 2012), which is a valid measure of randomness in the non-asymptotic cases, and degenerates to Shannon entropy in the i.i.d. limit. This approach is rather general to deal with non-i.i.d. case and can be applied to other quantum information processing protocols, such as one-shot coherence resource theory (Zhao et al., 2018) and device-independent QKD (Arnon-Friedman et al., 2018).

When Alice and Bob perform error correction, they need to know the error rates ahead. Normally, they can randomly announce parts of the measurement outcomes to determine $e_b$ and $e_p$. Of course, such error estimation can be replaced by error verification (Ma et al., 2011). In either case, there exists a small failure probability for error correction when finite data size is considered.

C. Security assumptions

In the following discussions, we focus on the BB84 protocol, but most of the discussions can be applied to other protocols, such as BBM92. In security proofs (Lo and Chau, 1999; Shor and Preskill, 2000), as shown in Section II.B, we assume Alice sends ideal qubit states in $\{|0\rangle, |1\rangle, |+\rangle, |-\rangle\}$ and Bob performs in ideal qubit $Z$-basis measurement. The channel, on the other hand, is assumed to be under a full control of Eve.

1. Source

First, let us relax the requirement on source by considering a more general source. In a prepare-and-measure QKD protocol, Alice randomly prepares system $B$ on one of the four states, $\{|\rho_{x0}, \rho_{x1}, \rho_{z0}, \rho_{z1}\}$, and sends it to Bob. These four states can be denoted as $\rho_{\beta\kappa}$, where $\beta \in \{X, Z\}$ represents the encoding basis, and $\kappa \in \{0, 1\}$ represents the encoding key bit. Here, we consider four states with two bases, but such scenario can be easily extended to a more general cases with an arbitrary number of states and bases.

The prepare-and-measure protocol can be linked to the entanglement-based one as follows. Define the purification of state $\rho_{\beta\kappa}$ as $|\psi_{\beta\kappa}\rangle_{A_0B}$, where system $A_0$ is an ancillary system. From an entanglement-based view of protocol, Alice sends out state $\rho_{\beta\kappa}$ is equivalent for her to first prepare

$$|\Psi_{\beta}\rangle_{A_0B} = \frac{1}{\sqrt{2}} \sum_{\kappa} |\beta\rangle_A |\psi_{\beta\kappa}\rangle_{A_0B},$$

(12)

then to measure system $A$ on $\beta$-basis, and to send out system $B$ according to measurement result $\kappa$. Here, system $A$ is a qubit system, $|\beta\rangle_A$ is the $\beta$-basis eigenstate whose eigenvalue is $\kappa$. For the ideal BB84 protocol, there is no ancillary system $A_0$ (or $A_0$ is just a detached trivial system), since all encoding states $\rho_{\beta\kappa}$ are pure. Then, the states sent by Alice are

$$\rho_{\beta\kappa} = Tr_{A_0}(|\psi_{\beta\kappa}\rangle \langle \psi_{\beta\kappa}|_{A_0B}),$$

(13)

the four BB84 states.

To send out $\rho_{x\kappa}$, in the entanglement-based equivalent protocol, Alice prepares $|\Phi^+\rangle_{AB} = \frac{1}{\sqrt{2}}(|++\rangle+|--\rangle)_{AB},$
measures system $A$ on the $X$ basis, and obtains the measurement result $\kappa$. Similarly, to send out $\rho_{x\kappa}$, Alice first prepares $|\Phi^+\rangle_{AB} = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)_{AB}$, measures $A$ on the $Z$ basis, and obtains the measurement result $\kappa$. No matter which basis Alice wants to send, the initial entangled states prepared are the same. Denote the $X$-basis state and $Z$-basis state to be

$$
\rho_x = \frac{1}{2}(\rho_{x0} + \rho_{x1}),
$$

$$
\rho_z = \frac{1}{2}(\rho_{z0} + \rho_{z1}),
$$

which are the quantum state transmitted given Alice and Bob choose the $X$ and $Z$ bases, respectively. Thus, in the ideal BB84 source case, the state sent out by Alice is independent of the basis choice,

$$
\rho_x = \rho_z.
$$

We call this kind of source basis-independent (Koashi and Preskill, 2003; Ma et al., 2007).

In the original proposal of the BB84 protocol, the basis choice is assumed to be unknown to Eve. This is also a crucial assumption in security proofs (Lo and Chau, 1999; Shor and Preskill, 2000), as shown in Section II.B. This is important for phase error estimation. If the source is basis-dependent, one cannot simply use one basis information to estimate the other. This is guaranteed by Eq. (15). In fact, as long as the source is basis-independent, it can be in arbitrary dimension or state. It can even be assumed to be under the control of Eve.

In practice, it is hard to construct single-qubit sources. Instead, entangled photon sources are widely used as a basis-independent source. Later in Section II.D, we show that the security can be guaranteed once the source contains a certain amount of basis-independent components.

In some QKD schemes, such as BBM92 (Bennett et al., 1992c), Alice and Bob choose basis after the quantum signals transmitted through the channel. In BBM92 protocol, Alice prepares an entangled source, holds one party by herself and sends another party to Bob. Alice measures her own party in some basis to realize the basis choice and encoding. In these schemes, the quantum source can even be assumed to be in the possession of Eve. Then for these schemes, Eq. (15) can be guaranteed by the experimental setting.

In some CV-QKD schemes, there is also an entangled source scheme where Alice prepares a two-mode EPR state and sends one mode to Bob (Grosshans et al., 2003a; Madsen et al., 2012). This can be regarded as a continuous variable version of BBM92 scheme.

2. Measurement

The requirement on measurement is very similar. Again, take the BB84 protocol as an example. There are four measurement outcomes labeled by two bits, $\beta, \kappa$. The corresponding four POVM elements are $M_{\beta\kappa}$,

$$
M_x = M_{x0} + M_{x1},
$$

$$
M_z = M_{z0} + M_{z1}.
$$

Here, $\{M_{x0}, M_{x1}\}$ form the $X$-basis measurement, while $\{M_{z0}, M_{z1}\}$ form the $Z$-basis measurement. We also require the measurement to be basis-independent,

$$
M_x = M_z.
$$

On the measurement side, the requirement is more strict. For the security proof presented in Section II.B, it must be qubit measurements in the $X$ and $Z$ bases. Such requirement can be extended to more general projection measurements.

In practice, a squashing model is widely employed (Beaudry et al., 2008; Gottesman et al., 2004). In a squashing model, an arbitrary quantum state (from the channel) is projected to a qubit or vacuum. Then the $X$ or $Z$ measurement is performed. It has been shown that a typical threshold detector model can be proven to be adapt to the squashing model (Beaudry et al., 2008; Tsurumaru and Tamaki, 2008).

Now, one can see that the assumptions on the source and measurement are quite different. For source, one only needs to guarantee its basis-independent property in Eq. (15). On measurement, it must be specific projection measurements. In practice, the source requirement is easier to meet comparing to the measurement requirement. Hence, there are more practical security issues on measurement than on source. A full security analysis needs to take account of these measurement deviations.

We present it in Section II.D. This problem is finally resolved by MDI-QKD (see Section VI.B).

3. Channel

In security proofs, the channel is assumed to be under the full control of Eve. Thus, in principle, we do not put any requirement on channel. In fact, if any implementation deviation from the ideal QKD protocol can be put into the channel, it would not cause any security problem. For example, detector normally have a finite efficiency. The loss caused by detectors can be moved to channel. Then, a detector can be replaced by a 100\% efficiency one in security analysis.

Now, the question is what kind of implementation deviations can be moved to channel. The implementation deviation can be regarded as some deviation operation acting on an ideal implementation. The key requirement is that the deviation operation must commute with basis switch operation. Alice and Bob each uses a basis switching device (say, a phase modulator in phase-encoding schemes). The channel is defined as the operation on
the quantum signals in between the two basis switching devices.

D. GLLP

In practice, there are several deviations between the realistic QKD system and the ideal QKD protocol. Based on previous works on the topics (Inamori et al., 2007; Lütkenhaus, 2000), Gottesman, Lo, Lütkenhaus, and Preskill (GLLP) established a general framework for security analysis with realistic devices (Gottesman et al., 2004).

Suppose Alice uses a source which is not basis-independent. For example, she employs a weak coherent state photon source. With phase randomization, one can treat it as a mixture of Fock states (Lo et al., 2005). The vacuum and single-photon components are basis-independent, whereas the multiphoton components are not. In principle, Alice can measure the photon number to determine whether or not each encoded state is basis-independent or not. Denote the ratio of Bob’s detected bits from the basis-independent source (good part) to be $1 - \Delta$, and the rest (bad part) is $\Delta$. Suppose the totally error rate is $E$,

$$r \geq -H(E) + (1 - \Delta)[1 - H\left(\frac{E}{1 - \Delta}\right)]. \quad (18)$$

This key rate formula is deviated from Eq. (11)

III. QKD IMPLEMENTATION

In practice, security of a QKD system is often related to its implementation. A QKD implementation is composed of three parts: source, channel, and detection. In a rigorous security proof, the channel is assumed to be under the full control of Eve, who can replace the channel with any quantum operation she desires. In the security proof model, no implementation assumption is required on the channel. As a result, the security of the system does not depend on the physical realization of the quantum channel. Therefore, the practical security for the channel is not an issue. For the quantum source and detection, on the other hand, a security proof normally requires some assumptions on practical realization.

Here, we review the practical components of a QKD system. Photons are most widely used for communication, due to their robustness against decoherence due to noisy environment and fast traveling speed. Hence, we mainly focus on the quantum optical realization of QKD systems. We first discuss the encoding and decoding method in QKD systems, and then briefly introduce the practical source, channel and detection devices used in the QKD experiments.

A. Encoding and decoding

Depending on various encoding and decoding, QKD can be classified into two types: discrete-variable QKD schemes and continuous-variable QKD schemes. Different encoding and decoding methods are reflected on source, channel, and detection. For discrete-variable QKD schemes, Alice needs to figure out an efficient method to encoding her qubit (or qudit) into the quantum states. Accordingly, Bob needs to develop an efficient method to read out the quantum information encoded by Alice.

In general, for qubit-based QKD, the quantum information can encoded into two quantum modes, $s$ and $r$, and their relative phases. Normally, the two modes are assumed to be orthogonal, say, using orthogonal polarizations or distinct time bins. Then, for a photon, the states \{10\}$_{sr}$, \{01\}$_{sr}$ form a Hilbert space, named $Z$ basis. Here, “0” and “1” refer to the photon number in a mode. Two complementary bases, $X$ and $Y$, are defined with the relative phases. The $X$ and $Y$ basis states can be written as, \{10\}$_{sr} \pm \{01\}$_{sr} and \{10\}$_{sr} \pm i \{01\}$_{sr}.

In reality, a widely applied method is polarization encoding, which utilizes the polarization modes. The horizontal and vertical polarizations of a photon, denoted by \{01\}$_{HV}$ and \{10\}$_{HV}$, are used for the $Z$ basis encoding. Then, the $X$ basis states, \{10\}$_{HV} \pm \{01\}$_{HV}, denote the linear polarization modes along the directions of ±45°, respectively. The $Y$ basis states, \{10\}$_{HV} \pm i \{01\}$_{HV}, denote the left- or right-handed circular polarizations. In the decoding process, the basis choice is realized by a polarization controller (Fig. 4), and the polarization measurement is realized by polarization beam splitter (PBS) connected with single photon detectors.

Another common method is time-bin phase encoding, where Alice chooses two pulses, a signal pulse and a reference pulse, for two encoding modes, denoted by $s$ and $r$, respectively. Similar to the polarization encoding, for a single photon, the two time-bin modes form the $Z$ basis, \{10\}$_{sr}$, \{01\}$_{sr}$. Here, the qubit in the $Z$ basis determines whether the photon stays in the signal time bin or the reference time bin. The $X$ and $Y$ basis states, \{10\}$_{sr} \pm \{01\}$_{sr} and \{10\}$_{sr} \pm i \{01\}$_{sr}, denote the photons with a relative phase $0, \pi$ and $\pi/2, 3\pi/2$ between the signal and reference pulses, respectively. In the decoding process, an interferometer (Fig. 4) is employed to extract the phase information.

For qubit-based QKD, Alice and Bob need to find $d$ orthogonal modes and the encoding and decoding are similar. For example, the orbital angular momentum is the freedom of photons on spatial distribution, which contains a large Hilbert space. By encoding the high-dimensional key information into the orbital angular momentum, one can enhance the performance of QKD (Cerf et al., 2002; Gröblacher et al., 2006; Mafu et al., 2013). Another example is to encode with multiple time bins. In
differential phase shift quantum key distribution (DPS-QKD), the relative phase or each time-bin pulse is only 0 or π, and the key is encoded into relative phase of two neighbouring pulses. Round-Robin differential phase shift quantum key distribution (RRDPS QKD) (Sasaki et al., 2014) encoding and decoding the phase difference circularly.

In Gaussian modulated continuous-variable QKD schemes (Cerf et al., 2001; Grosshans and Grangier, 2002; Grosshans et al., 2003b), the key is encoded in displacement of quadratures for Gaussian modulated coherent state protocol or squeezed state protocol. For Non-Gaussian discrete modulated continuous-variable-QKD, the key is encoded into the random phases of coherent states (Hiroshima, 2006; Ralph, 1999; Reid, 2000). The decoding process is based on coherent detection, e.g., homodyne detection and heterodyne detection, measuring quadratures of optical fields.

B. Photon sources

Here, we mainly discuss various practical photon sources for QKD: weak coherent-state source, thermal source, heralded single photon source, and entangled photon source. For most of prepare-and-measure QKD protocols, a single photon source is preferred. However, it is experimentally challenging to realize a high-quality and high-performance single photon source. The common way is to employ other practical weak light sources to approximate the single photon source. In general, they are modulated to be a Fock state mixture,

$$\rho = \sum_{n=0}^{\infty} P(n) \ket{n}\bra{n},$$  \hspace{1cm} (19)

where $P(n)$ is the photon number distribution and $\ket{n}$ is the $n$-photon number state. For different types of sources, the photon number distribution will also be different. Normally, the single photon component, $\ket{1}\bra{1}$, is required to be dominant comparing to higher order components.

The weak coherent-state source is the most widely employed in QKD, which can be easily realized by attenuating laser lights. The light generated by a laser can be regarded as a coherent pulse $|\alpha\rangle$ within the coherence time, where $\alpha$ is a complex number, and $\mu = |\alpha|^2$ is the average photon number. The coherent state can be expanded in the Fock basis as

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} \ket{n}. \hspace{1cm} (20)$$

The phase of $\alpha$ reflects the relative phase between different photon number components. To realize a photon source in the form of Eq. (19), Alice can randomize the phase of coherent pulses, and make it a mixture of photon number states (Lo et al., 2005),

$$\rho_{\mu} = \frac{1}{2\pi} \int_{0}^{2\pi} d\phi |\alpha e^{i\phi}\rangle\langle \alpha e^{i\phi}|$$

$$= \sum_{n=0}^{\infty} P_\mu(n) \ket{n}\bra{n}, \hspace{1cm} (21)$$

where the photon number follows a Poisson distribution, $P_\mu(n) = e^{-\mu} \frac{\mu^n}{n!}$. In many QKD protocols, such as BB84, only single photon component is secure for key distribution. Thus, the light intensity $\mu$ is typically in the single photon level, $\mu = O(1)$.

The thermal source is a Fock state mixture, expanded by

$$\rho_{th} = \sum_{n=0}^{\infty} P_{th}(n) \ket{n}\bra{n}$$

$$= \sum_{n=0}^{\infty} \frac{\mu^n}{(\mu + 1)^{n+1}} \ket{n}\bra{n}, \hspace{1cm} (22)$$

where $\mu$ is the average photon number and the photon number follows a thermal distribution $P_{th}(n)$. Note that for a small average photon number $\mu \leq 2$, the single photon component ratio is bigger in a Poisson distribution.

| Source | PM | Channel | PC | SPD |
|--------|----|---------|----|-----|
| Polarization |     |         |    |     |
| Encoding | Source | PM | Channel | PC | SPD |
| Decoding | Channel | PM | Channel | PC | SPD |

FIG. 4 Illustration of optical device of (a) polarization encoding, and (b) relative phase encoding. PM: phase modulator; PC: polarization controller; PBS: polarization beam splitter; SPD: single photon detector; BS: beam splitter.
than in a thermal distribution. This is the reason why the weak coherent state source normally can outperform the thermal one in QKD (Curty et al., 2010).

In a parametric down-conversion (PDC) process, a high frequency photon is converted to a pair of low frequency photons. A PDC source emits a superposition state of different number of photon pairs (Ma and Lo, 2008; Walls and Milburn, 2008),

\[ |\Psi\rangle = (\cosh \chi)^{-1} \sum_{n=0}^{\infty} (\tanh \chi)^n |n, n\rangle, \tag{23} \]

where \( \chi \) is the nonlinear parameter for the down-conversion process, \( \mu = \sinh^2 \chi \) is the average photon pair number, and \( |n, n\rangle \) represents \( n \) photon pairs in two optical modes. If we only focus on one of the optical modes (normally called signal mode), tracing out the other (normally called idle mode), the photon number follows the thermal distribution, \( P_{th}(n) \) given in Eq. (22). A typical usage of a PDC source involves measuring the idle optical mode locally as a trigger and encoding the signal mode for QKD. In this case, once Alice obtains a trigger locally, she can largely rule out the vacuum component in the signal mode. In fact, conditioned on whether or not a detection clicks on the idle mode, the photon number distribution is different on the signal mode. Such source can be used as a passive decoy-state source (Adachi et al., 2007; Ma and Lo, 2008). Note that when \( \mu \) is very small, such heralded photon source can well approximate a single photon source, which is widely used in multi-photon processing (Pan et al., 2000).

For the entanglement-based QKD protocol, such as BBM92 (Bennett et al., 1992c), an entangled photon source is required. Similar to the heralded single photon source, the PDC process is widely used to generate photon pairs. In this case, four optical modes are used. For example, a typical PDC photon source emits photon pairs in two directions. In each direction, the photon can be in \( H \) or \( V \) polarization. The two optical modes are entangled in polarization. Comparing to Eq. (23), due to different collection means, the amplitudes of photon pair numbers are slightly different from the one in Eq. (23) (Kok and Braunstein, 2000; Ma et al., 2007),

\[ |\Psi\rangle = (\cosh \chi)^{-2} \sum_{n=0}^{\infty} \sqrt{n+1} \tanh^n \chi |\Phi_n\rangle, \tag{24} \]

where \( \chi \) is the nonlinear parameter for the down-conversion process, \( \mu = 2 \sinh^2 \chi \) is the average number of entangled photon pairs, and \( |\Phi_n\rangle \) is the state of an \( n \)-entangled-photon pair,

\[ |\Phi_n\rangle = \frac{1}{\sqrt{n+1}} \sum_{m=0}^{n} (-1)^m |n-m, m\rangle_a |m, n-m\rangle_b. \tag{25} \]

In the aforementioned example, \( a \) and \( b \) represent two direction of the light, and \( |n-m, m\rangle_a \) represents \( n-m \) photons in the \( H \) polarization and \( m \) photons in the \( V \) polarization. The number of the entangled-photon pairs follows a Super-Poissonian distribution, slightly different from the thermal distribution,

\[ P(n) = \frac{(n+1)(\frac{\mu}{2})^n}{(1+\frac{\mu}{2})^{n+2}}. \tag{26} \]

In Gaussian modulated continuous-variable QKD schemes, coherent-state photon source (Grosshans and Grangier, 2002; Grosshans et al., 2003b) and squeezed photon source (Cerf et al., 2001) are widely used. Different from discrete-variable cases, the key is encoded in the quadrature displacement. We take the Gaussian modulated coherent state protocol as an example. The source is a mixture of coherent state \( |\alpha_j\rangle = |x_j + ip_j\rangle \) with quadrature components \( x_j \) and \( p_j \) as realisations of two independent and identically distributed (i.i.d.) random variables \( X \) and \( P \). These two random variables obey the same zero-centred Gaussian distribution \( N(0, V_m) \), where \( V_m \) is the modulated variance. The total variance of the Gaussian modulated source is \( V = V_s + V_m + V_{th} \) with an additional thermal variance \( V_{th} \). This type of protocol is also widely used for its low cost in state preparation and feasibility in wavelength longer than optical. In discrete modulated (non-Gaussian) continuous continuous-variable QKD schemes (Hiroshima, 2006; Ralph, 1999; Reid, 2000), the key is encoded in the phase of coherent state. And the source is a \( N \)-discrete randomized coherent state mixture (Cao et al., 2015)

\[ \rho = \sum_{k=1}^{N} p_k |\sqrt{\mu} e^{i2\pi k/N}\rangle \langle \sqrt{\mu} e^{i2\pi k/N}|. \tag{27} \]

C. Channel

Theoretically, we put no assumption on the quantum channel used for QKD. However, in the real world implementation, we will use build the QKD channel with mature optical communication technology to enhance the performance of QKD protocol.

The most common channel used in QKD is built with commercial optical fiber. Comparing to the free space optical communication, the transmittance of fiber is higher. Also, the stability of fiber is much higher than the free space. For a common commercial fiber, the loss rate will be roughly 0.2 dB/km. The noise in the transmission process will be highly dependent on the background environment.
However, the loss rate can still be remarkable if we extend the transmission distance to over 400 km. To overcome this issue, the satellite-based free space communication has been proposed and realized (Liao et al., 2018, 2017a), which makes the QKD over 1000 km possible.

In DV-QKD and CV-QKD schemes, the channel model is different. In DV-QKD schemes, lossy qubit channel is considered. For the source with multiple photon components, like the phase randomized coherent state source or thermal state source, a photon number channel model can be introduced (Ma, 2008). In the photon number channel model, we can regard the channel as the combination of many independent lossy channels with respect to different photon numbers \( n \) in the light source. By applying the decoy-state method (Lo et al., 2005), we can estimate the loss rate and the error of each photon number component.

In continuous-variable QKD schemes, a lossy bosonic channel is considered. It turns out that the optimal attack for an arbitrary adversary is Gaussian collective attack, which corresponds to a Gaussian channel with a canonical form (Pirandola et al., 2008).

D. Detection

Generally speaking, the detection method in QKD implementation can be classified into single-photon detection and coherent detection, which are applied in DV-QKD and CV-QKD schemes, respectively.

For DV-QKD schemes, single photon detection is realized with threshold detectors which can only distinguish the vacuum (zero photon) from single photon or multi-photon cases. Besides, some imperfections may exist in the single-photon detector (SPD): the detector efficiency \( \eta \) is not 100\%, which means some non-vacuum signals will not cause a click on the SPD; there exists a dark count factor \( p_d \), which means some vacuum signals will incorrectly cause a click. This will affect the performance of QKD systems.

The measurement model is based on the threshold SPDs mentioned above. For the single-photon subspace, the detection here can be regarded as \( X/Y \) basis qubit measurement. However, there are multi-photon components in the final signal, and the behavior of the measurement device will be different from the required Z-basis and X-basis measurement in DV-QKD. For example, there will be double-click signals caused by multi-photon component, which will not happen in the ideal \( X/Y \) basis detection. To address this issue, the squash model of measurement is proposed, combined with the random-assignment of double-clicked signals (Beaudry et al., 2008; Fung et al., 2011).

In 2012, the measurement-device-independent QKD (MDI-QKD) scheme (Lo et al., 2012) was proposed to fill the detection loophole. The design of measurement devices in MDI-QKD is similar to the one in point-to-point QKD protocol. In discrete variable MDI-QKD scheme, the measurement device, assumed to be manipulated by the adversary, can be divided into two categories, single detection and coincidence detection. The coincident detection MDI-QKD schemes (Lo et al., 2012; Ma and Razavi, 2012) is based on the schemes where the two communication parties, Alice and Bob, encode their key information into a single photon, and build correlation between their key value by a Bell state projection. The single detection MDI-QKD schemes (Lucamarini et al., 2018; Ma et al., 2018; Tamaki et al., 2012) can be regarded as the detection on the coherent states rather than the single photon. They both build correlations between Alice’s and Bob’s bit values by Bell state projections.

For CV-QKD schemes, coherent detection can be classified into homodyne detection and heterodyne detection, measuring quadratures of optical fields (Weedbrook et al., 2012). In CV-MDI-QKD scheme, the detection is also a coherent detection announcing a complex variable with some certain probability distribution, building connections between Alice’s and Bob’s complex value of prepared coherent states (Pirandola et al., 2015).

IV. QUANTUM HACKING

In theory, it is traditional to divide Eve’s hacking strategy to three main classes: individual, collective and coherent (or general) attack. Individual attack means that Eve interacts with each secure qubit in the channel separately and independently; Collective attack means that Eve prepares independent ancilla, interacts each qubit independently, but can perform a joint measurement on all the ancilla; Coherent attack means that Eve can prepare an arbitrary joint (entangled) state of the ancillas, which then interact with the qubits in the channel before being measured jointly. The last one does not limit Eve’s capabilities beyond what is physically possible. Any QKD system aiming to implement an information-theoretically secure protocol therefore has to be proven secure against coherent attacks. Another aspect which cannot be neglected is security in a finite size scenario. No key transmission session can be endless and the resulting statistical fluctuations have to be taken into account (Scarani et al., 2009).

In this section, different from the theory attacks, we focus on the practical attacks which exploit the device imperfections in QKD systems. Specifically, Eve may try to exploit the imperfections in real QKD systems and launch the so-called quantum hacking not covered by the original security proofs. Researchers have demonstrated several quantum hacking attacks in practical QKD systems. Table I summarizes the attacks developed from early 2000 to the present. Here, we will review these at-
tacks, with a special focus on those demonstrated already in experiment.

A. Attacks at source

In the standard QKD scheme, it is assumed that Alice (state preparation) is placed in a protected laboratory and she prepares the required quantum state correctly. Unfortunately, imperfect state preparation may leak information about the secret key. Indeed, practical preparation may introduce some errors due to imperfect devices or Eve’s disturbance (Brassard et al., 2000; Fung et al., 2007; Lütkenhaus, 2000; Sun et al., 2012, 2015; Tang et al., 2013; Xu et al., 2010). To steal the information about the states, Eve can also actively perform the Trojan-horse attack (Gisin et al., 2006; Jain et al., 2014, 2015) on intensity modulators and phase modulators. This section will review some examples of attacks at source.

1. Photon-number-splitting attack

The first well known kind of hacking strategy that was considered is the photon-number-splitting (PNS) attack (Brassard et al., 2000; Lütkenhaus, 2000) aiming at the imperfect photon source. As described in section III.B, because of technological challenge, weak coherent pulses (WCPs) generated by a highly attenuated laser are widely used in QKD implementations. Since the photon number of a phase-randomized WCP follows the Poisson distribution (Eq. (21)), there is a non-zero probability for multiple-photon pulses, i.e., those pulses containing two or more photons. Consequently, Eve may exploit the multiple-photon pulses and launch the PNS attack. In this attack, for each WCP, Eve first utilizes a quantum non-demolition (QND) measurement to obtain the photon number information. Conditioned on the QND measurement result, Eve either blocks the one-photon pulse or splits the multiple-photon pulse into two. She stores one part of the multiple-photon pulse and sends the other part to Bob. Later on, during the basis-reconciliation process of the BB84 protocol, Eve can get the secret key information for the multiple-photon pulse without introducing any errors. By doing so, Alice and Bob could not notice Eve’s attack.

The PNS attack restricts the secure transmission distance of QKD typically below 30 km (Gottesman et al., 2004). Actually, in early 2000s, there were not many research groups working on QKD experiments. Researchers in the field had a serious doubt on the future of QKD, and they generally thought that QKD may be impractical with WCP source. This concern severely limits the development of QKD at that time. Fortunately, the discovery of the decoy state method perfectly resolved the problem of PNS attack and made QKD practical with standard WCP (Hwang, 2003; Lo et al., 2005; Wang, 2005). More details on the decoy state method will be discussed in section V.

2. Phase-remapping attack

Phase modulators are commonly used to encode random bits in the source of phase-coding QKD systems (Gisin et al., 2002). In practice, a phase modulator has finite response time, as shown in Fig. 5a. Ideally, the pulse passes through the phase modulator in the middle of the modulation signal and undergoes a proper modulation (time $t_0$ in Fig. 5a). However, if Eve can change the arrival time of the pulse, then the pulse will pass through the phase modulator at a different time (time $t_1$ in Fig. 5a), and the encoded phase will be different. This phase-remapping process allows Eve to launch an intercept-and-resend attack, i.e., phase-remapping attack (Fung et al., 2007). The phase-remapping attack is a particular threat for the bidirectional QKD schemes, such as the plug-and-play QKD structure (Stucki et al., 2002).
In 2010, the phase-remapping attack was successfully demonstrated in a commercial ID-500 plug-and-play QKD system (manufactured by ID Quantique)\(^{13}\) (Xu et al., 2010), as shown in Fig. 5b. In this experiment, Eve utilized the same setup as Bob to launch her attack. Eve modified the length of the short arm of her Mach-Zehnder interferometer by adding a variable optical delay line (VODL in Fig. 5b) to shift the time delay between the reference pulse and the signal pulse. To remap the phase small enough into the low QBER range, Eve shifted the forward signal pulse out and only the backward signal pulse in the phase modulation range by using VODL, and properly aligned the polarization direction of the backward signal pulse orthogonal to the principal axis of the phase modulator by using a polarization controller (PC in Fig. 5b). The experiment demonstrated that Eve could get full information and only introduce a QBER of 19.7\%, which is much lower than the well-known 25\% error rate for an intercept-and-resend attack in BB84.

3. Nonrandom-phase attack

Phase randomization is a basic assumption in most security proofs of QKD (Gottesman et al., 2004; Hwang, 2003; Lo et al., 2005; Wang, 2005). Although the security of QKD with non-random phase had been proven (Lo and Preskill, 2007), the performance is very limited in distance and key rate. By assuming that the overall phase is uniformly distributed in \([0, 2\pi]\), a coherent state with intensity can be reduced into a classical mixture of photon number states, i.e., Eq. (21). This can greatly simplify the security proofs and allow one to apply classical statistics theory to analyze quantum mechanics. In practice, however, the phase randomization assumption may be violated in practice, thus resulting in various attacks (Sun et al., 2012, 2015; Tang et al., 2013).

The first example is the USD attack demonstrated in (Tang et al., 2013). When the phase of WCPs is not properly randomized, the quantum state will be a pure state. Then in decoy state QKD (Hwang, 2003; Lo et al., 2005; Wang, 2005), it is possible for Eve to distinguish the signal state and decoy state with an unambiguous state discrimination (USD) measurement. Hence, Eve first measures each of Alice’s WCPs to distinguish between signal state and decoy state by performing a USD measurement, which is combined with positive operator-valued measurement (POVM) operators without disturbing the quantum state sent by Alice. After the USD, Eve performs the PNS attack. Since Eve knows which state the pulse belongs to (signal or decoy), she could do different strategies for signal state and decoy state. As a result, the key assumption in decoy state QKD (Lo et al., 2005) – a decoy state and a signal state have the same characteristics – is violated.

The second example is the laser seed-control attack which was proposed and demonstrated in (Sun et al., 2015). Semiconductor laser diode (SLD) is normally used as a single-photon source in most commercial and research QKD systems. In the interdriven mode, the semiconductor medium of the SLD is excited from loss to gain by each driving current pulse. A laser pulse is generated from seed photons originating from spontaneous emission. The phase of the laser pulse is determined by the seed photons. Since the phase of the seed photons is random, the phase of each laser pulse is random inherently. However, if a certain number of photons are injected from an external source into the semiconductor medium, these photons will also be amplified to generate laser pulses. Consequently, the seed photons consist of two parts: one from spontaneous emission and the other part from the external source. Both parts will affect the phase of the resulting laser pulse. If the injected photons greatly outnumber the photons from spontaneous emission, the phase of the output laser pulse is largely determined by the phase of the injected photons. Therefore, Eve can control the phase of Alice’s signal laser by illuminating the SLD from an external control source and successfully violate the phase randomization assumption (Gottesman et al., 2004).

B. Attacks at detection

The detection component is much more vulnerable to quantum hacking attacks than the source. Since Eve controls the channel and can send any signals (e.g., strong optical pulses combined with X-ray and neutrinos) to Bob and Bob has no choice but to receive Eve’s signal and any filters used by Bob may be imperfect, it may be hard for Bob to isolate his lab and avoid side channels or detector control from Eve. For instance, a significant number of attacks have been proposed to hack single-photon detectors (SPDs) (Gerhardt et al., 2011a,b; Lydersen et al., 2011, 2010a,b,c; Makarov, 2009; Sauge et al., 2011; Wiechers et al., 2011; Yuan et al., 2010). SPDs are regarded as the “Achilles heel” of QKD by Charles Bennett. This section will review some examples of attacks at detection. The first two examples, double-click attack and fake-state attack, were proposed only in theory, while the last two examples, time-shift attack and detector-blinding attack, were successfully demonstrated in experiment.

\(^{13}\) https://www.idquantique.com/
1. Double-click attack

Since QKD systems require the detection of two different bit values, bit 0 and bit 1, they require at least two SPDs. The double-click event refers to the case where both SPDs detect signals. The double-click event will introduce a QBER of 50% when either one of the two bits is selected. A naive strategy is to determine double-click events as abnormal events and discard these events so as to minimize the QBER. However, this strategy results in the problem of double-click attack. In this attack, Eve simply floods Bob’s polarization beam splitter with multiple photons or a strong pulse of the same polarization. Then, when Bob makes a measurement using a conjugate basis different from that of Eve, a double-click event occurs and it is discarded; when the receiver makes a measurement using the same basis as Eve’s, a normal event is detected. Consequently, Alice and Bob finally share the same information with Eve. To solve this problem, Lütkenhaus has proposed that double-click events are not discarded and bit 0 or bit 1 is randomly allocated by Bob whenever a double-click event occurs (Lütkenhaus, 1999; Lütkenhaus, 2000).

2. Fake-state attack

In 2005, Makarov et al. proposed a faked-state attack, which exploits the efficiency mismatch of two detectors in a practical QKD system (Makarov et al., 2006; Makarov and Hjelme, 2005). In practice, the standard SPDs such as Si/InGaAs APDs are often operated in a gated mode. Therefore, the detection efficiency of each detector is time-dependent. Since QKD systems require the detection of two different bit values, 0 and 1, they often employ at least two SPDs. It is inevitable that finite manufacturing precision in the detector and the electronics, and difference in optical path length will slightly misalign the two detector gates, and cause detector-efficiency mismatch. This is illustrated in Fig. 6a. At the expected arrival time T, the detection efficiencies of SPD0, η0, for the event of bit 0, and SPD1, η1, for the event of bit 1 are the same. However, at time $t_1$, SPD0 is more sensitive to the incoming photon than SPD1, while at time $t_2$, SPD1 is more sensitive to the incoming photon than SPD0. b, Real detector efficiencies of the two SPDs characterized on commercial QKD system (manufactured by IDQ) by Zhao et al. (Zhao et al., 2008).

The faked-state attack, while conceptually interesting, is hard to implement in a real-life QKD system. This is because it is an intercept-resend attack and as such involves finite detection efficiency in Eve’s detectors and precise synchronization between Eve and Alice-Bob’s system. A typical countermeasure against detector efficiency mismatch is the four-state QKD protocol (Makarov et al., 2006).

3. Time-shift attack

Motivated by the faked-state attack, in 2007, Qi et al. (Qi et al., 2007) proposed the time-shift attack, which is also based on the detection-efficiency mismatch for gated SPDs in the time domain, but is much easier to implement than the faked-state attack. Let us suppose Fig. 6a illustrates the detection efficiencies of the two gated SPDs in a real-life QKD system. Eve can simply shift the arrival time of each pulse sent from Alice by employing a variable optical delay line. For example, Eve randomly shifts the pulse from Alice to arrive at $t_1$ or $t_2$ through a
shorter path or a longer path of optical line. This shifting process can partially reveal the bit value of Bob: if the pulse arrives at $t_1$ (or $t_2$) and Bob announces receipt, the bit value is more likely to be 0 (1). Moreover, Eve can carefully set how many bits should be shifted forward and how many should be shifted backward to ensure that the distribution of bit 0 and bit 1 received by Bob is balanced. Hence, the time-shift attack does not make any measurement on the quantum state, and quantum information is not destroyed.

Since Eve does not need to make any measurement or state preparation, the time-shift attack is practically feasible with current technology. In 2008, it has been successfully implemented on a commercial QKD system by Zhao et al. (Zhao et al., 2008) as shown in Fig. 6b. This is one of the first successful demonstrations of quantum hacking on a widely-used commercial QKD system. In their experiment (Zhao et al., 2008), Eve got an information-theoretical advantage in around 4% of her attempts. The successful implementation of the quantum attack shows that a practical QKD system has non-negligible probability to be vulnerable to the time-shift attack.

4. Detector-blinding attack

The detector blinding attack is the most powerful attack and it has been successfully demonstrated on several types of practical QKD systems (Lydersen et al., 2011, 2010b; Makarov, 2009). Most available SPDs are InGaAs/InP APDs operating in a Geiger mode (Hadjfield, 2009), in which they are sensitive to a single photon. The working principle of this type of APDs is shown in Fig. 7a. In the detector blinding attack, by sending a strong light to Bob, Eve can force Bob’s SPDs to work in a Linear mode instead of Geiger mode, as shown in Fig. 7a. In the Linear mode, the SPD, such as the one based on InGaAs APD, is only sensitive to bright illumination. This detector operation mode is called “detector blinding”.

After blinding the detectors, Eve sends a bright pulse with tailored optical power such that Bob’s detector always reports a detection event from the bright pulse, but never reports a detection event from a pulse with half power. This is illustrated in Fig. 7b. Consequently, Eve can successfully launch an intercept-and-resend attack without increasing QBERs. For example, when Eve uses the same basis as Bob to measure the quantum state from Alice, Bob gets a detection event as if there were no eavesdropper. But if Eve uses the opposite basis from Bob to measure the quantum state from Alice, her bright pulse will strike each of Bob’s detectors with half power, and neither detector will report a detection event. In practice, a simple detector blinding attack will introduces a 50% total loss. However, Eve can place her intercept-unit close to Alice’s laboratory while compensating the loss in the remaining fiber by re-sending brighter states.

The detector blinding attack is applicable to various types of SPDs, such as gated APDs (Lydersen et al., 2010b), passively or actively quenched APDs (Makarov, 2009; Sauge et al., 2011), superconducting single-photon detectors (Lydersen et al., 2011), and so forth. A full field implementation of the attacking strategy has been investigated in (Gerhardt et al., 2011a), as shown in Fig. 8. The blinding attack was also demonstrated to fake the violation of Bell’s inequality (Gerhardt et al., 2011b). How to remove the detector blinding attack is a challenge in the field of QKD. One proposed countermeasure is carefully operating the single-photon detectors inside Bob’s system and monitoring the photocurrent for anomalously
high values (Yuan et al., 2010, 2011). However, such a countermeasure may seem ad hoc and lead away from provable security models of QKD and can often be defeated by advanced hacking technologies. A practical and promising solution is the MDI-QKD protocol, which will be reviewed in section VI.B.

![FIG. 8 Full-field implementation of detector blinding attack (Gerhardt et al., 2011b). Using a similar setup, the detector blinding attack was also demonstrated to fake the violation of Bell’s inequality (Gerhardt et al., 2011b). a, Principle of the faked-state attack. b, Attack on installed QKD system spanning four buildings at the campus of the National University of Singapore. In Alice, polarization-entangled photon pairs were produced in a type-II spontaneous parametric down-conversion (SPDC) source. One photon was measured locally by Alice; the other one was sent through a 200m single-mode (SM) fibre line to Bob. Eve was inserted at a mid-way point. All three parties used identical polarization analysers (PA); clicks were registered with time-stamp (TS) units[Figure adapted from (Gerhardt et al., 2011a)].](image)

![FIG. 9 Schematic illustration of the Trojan-horse attack (Jain et al., 2015). Eve attacks Alice by sending bright Trojan-horse pulses to know the bases selected by the latter during the operation of the QKD protocol. This information is carried by the back-reflected pulses coming out of Alice. As a rule of thumb, Eve must avoid disturbing the legitimate quantum signals travelling from Alice to Bob as much as possible since she is interested in knowing only the basis settings. [figure reproduced from (Jain et al., 2015)]](image)

C. Other attacks

Another well-known hacking strategy is the Trojan-horse attack (THA), as shown in Fig. 9, in which Eve sends a probe light to Alice or Bob and reads their information from the backscattered probe light. In 2001, Vakhitov et al. proposed the large pulse attack (Vakhitov et al., 2001) and Kurtsiefer et al. analyzed the possibility of THA by detecting the detector fluorescence of Si-based avalanche photodiodes (Kurtsiefer et al., 2001). Gisin et al. studied the problem of THA in the QKD implementations where light goes two ways (Gisin et al., 2006). Later, Jain et al. performed a comprehensive analysis of the risk of THA against typical components in standard QKD systems (Jain et al., 2014, 2015). A countermeasure against the THA is to add proper isolations and consider the leaking information in privacy amplification (Lucamarini et al., 2015a; Tamaki et al., 2016; Wang et al., 2018a), which will be reviewed in Section V.C.

Besides the above attacks, Lamas-Linares and Kurtsiefer demonstrated that the timing information revealed during public communicating can be exploited to attack the entanglement-based QKD system (Lamas-Linares and Kurtsiefer, 2007). In two-way QKD system such as the “plug-and-play” structure, Sun et al. studied the imperfections of Faraday mirror and proposed the Faraday-mirror attack (Sun et al., 2011); Jain et al. experimentally demonstrated that the calibration routine of a commercial “plug-and-play” system can be tricked into setting a large detector efficiency mismatch, and proposed an attack strategy on such a compromised system with a QBER less than 7% (Jain et al., 2011). Moreover, Li et al. (Li et al., 2011) studied the imperfection of a practical beam splitter and demonstrated a wavelength-dependent beam-splitter attack on top of a polarization-coding QKD system. The detector dead-time issue was widely studied in (Rogers et al., 2007) and demonstrated in (Henning et al., 2011). Andun et al. and Makarov et al. demonstrated the laser damage attack by using a high-power laser to damage the SPDs (Bugge et al., 2014; Makarov et al., 2016).

The aforementioned hacking attacks are against discrete variable QKD systems. Besides discrete variable QKD, the practical security of CV-QKD (Diamanti and Leverrier, 2015; Weedbrook et al., 2012) is still unclear and deserves future investigations. For instance, the attacks by controlling the transmitted local oscillator (LO) were proposed and demonstrated in 2013 (Jouguet et al.,...
2013; Ma et al., 2013). Huang et al. studied the beam-splitter attack in CV-QKD based on heterodyne detection (Huang et al., 2013). Later, Qin et al. proposed and demonstrated the detector saturation attack against homodyne detectors in CV-QKD (Qin et al., 2016). Fortunately, the locally LO CV-QKD scheme has provided a promising solution to the security loopholes associated with transmitted LO (Huang et al., 2015a; Qi et al., 2015; Soh et al., 2015).

Most of the imperfections that have been reviewed so far are in fiber-based QKD systems. It is still unclear about the practical security of the free space QKD systems. Indeed, imperfect encoding methods result in side channels from which encoded states are partially distinguishable (Nauerth et al., 2009). The imperfection due to non-single-mode quantum signals is a crucial issue in free-space QKD. Eve can exploit this imperfection and launch the spatial-mode attack against a free-space QKD system. This problem has been carefully studied in (Sajeeed et al., 2015a), following an earlier discussion on the origins of detection efficiency mismatch in (Fung et al., 2009).

More generally, as noted in (Curty and Lo, 2019), in principle, there are simply too many side channels for Alice and Bob to close. This is because Eve might, in principle, attack Alice’s and Bob’s system via X-ray, neutrons, neutrinos or even gravitational waves. And, whatever detection systems Alice and Bob have will probably have limited ranges of responses. Moreover, classical post-processing units pose a serious threat to the security of QKD. Most QKD security framework assumes without proofs that classical post processing units are secure. However, in conventional security, it is well known that hardware Trojans and software Trojans are commonly used to compromise the security of conventional cryptographic system. It was proposed in (Curty and Lo, 2019) to use redundancies in QKD units and classical post-processing units to achieve security through e.g., verifiable secret sharing.

V. SOURCE SECURITY

In this section, we review the various approaches to resolve the security issues of practical sources. On one hand, the imperfections in quantum state preparation, including multi-photon components of laser, nonrandomized phases, encoding flaws and so forth, need to be carefully quantified and taken into account in the security proof. In particular, we will discuss the decoy state QKD protocol in more detail. On the other hand, practical countermeasures are required to prevent the Trojan horse attacks on the source. Note that we focus on the BB84 protocol, but most of techniques can be extended to other protocols.

A. Decoy-state method

Among the various protocols (Hwang, 2003; Inoue et al., 2002; Lo et al., 2005; Scarani et al., 2004; Stucki et al., 2005; Wang, 2005) to prevent the PNS attacks (Section IV.A.1), the notable one was the decoy state method (Hwang, 2003; Lo et al., 2005; Wang, 2005), which made weak coherent lasers much more appealing to implement BB84 over long distance. Under the PNS attack, the resulting quantum channel has a photon number dependent transmittance, which is much different from a passive channel. The insight of the decoy idea is that the PNS attack can be detected by testing the quantum channel during QKD process.

1. Theory

![Decoy-state BB84 Transmitter](image)

FIG. 10 A schematic implementation of decoy state QKD. In a decoy-state BB84 transmitter, the WCPs are generated using four emitting laser diodes for the four BB84 polarization states. Decoy states are prepared using an amplitude modulator (AM). In the figure: (M) mirror, (BS) beam-splitter, (F) optical filter and (I) optical isolator.

For the source with different photon number component, we can assume a photon number channel model (Ma, 2008). Decoy state method is a tomography to the photon number channel model, providing tighter estimations on single photon component (Lo et al., 2005; Wang, 2005). In the decoy state method, the source is operated at different photon number distributions, leading to different measurement outcome statistics. The communication partners can estimate the channel parameters of yield \( Y_n \) and QBER \( e_n \) for each photon number component. One crucial assumption in the decoy-state QKD is that the signal state and decoy states are identical except for their average photon numbers. This means after Eve’s photon-number measurement, she has no way of telling whether the resulted photon number state is originated from the signal state or decoy states. Hence, the yield \( Y_n \) and QBER \( e_n \) can depend on only the photon number, \( n \), but not which distribution (decoy or signal) the state is from. That is,

\[
Y_n(signal) = Y_n(decoy),
\]
\[
e_n(signal) = e_n(decoy).
\]

The implementation of decoy state method can be di-
vided into active one and passive one. In the active decoy state method, the source intensity is changed by the user to change the probability distributions of each photon number component. The key part is to prepare signals with different intensities. A simple solution, as shown in Fig. 10, is to use an amplitude modulator (AM) to modulate the intensities of each WCP to the desired intensity level. This is indeed the implementations reported in most of decoy state QKD experiments. Another solution for decoy state implementation is to use multiple laser diodes of different intensities to generate different states (Peng et al., 2007). In the passive decoy state method, heralded single photon source are often applied (Adachi et al., 2007; Ma and Lo, 2008; Mauerer and Silberhorn, 2007). The probability distribution is changed by observing different measurement outcomes of the heralded photons.

A popular source for decoy state method is the phase-randomized weak coherent state source, as shown in Eq. (21). To apply the active decoy method, Alice randomly adjusts the intensity $\mu$ of the coherent state, which is related to different Poisson distribution $P_\mu(n)$. Alice estimates the single photon yield $Y_1$ and error $e_1$ by solving the equation provided by the observed gain $Q_\mu$ and quantum bit error rate (QBER) $E_\mu$ related to different intensity $\mu$

$$Q_\mu = \sum_{n=0}^{\infty} P_\mu(n)Y_n, $$
$$E_\mu Q_\mu = \sum_{n=0}^{\infty} P_\mu(n)e_nY_n, $$  \tag{29}

with a tight estimation on $Y_1$ and $e_1$, the key rate can be improved from $O(\eta^2)$ to $O(\eta)$.

In practice, only several different intensities are enough to make an accurate estimation. The most popular practical decoy state method is vacuum and weak decoy state method (Ma et al., 2005; Wang, 2005). That is, Alice randomly generates coherent states with three different intensities $\{0, \nu, \mu\}$, where states with intensity $\mu$ is the signal states for key generation, and states with intensity $\nu < \mu$ and vacuum state with intensity 0 is for parameter estimation. For finite-key effect, Ma et al. took the first step to analyze the statistical fluctuations under collective attacks (Ma et al., 2005). Recently, the finite-key security was discussed in a more rigorous manner in (Lim et al., 2014; Lucamarini et al., 2015b). For the requirement of randomized phase, recent research shows that the phase of coherent state source needs not to be fully randomized or continuously randomized (Cao et al., 2015). Actually the uniformly discrete phase randomization with discrete phase number $m = 10$ can already achieve a good approximation of continuous phase randomization.

2. Experiment

The decoy-state experiments are summarized in Table II. In 2006, four experimental groups demonstrated that decoy state BB84 was secure and feasible under real-world conditions (Peng et al., 2007; Rosenberg et al., 2007; Schmitt-Manderbach et al., 2007; Zhao et al., 2006a,b). Specifically, Zhao et al. reported decoy state experiments (Zhao et al., 2006a,b) up to 60-km fiber on top of a commercial two-way QKD system; Peng et al. (Peng et al., 2007) implemented decoy-state QKD over 102-km fiber using a one-way polarization-encoding QKD system; Rosenberg et al. (Rosenberg et al., 2007) implemented decoy-state QKD over 107-km fiber using a one-way phase-encoding QKD system; Schmitt-Manderbach et al. achieved 144 km decoy state QKD in free space (Schmitt-Manderbach et al., 2007). These four experiments are shown in Fig. 11. Later, Yuan et al. realized a stabilized one-way phase-encoding decoy state QKD system (Yuan et al., 2007). Since then, people have started to believe that QKD can be really secure with imperfect devices, and more and more experimental efforts have been made to QKD deployments in labs and field tests (Boaron et al., 2018; Dixon et al., 2008; Fröhlich et al., 2013; Fröhlich et al., 2017; Liao et al., 2017a; Liu et al., 2010; Lucamarini et al., 2013; Rosenberg et al., 2009; Wang et al., 2013; Yuan et al., 2009; Zhen-Qiang et al., 2008). Dixon et al. implemented decoy state QKD with a high clock rate of 1 GHz (Dixon et al., 2008) and Liu et al. extended decoy state QKD to long distance of 200-km fiber (Liu et al., 2010). Importantly, a number of field QKD networks that implemented decoy state QKD have been built in Europe (Peev et al., 2009), Japan (Sasaki et al., 2011), China (Chen et al., 2009, 2010; Wang et al., 2010) and so forth. An illustration of the Tokyo QKD network is shown in Fig. 12.

Notice that the decoy state method is a rather general idea that can be applied to other QKD sources. Wang et al. experimentally implemented decoy state with a parametric down conversion (PDC) source (Wang et al., 2008). Very recently, the decoy state experiment has been extended to a record-breaking distance of 1,200 km in free space (Liao et al., 2017a) and 421 km in low-loss optical fiber (Boaron et al., 2018). These two experiments are shown in Fig. 13 and Fig. 14. Overall, decoy state QKD is a standard technique in current QKD implementations.

B. Source flaws

1. Basis-dependent source

In practice, there is often some difference between $\rho_x$ and $\rho_z$, i.e., Eq. (15) might not be fulfilled. Then, in the worst case scenario, we should assume Eve is capable of
FIG. 11 Decoy state QKD experiments. a, Experiment on a commercial plug-and-play QKD system (Zhao et al., 2006b). CA, compensating AOM; CG, compensating generator; DA, decoy AOM; DG, decoy generator; LD, laser diode; \( \phi \), phase modulator; PD, classical photo detector; DL, delay line; FM, faraday mirror. b, Phase-encoding experiment (Rosenberg et al., 2007). DFB, distributed feedback laser; VOA, variable optical attenuator; AM, amplitude modulator; LP, linear polarizer. c, Polarization-encoding experiment (Peng et al., 2007). FCN, fiber coupling network; FF, fiber filter; EPC, electric polarization controller; DAC, digital-to-analog converter. d, Free-space experiment (Schmitt-Manderbach et al., 2007). BS, beam splitter; PBS, polarizing beam splitter; HWP, half-wave plate; APD, avalanche photo diode. [figures reproduced from (Peng et al., 2007; Rosenberg et al., 2007; Schmitt-Manderbach et al., 2007; Zhao et al., 2006b)]

distinguishing the basis choice and hence she can attack two basis states separately. This kind of source is called basis-dependent source. Obviously, the more state dependence on the basis, the easier for Eve to distinguish the bases and hence a lower key rate.

Without loss of generality, we take Z-basis as example. The general Shor-Preskill’s key rate formula is (Shor and Preskill, 2000)

\[
r \geq 1 - H(e_Z) - H(e_Z^b),
\]

where \( e_Z^b \) is the Z-basis phase error rate, defined in Eq. (10).

For a basis-dependent source, \( e_Z^b \neq e_X \) since \( \rho_Z \neq \rho_X \). However, if \( \rho_X \) is close to \( \rho_Z \), we can still bound \( e_Z^b \) from measured \( e_X \). In the GLLP security analysis framework (Gottesman et al., 2004), the basis dependence is quantified by a bias,

\[
\Delta = \frac{1 - F(\rho_X, \rho_Z)}{2},
\]

where \( F(\rho_X, \rho_Z) = \sqrt{\rho_Z \rho_X} \sqrt{\rho_Z} \) is the fidelity between the two states. Given this bias, the phase error rate used in the key rate formula can be bounded by (Koashi, 2009; Lo and Preskill, 2007),

\[
e_Z^b \leq e_X^b + 4\Delta(1 - \Delta)(1 - 2e_X^b) + 4(1 - 2\Delta)\sqrt{\Delta(1 - \Delta)e_X^b(1 - e_X^b)}.
\]

For the practical photon sources presented in Section III.B, Alice and Bob have more information than the bias in Eq. (31). For example, in principle, they can measure the photon number \( n \), with which they can tag each quantum signal. Then, in phase error correction of entanglement distillation process, which would be reduced to privacy amplification for prepare-and-measure schemes, they could take advantage of these tagging. With tagging, the GLLP key rate formula can be written as (Gottesman et al., 2004),

\[
r \geq -H(E) + (1 - \Delta)[1 - H(e_Z^b)],
\]

where \( E \) is the total QBER, \( \Delta \) is the ratio of tagged signals, and \( e_Z^b \) is the phase error rate of the untagged signals. Here, we use the same notation of the bias \( \Delta \) in Eq. (31).
2. Nonrandom phase

An example of source flaw is to use the weak coherent states with nonrandom phases to encode the basis and key information (Lo and Preskill, 2007). Their difference is treated as source flaw, i.e., a basis-dependence of the source. The encoded state $|\psi_{\beta\kappa}\rangle_B$ is

$$|\psi_{\beta\kappa}\rangle_B = |\alpha\rangle_R |\alpha e^{i\pi(\kappa + \frac{1}{2}\beta)}\rangle_S,$$

where $\alpha$ is constant and $\mu = 2|\alpha|^2$ is the intensity. In this case, the basis dependence $\Delta$ is

$$\Delta = \frac{1}{2} \left(1 - e^{\mu/2}(\cos(\mu/2) + \sin(\mu/2))\right) = \mu/8 + O(\mu^3).$$

Note that in the practical QKD experiment, we will post-select the clicked signals. In this case, to calculate the basis dependence, we have to take the channel transmittance $\eta$ into account. In a worst-case scenario, the channel loss is caused by Eve’s selection on the transmitted signals. To clarify this, we can consider Eve performs a unambiguous state discrimination (USD) attack (Brandt, 2005; Dušek et al., 2000), where Eve performs USD to discriminate $\rho_X$ and $\rho_Z$. If the discrimination is successful, Eve can learn the basis and key, then he generates the same state $\rho_{\beta\kappa}$, and sends it to Bob; if the discrimination fails, Eve partially block the signal as loss. In this case, the basis dependence $\Delta'$ of left signals will be amplified by $\eta$

$$\Delta' = \Delta/(\eta \mu) \approx \mu/(8\eta).$$

From Eqs. (30), (32), and (36), we can calculate the key rate. However, the achievable key generation rate scales only quadratically with the transmittance $\eta$ in the channel, i.e., $r = O(\eta^2)$. This questions can be potentially solved using the scheme of discrete phase randomization (Cao et al., 2015).

3. Encoding flaws

Another example of source flaw is the flaws in the phase and polarization encoding due to the device imperfections in the encoding devices. This will also make the source basis-dependent. Although GLLP allows the security proof to consider the encoding flaws, the key rate drops dramatically (Gottesman et al., 2004). This is because GLLP has a pessimistic consideration by assuming that the encoding flaws are in arbitrary dimensions. To address this issue, a loss-tolerant protocol was proposed in (Tamaki et al., 2014), which makes QKD tolerable to channel loss in the presence of source flaws (Yin et al., 2014).

On the basis of the assumption that the single-photon components of the states prepared by Alice remain inside a two-dimensional Hilbert space, it was shown that Eve cannot enhance state preparation flaws by exploiting the channel loss and Eve’s information can be bounded by the rejected data analysis. The intuition for the security of loss-tolerant QKD protocol (Tamaki et al., 2014) can be understood in the following manner. By assuming
that the state prepared by Alice is a qubit, it becomes impossible for Eve to perform an unambiguous state discrimination (USD) attack. Indeed, in order for Eve to perform a USD attack, the states prepared by Alice must be linearly independent; but by having three or more states in a two-dimensional space, in general the set of states prepared by Alice is linearly dependent, thus making USD impossible. The above loss-tolerant protocol has been further developed and demonstrated experimentally in (Tang et al., 2016a; Xu et al., 2015b).

C. Leaky source

As discussed in Section IV.C, the source is vulnerable under the Trojan-horse attack (THA). In particular, as shown in Fig. 15, Eve could inject bright light pulses into Alice’s transmitter and then measure the back-reflected light to extract information about Alice’s state preparation process. This problem has been analyzed in (Lucamarini et al., 2015a). The authors evaluated the security of a QKD system in the presence of information leakage from Alice’s phase modulator (PM), which is used to encode the bit and basis information of the generated signals. A key observation is that, the joint state of Alice’s transmitted signals and Eve’s back-reflected light from her THA is not basis-independent but it depends on Alice’s basis choice. The security of the system can be analyzed by quantifying Eve’s information and considering this information in privacy amplification, based on the techniques introduced in (Lo and Preskill, 2007). Recently, these seminal results have been generalized to prove the security of decoy-state QKD in the presence of arbitrary information leakage from both the PM and the intensity modulator (IM) (Tamaki et al., 2016; Wang et al., 2018a). Here the IM is normally used to select the intensity setting for each emitted signal. Consequently, it is possible to quantify the amount of device isolation, against THA, so as to achieve a certain performance with a realistic leaky QKD system.

VI. DETECTION SECURITY

In this section, we review the various approaches to address the detection security of practical QKD. We will review the measurement-device-independent QKD (MDI-QKD) protocol and twin-field QKD (TF-QKD) in more detail.

A. Countermeasures against detection attacks

Many approaches have been proposed to defeat the attacks at detection. These approaches can be divided into four classifications, namely security patch, full characterization, device-independent QKD (DI-QKD) and MDI-QKD. We will discuss the first three ones in this section and the forth one in next section.

1. Security patch

An effective solution to close the known loopholes is to patch them. That is, once one discovers a new type of attack, a corresponding countermeasure against this attack can be proposed and realized in an existing QKD system. This approach usually only requires modifying the software or the hardware of a current system. For instance, the time-shift attack introduced in the previous section can be avoided by simply shifting the gating window of the detectors at random (Qi et al., 2007). The detector blinding attack could, in principle, be avoided by monitoring the detector’s photocurrent for anomalously high values (da Silva et al., 2012; Yuan et al., 2011) or by randomly varying the detector efficiency (Lim et al., 2015). In CV-QKD, the attacks by controlling the transmitted local oscillator (LO) (Jouguet et al., 2013; Ma et al., 2013) can be countered by generating the LO locally in Bob’s lab, i.e., locally-LO CV-QKD, which was demonstrated in (Huang et al., 2015a; Qi et al., 2015; Soh et al., 2015).

Although security patch can defeat certain attacks, the patched countermeasures themselves might open other loopholes, introducing one more layer of security risk (Huang et al., 2016; Sajeed et al., 2015b). Furthermore, the major issue associate with the security patch is that they only prevent the known attacks. For poten-
tial and unknown attacks, the countermeasures may fail. Therefore, security patch is only ad-hoc, which abandons the information-theoretic security framework of QKD.

2. Full characterization

In principle, one can fully characterize the practical devices using in a QKD system and precisely describe the devices in mathematical models. Then the models can be included in the security proof to estimate the real secure key rate based on an imperfect setup. A well-known example is the GLLP security proof (Gottesman et al., 2004). While this approach seems straightforward, developing models to fully match the practical behavior of various QKD devices is rarely possible because the components are complex. Even so, there are several ongoing theoretical efforts to consider as many imperfections as possible into the security proof (Fung et al., 2009; Leverrier et al., 2015a; Mayers and Yao, 1998) (hinted earlier by Ekert (Ekert, 1991)) relaxes all modeling assumptions about the devices and allows the users to do QKD with uncharacterized devices. A schematic illustration of DI-QKD is shown in Fig. 16. DI-QKD performs self-testing of the underlying devices. The devices cannot pass the test unless they carry out the QKD protocol securely. Specifically, as long as certain necessary assumptions are satisfied, one can prove the security of DI-QKD based solely on the violation of a Bell’s inequality, which certifies the presence of quantum correlations. Table VII lists a summary of the necessary assumptions of DI-QKD (Pironio et al., 2009). The security proofs have required the assumption that the devices have no memory between trials, or that each party has many, strictly isolated devices (Acín et al., 2007; Barrett et al., 2005; Masanes et al., 2011; Pironio et al., 2009). If the devices have memory, DI-QKD will suffer from memory attacks (Barrett et al., 2013) and covert channels (Curty and Lo, 2019).

Recent theory efforts have significantly advanced the developments of DI-QKD to be possible in a large quantum system (Reichardt et al., 2013), secure against general attacks (Miller and Shi, 2016; Vazirani and Vidick, 2014) and robust against noise (Arnon-Friedman et al., 2018). Though DI-QKD is remarkable in theory, unfortunately, it is hard to realize with current technology, because it needs almost perfect efficiency of single-photon detection (Pironio et al., 2009).

An exciting news is that researchers have demonstrated the Bell’s inequality which simultaneously closed the non-locality loophole and the detection loophole in the same experiment (Giustina et al., 2015; Hensen et al., 2015; Liu et al., 2018c; Rosenfeld et al., 2017; Shalm et al., 2015). This is a milestone result towards the realization of DI-QKD. Advanced technology in the future might make DI-QKD more practical. We remark that in future, ideas such as qubit amplification by heralding (Gisin et al., 2010) might also be proved useful to increase the key rate and distance of DI-QKD, though the key rate might be relatively low (Curty and Moroder, 2011; Seshadreesan et al., 2016). We do believe that DI-QKD is an important subject for future research.

![FIG. 16 (Color online) Schematic diagram of DI-QKD (Acín et al., 2007; Mayers and Yao, 1998). Alice and Bob assume giving the untrusted quantum devices tests that cannot be passed unless they carry out the QKD protocol securely, which can be check via the violation of a Bell’s inequality (Pironio et al., 2009).](image)

| Source | True random number generators | Trusted classical post-processing | Authenticated classical channel | No unwanted information leakage from the measurement unit | Characterized source |
|--------|-------------------------------|----------------------------------|-------------------------------|---------------------------------|---------------------|
| MDI-QKD | No                            | Yes                              | Yes                           | No                              | Yes                 |
| DI-QKD  | Yes                            | Yes                              | Yes                           | No                              | Yes                 |

3. Device-independent QKD

Rather than relying on ad-hoc countermeasures, device-independent QKD (DI-QKD) (Acín et al., 2007; Barrett et al., 2005; Mayers and Yao, 1998) (hinted earlier by Ekert (Ekert, 1991)) relaxes all modelling assumptions about the devices and allows the users to do QKD with uncharacterized devices. A schematic illustration of DI-QKD is shown in Fig. 16. DI-QKD performs self-testing of the underlying devices. The devices cannot pass the test unless they carry out the QKD protocol securely. Specifically, as long as certain necessary assumptions are satisfied, one can prove the security of DI-QKD based solely on the violation of a Bell’s inequality, which certifies the presence of quantum correlations. Table VII lists a summary of the necessary assumptions of DI-QKD (Pironio et al., 2009). The security proofs have required the assumption that the devices have no memory between trials, or that each party has many, strictly isolated devices (Acín et al., 2007; Barrett et al., 2005; Masanes et al., 2011; Pironio et al., 2009). If the devices have memory, DI-QKD will suffer from memory attacks (Barrett et al., 2013) and covert channels (Curty and Lo, 2019).

Recent theory efforts have significantly advanced the developments of DI-QKD to be possible in a large quantum system (Reichardt et al., 2013), secure against general attacks (Miller and Shi, 2016; Vazirani and Vidick, 2014) and robust against noise (Arnon-Friedman et al., 2018). Though DI-QKD is remarkable in theory, unfortunately, it is hard to realize with current technology, because it needs almost perfect efficiency of single-photon detection (Pironio et al., 2009).

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![FIG. 16 (Color online) Schematic diagram of DI-QKD (Acín et al., 2007; Mayers and Yao, 1998). Alice and Bob assume giving the untrusted quantum devices tests that cannot be passed unless they carry out the QKD protocol securely, which can be check via the violation of a Bell’s inequality (Pironio et al., 2009).](image)

| Source | True random number generators | Trusted classical post-processing | Authenticated classical channel | No unwanted information leakage from the measurement unit | Characterized source |
|--------|-------------------------------|----------------------------------|-------------------------------|---------------------------------|---------------------|
| MDI-QKD | No                            | Yes                              | Yes                           | No                              | Yes                 |
| DI-QKD  | Yes                            | Yes                              | Yes                           | No                              | Yes                 |
protocol and leaves all the single photon detections to a public untrusted relay (Eve). We review MDI-QKD in more detail.

1. Time-reversed EPR QKD

The idea of measurement-device-independent (MDI) is inspired by the Einstein-Podolsky-Rosen (EPR) based QKD protocol (Bennett et al., 1992c; Ekert, 1991). This is illustrated in Fig. 17 (Biham et al., 1996). In the initial EPR-based protocol (Fig. 17a), Alice and Bob individually prepare an EPR pair at each side and send one photon from each pair to an untrusted center party, Charles. Charles then performs a Bell state measurement (BSM) for entanglement swapping. The measurement result is announced. Once the BSM is finished, Alice and Bob measure the other photon of the EPR pairs locally by choosing between the X and Z basis randomly. Comparing a subset of their measurement results allows Alice and Bob to know whether Charles is honest. Then Alice and Bob can generate the secret by using the BBM92 protocol (Bennett et al., 1992c).

Note that the EPR protocol can also work in a time-reversal version, as shown in Fig. 17b. That is, Alice and Bob can measure their local photons first, instead of waiting for Charles’ measurement results. This order of preparation and measurement is equivalent to that of the prepare-and-measurement QKD scheme, in which Alice and Bob prepare BB84 states and send them to Charles to perform the BSM. After that, the Charles’ honesty can be checked by comparing a part of Alice’s and Bob’s results. Importantly, Charles’ BSM is only used to check the parity of Alice’s and Bob’s bits, and thus, it does not reveal any information about the individual bit values. This time-reversal EPR protocol forms the main concept behind MDI-QKD.

This time-reversed EPR QKD protocol has been first proposed in (Biham et al., 1996). Later, Inamori provided a security proof (Inamori, 2002). Nevertheless, these two important works offered very limited performance and, therefore, they have been largely forgotten by the QKD community. For instance, the scheme in (Biham et al., 1996) requires perfect single-photon sources and long-term quantum memories, which renders it impractical with current technology. Inamori’s scheme (Inamori, 2002) uses practical weak coherent pulses (WCPs) but it does not include decoy states, since it was proposed long before the advent of the decoy-state protocol. Moreover, the two early papers (Biham et al., 1996; Inamori, 2002) were not specifically considering the side channel problem in QKD at all. The idea of using teleportation for the specific purpose of removing side channels was first discussed in footnote 21 of (Lo and Chau, 1999). In 2012, Braunstein and Pirandola performed a general security analysis of the time-reversed EPR QKD approach and proved that detector side-channel attacks can be eliminated by the fact that any incoming quantum signals are excluded from access to detectors (Braunstein and Pirandola, 2012).

2. MDI-QKD protocol

MDI-QKD proposal, introduced by Lo, Curty and Qi in 2012 (Lo et al., 2012), builds on the time-reversed EPR QKD. The main merits of MDI-QKD are twofold: first, it identified the importance of the results in (Biham et al., 1996; Inamori, 2002) to remove all detector side-channels from QKD implementations; second, it significantly improved the system performance with practical signals by including decoy states. The protocol can be summarized in four steps:

1. Alice and Bob randomly and individually prepare
FIG. 18 (Color online) Schematic diagram of MDI-QKD (Lo et al., 2012). Alice and Bob prepare BB84 polarization states using a decoy-state BB84 transmitter, same as the one illustrated in Fig. 10. They send BB84 states to an untrusted relay Charles/Eve, which can be treated as a “black box”. The relay is supposed to perform a Bell state measurement (BSM) that projects Alice’s and Bob’s signals into a Bell state.

| Coincident clicks | Triplet state $|\psi^+\rangle$ |
|-------------------|-----------------------------|
| $D_{1H} \& D_{2V}$ or $D_{2H} \& D_{1V}$ | $D_{1H} \& D_{1V}$ or $D_{2H} \& D_{2V}$ |

TABLE VIII Post-selection for MDI-QKD (Lo et al., 2012). Alice and Bob post-select the events where the relay outputs a successful result and they use the same basis in their transmission. Moreover, either Alice or Bob flips her/his bits, except for the cases where both of them select the diagonal basis and the relay outputs a triplet.

1. Triplet state

2. An honest Charles performs a BSM that makes Alice’s and Bob’s states interfere with each other, generating a Bell state. An example of a BSM implementation with linear optics in shown in Fig. 18: Charles interferes the incoming pulses at a 50:50 beam-splitter (BS), which has on each end a polarizing beam-splitter (PBS) that projects the photons into either horizontal (H) or vertical (V) polarization states. A “click” in the single-photon detectors $D_{1H}$ and $D_{2V}$, or in $D_{1V}$ and $D_{2H}$, indicates a projection into the singlet state $|\psi^-\rangle = (|HV\rangle - |VH\rangle)/\sqrt{2}$, while a “click” in $D_{1H}$ and $D_{1V}$, or in $D_{2H}$ and $D_{2V}$, implies a projection into the triplet state $|\psi^+\rangle = (|HV\rangle + |VH\rangle)/\sqrt{2}$. Other detection patterns are considered unsuccessful.

3. Whether Charles is honest or not, he announces the outcome of his claimed BSM using a classical public channel when he claims to obtain a successful measurement.

4. Alice and Bob keep the data that correspond to Charles’ successful measurement events and discard the rest. Next, similar to the sifting in BB84 protocol, Alice and Bob announce their basis choices for sifting the events and keep the events using same bases. Based on Charles’ measurement result, Alice flips part of her bits to guarantee the correct correlation with those of Bob. The post-selection strategy is illustrated in Table VIII. Finally, they use the decoy-state method to estimate the gain and QBER of the single-photon contributions.

In MDI-QKD, both Alice and Bob are senders, and they transmit signals to an untrusted third party, Eve, who is supposed to perform a Bell state measurement (BSM). Since the BSM is only used to post-select entanglement, it can be treated as an entirely “black box”. Hence, MDI-QKD can remove all detection side-channels. The only assumption in MDI-QKD is that the source should be trusted. The security assumptions of MDI-QKD are summarized in Table VII. A security comparison between MDI-QKD and DI-QKD, as commented by Charles H. Bennett in QCrypt 2018\textsuperscript{14}, is summarized in the following box 2.

Box 2: A security remark about MDI-QKD and DI-QKD by Charles H. Bennett.

MDI-QKD at first sounds weaker than DI-QKD, but in fact it is stronger. In MDI-QKD, Eve’s untrusted device remains outside Alice’s and Bob’s trusted enclosures. They need only trust themselves not to have inadvertently created a side channel to Eve through incompetent design of their do-it-yourself (DIY) light sources. By contrast, in DI-QKD they must trust Eve not to have deliberately created side channels from the untrusted devices to herself.

3. Theoretical developments

The decoy state analysis is essential for MDI-QKD. The analysis is similar to that of conventional decoy-state BB84. The major difference is that now both Alice and Bob send decoy signals to a common receiver (instead of only Alice sending decoy states to Bob), which makes the mathematics slightly more complex. Fortunately, it has been shown that it is enough to obtain a tight estimation if Alice and Bob employ just a few decoy settings each. The authors of (Ma et al., 2012) proposed a numerical method for decoy estimating based on linear programming. Wang (Wang, 2013) presented an analytical estimation approach with two decoy intensities.

\textsuperscript{14} http://2018.qcrypt.net/
Rates of MDI-QKD demonstrated in (Comandar et al., 2016; Yin et al., 2016a). The experimental results (symbols) agree well with the theoretical simulations (solid lines) with a maximum transmission distance of 404 km via ultralow-loss optical fiber. The dotted lines show simulations for the balanced basis passive BB84 protocol using ideal single-photon (SP) sources, the practical SP without the decoy-state method, the WCS with the decoy-state method, and the results of (Tang et al., 2014a) (denoted as Ref.[12]). The decoy state method used in this experiment is based on the four-intensity decoy state protocol (Zhou et al., 2016). b, 1-GHz MDI-QKD (Comandar et al., 2016). The rates are plotted against the total attenuation and the equivalent fibre distance. Filled squares refer to key rates without the finite-size analysis. The star is the key rate obtained using two 25-km spools of fibre. The filled and open dots represent key rates with the finiteness of the data sample taken into account. The finite-size distillation methods are (1) standard error analysis (Ma et al., 2012), and (2) composable security analysis (Curty et al., 2014). The dashed lines are simulations of the key rate for two different detector temperatures. [Figures reproduced from (Comandar et al., 2016; Yin et al., 2016a)]

A vacuum state is hard to realize in practice due to the finite extinction ratio of a practical intensity modulator.
4. Experimental developments

Table III summarizes the MDI-QKD experiments after its invention. The main experimental challenge of MDI-QKD is to perform a high-visibility two-photon interference between photons from two (Alice’s and Bob’s) independent laser sources (Lo et al., 2012), which is not required in conventional QKD schemes. To do so, Alice’s photons should be indistinguishable from those of Bob. Importantly, if one implements MDI-QKD over telecom fibres, it is necessary to include feedback controls to compensate the time-dependent polarization rotations and propagation delays caused by the two separated fibres. Note that in standard BB84 QKD systems, the requirement of compensating polarization rotations and propagation delays can be relaxed by using phase encoding, because the two optical pulses, which interfere with each other at the receiver’s end, pass through the same optical fibre and thus experience the same polarisation rotation and phase change. Therefore, one can achieve high interference visibility without performing any polarization control. Nevertheless, this advantage of phase encoding (in comparison to other encoding schemes) cannot be directly translated to MDI-QKD, because the two pulses pass through two independent quantum channels.

In 2013, several groups performed independent experimental study for MDI-QKD. Liu et al. (Liu et al., 2013) reported the first demonstration of MDI-QKD with random modulation for encoding states and decoy states over 50 km fibre. Simultaneously, Rubenok et al. were the first to demonstrate the feasibility of high-visibility two-photon interference between two independent lasers, passing through separate field-deployed fibres in a real world environment (Rubenok et al., 2013). Later, Ferreira da Silva et al. observed a similar interference using polarization encoding in the lab (Ferreira da Silva et al., 2013) and Tang et al. reported a full demonstration of polarization encoding MDI-QKD with random modulation of encoding states and decoy states (Tang et al., 2014b). All these four initial experiments, when taken together, complete the cycle needed to demonstrate the feasibility of MDI-QKD using off-the-shelf optoelectronic devices. There experiment diagrams are illustrated in Fig. 20.

MDI-QKD is attractive not only because of its security against detection attacks, but also due to its practicality. It can resist high channel loss and reach long distance. Tang et al., implemented MDI-QKD over 200 km fiber (Tang et al., 2014a) and in field environment (Tang et al., 2015) by increasing the system clock rate from 1 MHz to 75 MHz, by developing an automatic feedback system, and utilizing superconducting single photon detectors (SNSPDs).

In 2016, two millstone MDI-QKD experiments that were subsequently reported. In the first one, Yin et al., extended the MDI-QKD distance to a record-breaking distance of 404 km by optimizing the implementation parameters and using a ultra-low loss fiber (0.16 dB/km) (Yin et al., 2016a). Importantly, the key rate achieved in the experiment at 100 km is around 3 kbps, which is sufficient for one-time-pad encoding of voice messages. The results demonstrated in (Yin et al., 2016a) are shown in Fig. 19a. In the second one, Comandar et al., increased the system clock rate of MDI-QKD to 1 GHz by exploiting the technique of optical seed lasers (Comandar et al., 2016). The 1 GHz system demonstrated the feasibility for MDI-QKD to reach 1 Mbps key rate. The achieved secret rates in (Comandar et al., 2016) are shown in Fig. 19b.

Besides long distance and high rate, several research groups have analyzed the practical aspects in the implementation of MDI-QKD. For instance, Valivarthi et al., analyzed the trade-offs among complexity, cost, and system performance associated with the implementation of MDI-QKD (Valivarthi et al., 2015) and implemented a cost-effective system (Valivarthi et al., 2017). Wang et al., demonstrated a reference-frame-independent MDI-QKD that requires no phase reference between Alice and Bob (Wang et al., 2015a, 2017a) and this scheme was recently improved to a clock rate of 50 MHz by Liu et al. (Liu et al., 2018a). Tang et al., demonstrated MDI-QKD with source flaws (Tang et al., 2016a). Roberts et al., reported a reconfigurable system to switch between QKD and MDI-QKD (Roberts et al., 2017). Besides MDI-QKD demonstration with WCP sources, Kaneda et al., demonstrated MDI-QKD using heralded single-photon source (Kaneda et al., 2017). Also, beside discrete-variable MDI-QKD, Pirandola et al., proposed and demonstrated a proof-of-principle continuous-variable (CV) MDI-QKD (Pirandola et al., 2015), but a full implementation seems still a challenge in experiment (Xu et al., 2015a).

With all the above experimental efforts, MDI-QKD is ready for the applications in the future quantum network. Particularly, MDI-QKD is well suited to construct a centric star-type QKD network even with untrusted relays. Indeed, as shown in Fig. 21, Tang et al., performed the first implementation of a MDI-QKD network in the Hefei city (Tang et al., 2016b), which has a star topology and four nodes with one relay node and three-user nodes. The central relay node needs not to be trustful in a MDI-QKD network. Nonetheless, if the central relay is trusted, one can reconfigure the MDI-QKD network to allow many quantum communication protocols (Roberts et al., 2017). Moreover, beside MDI-QKD over symmetrical channels, high-rate MDI-QKD over asymmetric fiber channels was demonstrated recently in (Liu et al., 2018b).
FIG. 20 The four initial MDI-QKD experiments. a, Proof-of-principle MDI-QKD with time-bin encoding (Rubenok et al., 2013). b, Full MDI-QKD with time-bin encoding (Liu et al., 2013). c, Proof-of-principle MDI-QKD with polarization encoding (Ferreira da Silva et al., 2013). d, Full MDI-QKD with polarization encoding (Tang et al., 2014b).

FIG. 21 (Color online) A three-user and four-node MDI-QKD network within the city of Hefei, China. (Tang et al., 2016b). The users (U1-U3) utilize an internally modulated signal laser and modulate the decoy intensity according to the vacuum + weak decoy scheme by an amplitude modulator (AM). Then, they adopt a circulator, an asymmetrical Mach-Zehnder interferometer (AMZI), three AMs, and one phase modulator (PM) to encode qubits. The idle ports of circulators and beam splitters for the AMZI are exploited for phase synchronization and feedback, which are represented by the dashed line. After being attenuated by an electrical variable optical attenuator (EVOA), the signal laser pulses are sent via the deployed fiber to the relay comprised of an interference BS and two superconducting nanowire single-photon detectors (SNSPDs). [Figure reproduced from (Tang et al., 2016b)].

C. Twin-field QKD

Fundamental limit for the key rate vs distance for secure QKD has been obtained in (Pirandola et al., 2017; Takeoka et al., 2014). It was proven that, in the absence of relays, the key rate basically scales as $O(\eta)$, where $\eta$ is the transmittance of the channel between Alice and Bob. There is a tremendous research interest towards developing a feasible scheme to overcome the fundamental rate-distance limit (Kimble, 2008; Sangouard et al., 2011). Remarkably, Lucamarini et al. (Lucamarini et al., 2018) have recently proposed a novel phase-encoding MDI-QKD type protocol, called twin-field QKD (TF-QKD), which is conjectured to overcome the rate-distance limit and achieve a quadratic improvement, i.e., scaling as $O(\sqrt{\eta})$. In TF-QKD (see Fig. 22a), weak optical pulses are generated by two phase-locked laser sources, which are phase-randomized and then phase-encoded with secret bits and bases. The pulses are sent to Charlie for interference on a beam splitter; depending on which detector clicks, Charlie can infer whether the secret bits of the users (Alice and Bob) are equal or different, but cannot learn their absolute values.

The TF-QKD scheme essentially uses single-photon interference, which has been originally proposed in the quantum repeater design (Duan et al., 2001), the original phase-encoding MDI-QKD protocol (Tamaki et al., 2012), and the MDI version of the Bennett1992 protocol (Ferenczi, 2013). The new observation is to apply the decoy state method to the phase-locked MDI-QKD system to estimate the single-photon "twin-field"
protocols without phase-randomization on the key generation mode have been proposed (Cui et al., 2018; Curty et al., 2018; Lin and Lütkenhaus, 2018) and analyzed in the infinite data size case. All these recent theory works make the new phase-encoding MDI-QKD protocols important for the deployment of QKD over long distances.

From a technical point of view, the single-photon detection is the key reason for the quadratic improvement, but single-photon interference requires subwavelength-order phase stability for optical channels, which is slightly more demanding than achieving two-photon interference (Duan et al., 2001). Nonetheless, TF-QKD is expected to be feasible with current technology with the techniques of active phase randomization, phase-locking and so forth. Indeed, very recently, we note several groups reported experimental demonstrations on the feasibility of TF-QKD (Liu et al., 2019; Minder et al., 2019; Wang et al., 2019; Zhong et al., 2019).

VII. OTHER QUANTUM CRYPTOGRAPHIC PROTOCOLS

A. New QKD protocols and implementations

Besides the efforts in the security with imperfect devices, quite a few new QKD protocols are proposed and implemented during the past ten years, which are summarized in Table IV.

1. Round-robin differential phase shifted QKD

In general, there exists a threshold of the error rate for each scheme, above which no secure key can be generated. This threshold puts a restriction on the environment noises. Especially, in the key rate formula, the bit error can be directly computed from the experimental data, whereas the phase error needs to be estimated or bounded. In the BB84 protocol with strong symmetries, both error rate are approximately the same in the long key length limit. In other protocols, normally there is a relation between the two error rates. In the end, when the bit error rate goes beyond some threshold level, no secure key can be generated. For example, BB84 cannot tolerate error rates beyond 25% considering a simple intercept-and-resend attack (Bennett and Brassard, 1984). This threshold puts a stringent requirement on the system environment, which makes some practical implementations challenging.

Round-robin differential phase shifted (RRDPS) QKD, proposed by Sasaki et al. (Sasaki et al., 2014) in 2014, essentially removes this restriction and can in principle tolerate more environment disturbance. In this protocol, Eve’s information can be bounded only by user’s certain experiment parameters other than the error rates. In particular, the phase error rate $e_p$ is determined by the user’s own settings rather than the channel performance,
which makes the protocol fundamentally interesting and tolerate more errors.

In the RRDPS QKD protocol, the sender Alice puts a random phase, chosen from \( \{0, \pi\} \), on each of \( L \) pulses, with an average photon number of \( \mu \) in such an \( L \)-pulse signal. Upon receiving the block, the receiver Bob implements a single-photon interference with a Mach-Zehnder interferometer (MZI), as shown in Fig. 23a. Bob can randomly adjust the length difference of the two arms of the MZI. After obtaining a detection click, Bob first identifies which two pulses interfere and then announces the corresponding indices \( i, j \) to Alice. Alice can derive the relative phase between the two pulses as the raw key, and Bob can record the raw key from the measurement results. The phase error rate depends only on the number of photons in the \( L \)-pulse signal and \( L \), not the bit error rate. By setting a larger \( L \), the phase error tends to 0, and the scheme can tolerate a higher bit error rate.

Triggered by the original protocol, an alternative passive type of RRDPS QKD is proposed by Guan et al. (Guan et al., 2015). As is shown in Fig. 23b, when Bob receives a block from Alice, he prepares a local \( L \)-pulse reference in plain phases, i.e., all phases are encoded at phase 0. This \( L \)-pulse reference interferes with the \( L \)-pulse signal sent by Alice on a beam splitter. For each block, Bob records the status of his two detectors with time stamps, \( i \) and \( j \). If Bob’s reference is in phase with Alice’s signal, i.e., Bob has a phase reference, the whole setup is essentially a huge Mach-Zehnder interferometer. Any detection signal at time slot \( i \) will tell the phase difference between \( i \) and the phase reference. Then the encoding bit value can be figured out by Bob. If the phase Bob’s reference is random relative to Alice’s signal, the interference is a Hong-Ou-Mandel type interference (Hong et al., 1987) instead of a MZI. Bob post-selects the block where there are exactly two detections and announces their positions \( i \) and \( j \) (if \( i = j \), the detection result is discarded). The raw key is the relative phase between these two pulses in the \( L \)-pulse signal. Alice can derive this phase difference from her record. While Bob can infer the bit value depending on that the coincidence happens between two different detectors or one detector at different time slots. The security proofs of the two protocols are beyond the scope of the paper and we refer the readers to the original papers (Guan et al., 2015; Sasaki et al., 2014).

The first published experimental result is based on the passive protocol (Guan et al., 2015). As is shown in Fig. 24a, Alice modulates a tunable extra cavity diode laser with a central wavelength of 1550.14 nm and a linewidth of 50 kHz into a pulse train with a repetition frequency 500 MHz. A beam splitter (BS) is used to separate the pulse train into two beams, one is for Alice’s encoding and the other one is sent to Bob as a reference. Alice then encodes random \( \{0, \pi\} \) phase into each individual pulse of the pulse train and attenuates the average photon number per pulse into 0.004. The signal light goes through the channel of a fiber spool to Bob. On Bob’s side, he interferes the reference pulse with the signal pulse on a BS after attenuating his reference pulse intensity into an average photon number \( \mu = 0.004 \) per pulse. The output ports of the BS are led to two up-conversion single photon detectors.

The final key rate depends on the block length \( L \). Given the laser intensity of every pulse and the transmission distance, there exists an optimal \( L \) for the key rate. The system can still distill secure key with a bit error rate of 28% (Guan et al., 2015) with a distance of 53 km when \( L \) equals to 131072. Comparing to the original protocol, the passive one avoids randomly adjusting the length difference of the MZI. Based on the current technology, the main adjust-delay method is to utilize optical switches, which cannot provide both high speed and low insertion loss simultaneously. But meanwhile, it requires remote optical phase locking, which is challenging in the real deployment.

Therefore, the key point for an active RRDPS is to realize the random time delay. Takesue et al. (Takesue et al., 2015) exploits a one-input, four-output optical splitter followed by four silica waveguides based MZI with 0.5, 1.0, 1.5, 2.0 ns temporal delays respectively, as is shown in Fig. 24b. Any two delays constitute a new MZI and the whole system realizes a \( L = 1 - 5 \) variable delay. With this delay, the authors achieved secure key rate through 30 km fiber with an error rate of 18%. Later, Wang et al. (Wang et al., 2015c), shown in Fig. 24c, combines a three-port circulator, a beam splitter, two 1 × 8 optical switches followed with two groups of fiber delays, whose lengths are 0, 1, 2, 3, 4, 5, 6, 7 ns and...
FIG. 24 The experimental setup for RRDPS QKD, reported in the references of a, (Guan et al., 2015); b, (Takesue et al., 2015); c, (Wang et al., 2015c); d, (Li et al., 2016).

8,16,24,32,40,48,56,64 ns, respectively. The two optical switches shall actively choose different delays and achieve a $L=1$ to 64 bit variable-delay Faraday-Michelson interferometer. Based on the delay, Wang et al. distributed a secret key over a distance of 90 km fiber. Li et al. (Li et al., 2016) exploited a different configuration, which can be seen in Fig. 24d. They put 7 MZI in series to achieve a 127-value variable delays. And each MZI is constructed of a Pockels cell, a fiber, or free-space link with specific length and two polarizing beam splitters (PBSs). The Pockels cell, controlled by a random number, may change the polarization of the photon and thus provide a delay. Very recently, the secure distance is extended to 140 km by increasing the bound on information leakage (Yin et al., 2018).

2. High-dimensional QKD

Mainly, there are two categories for QKD protocols, prepare-and-measure, and entanglement based. Most of this review focuses in the prepare and measure type since it is much more widely researched and deployed. Actually, most known commercialized systems belong to the prepare and measure type. Nevertheless, entanglement based QKD has some additional advantages and is still broadly interested for basic research. The first entanglement based QKD was invented in 1991 by Artur Ekert (Ekert, 1991). The correlation character of entanglement is used for key generation and the nonlocality character is used for security check. After that, plenty of efforts have been made in this direction, at both theoretical and experimental sides. So far, the distance record for QKD based entanglement is 100 km optical fiber (Honjo et al., 2008; Namekata et al., 2011). Most research concentrated on the two level system or the qubit system. Here, in this review, we would like to focused on a the entanglement based QKD with multi-level system, i.e. high dimensional QKD (HD QKD), which has been a hot topic in the past decade. The discussion on the qubit system can be found in the previous review paper (Gisin et al., 2002; Scarani et al., 2009).

It is naturally to conclude that HD QKD can provide higher key rate per particle comparing to the qubit system (Bourennane et al., 2001; Scarani et al., 2009). Later, it has been demonstrated that HD QKD has a higher security tolerance to noise (Cerf et al., 2002). The first experimental attempt of HD QKD is utilizing energy-time entangled photon pairs (Ali-Khan et al., 2007). As is shown in Fig. 25a, Alice uses a 50 mW, 390 nm, cw laser having a bandwidth of 2 MHz to pump a beta-barium borate (BBO)-I crystal to generate collinear, degenerate down-converted photon pairs. The signal rate is 800 kHz and coincidence rate is around 60 kHz at single photon detector. The down-converted photons are coupled into a single mode, 50:50, fiber beam splitter, where one photon is sent to Alice and the other to Bob. We post select the coincidence for QKD and the instances where both photons travel to either Alice or Bob can presently be ignored. Using a variable beam splitter, Alice and Bob randomly and independently send their photons either to a low timing jitter detector to generate key or an unbalanced Michelson interferometer for security issue. With this setup, Ali-Khan et al. can generate a large-alphabet key with over 10 bits of information per photon pair, albeit with large noise. QKD with 5% bit error rate is demonstrated with 4 bits of information per photon pair, where the security of the quantum channel is determined by the visibility of Franson interference fringes.

Later, Zhang et al. (Zhang et al., 2014b) reported a security proof of time-energy entanglement quantum key distribution using dual-basis interferometry. Mower et al. (Mower et al., 2013; Zhang et al., 2014b) suggested to utilize dispersive optics to replace the Franson interferometer and demonstrated its security against collective attack. Fig. 25b illustrates the experimental setup (Lee et al., 2014). Alice pumps the periodically poled potassium titanyl phosphate (PPKTP) waveguide to produce wavelength-degenerate, type II time energy entangled photon pairs, which are fiber coupled and separated by a polarizing beam splitter. Alice and Bob each use a passive 50:50 beam splitter to randomly switch between the time and frequency bases. When the photon is routed to the time basis, the arrival time is directly detected. In
A key is obtained with a qutrit error rate of approximately 10%. Later, higher dimension OAM up to 5 is exploited for HD QKD (Mafu et al., 2013). Inspired by the OAM HD QKD, Mirhosseini et al. uses the OAM of weak coherent state and the corresponding mutually unbiased basis of angular position. Through the use of a 7-dimensional alphabet encoded in the OAM bases, a channel capacity of 2.05 bits key per sifted photon is achieved. Actually, OAM degree has been widely used in optical communication. Sit et al. (Sit et al., 2017) implement a field test of OAM HD QKD in the city of Ottawa.

Detailed setup can be found in Fig. 25c. A free-space link between the rooftops of two buildings, 0.3 km apart and 40 m above the ground, on the University of Ottawa campus has been built. Alice utilizes a heralded single-photon source, which are generated via the non-degenerate spontaneous parametric down-conversion process in a 5 mm long ppKTP crystal pumped by a 405 nm laser diode (200 mW). The signal and idler photon are coupled into single mode fiber to spatially filter the photons into the fundamental mode, respectively. The signal photon is encoded with different OAM or its complemented state with wave plates and q-plates. Alice then recombines the signal and idler photons on a dichroic mirror and sends to Bob. After propagation over the 0.3 km distance, Bob demagnifies the photon’s structure with another set of lenses and decoupling the signal and idler photons with another dichroic mirror. The idler is directly detected by a single photon detector as a trigger. With a sequence of wave plates, q-plates, PBSs, and SMFs, Bob take the measurement. With this setup, Sit et al. implement a 4-dimensional OAM QKD. A quantum bit error rate of 11% was attained with a corresponding secret key rate of 0.65 bits per sifted photon. The OAM HD QKD still suffers from low key rate. In order to increase the key rate, high speed modulators for OAM is urgently needed but remains technology challenging.

Naively, one might think that since a HD QKD system offers a higher key rate per signal than a qubit-based QKD system. It seems always better to use a HD-QKD system. One has to be very careful in making such a comparison because key rate per signal may not be the best measure when the signal size itself is big. In fact, a HD QKD protocol can use many e.g. time-bins/modes for each signal. Now, if one were to use the many time-bins/modes separately and in parallel (with many sets of high-speed single photon detectors), one would actually get a higher key rate in such a multiplexed QKD system. At the end of the day, the private capacity per mode of a simple prepare-and-measure QKD system is limited by fundamental bounds such as TGW (Takeoka et al., 2014) and PLOB (Pirandola et al., 2017). The key rate of HD-QKD is still limited by those fundamental bounds. Nonetheless, HD QKD may be useful in a practical situation, where the detector has long dead time or resetting.

With the time energy entangled photon pairs, Zhong et al. observed a secure key rate of 2.7Mbps after 20 km fiber transmission with a key capacity of 6.9 bits per photon coincidence (Zhong et al., 2015). Recently, high-rate quantum key distribution using time-bin qubits was reported in (Islam et al., 2017). Time energy type HD QKD has advantage with a constant clock rate because it can utilize more time slots with high time resolution single photon detector. However, the advantage will be offset when the clock rate can be increased to the bandwidth of the single photon detector (Zhang et al., 2008). One solution is to utilize a degree of freedom other than time, for example, the optical angular momentum (OAM). The first HD QKD for OAM was published in 2006 (Gröblacher et al., 2006). Qutrit entangled photon pairs were utilized to generate quantum key. In an Ekert-type protocol the violation of a three-dimensional Bell inequality verifies the security of the generated keys.
time and it can not operate at high rates (Zhong et al., 2015). Overall, the practical advantages of HD-QKD in real-life applications remain to be seen in future.

3. QKD with wavelength-division multiplexing

Except for the new protocols, reducing the cost of QKD system is another hot topic in the field. Wavelength-division multiplexing (WDM) technology is exploited to reduce the cost of the channel and integrated optics is utilized to reduce the cost of the equipment.

In order to protect ultra-weak QKD signals, previous QKD experiments are always implemented in dark fibers. Considering the current shortage of fiber resource in optical communication, reducing the requirement of fiber resource become inevitable. In classical optical communications, WDM technology has been widely exploited to increase the data bandwidth and reduce the requirement of fiber resource. Then, it is natural for QKD to coexist with classical optical communication with WDM technology. The scheme of simultaneously transmitting QKD with conventional data was first introduced by Townsend in 1997 (Townsend, 1997). A series of QKD experiments integrating with various classical channels have been demonstrated (Chapuran et al., 2009; Choi et al., 2010; Dynes et al., 2016; Eraerds et al., 2010; Fröhlich et al., 2015; Huang et al., 2015b; Kumar et al., 2015; Patel et al., 2014, 2012; Wang et al., 2015b). Currently, by using spectral and temporal controls, state-of-the-art developments have been made to realize co-propagation of QKD with one 100 Gbps dense wavelength-division multiplexing (DWDM) data channel in 150 km ultra-low loss fiber at $-5$ dBm launch power (Fröhlich et al., 2017). By setting QKD wavelength to 1310 nm and inserting 100GHZ DWDM filters, Wang et al. implement QKD together with classical traffic with 11dBm input power over 80 km fiber spoons (Wang et al., 2017b). A field trial of simultaneous QKD transmission and four 10 Gbps encrypted data channels was implemented over 26 km installed fiber at $-10$ dBm launch power (Choi et al., 2014).

Recently, the coexistence of QKD and commercial backbone network of 3.67Tbps classical data over 66 km fiber at 21 dBm launch power has been demonstrated (Mao et al., 2018). The system provides 3 kbps secure key rate with a 2.5% quantum bit error rate. Note that in current backbone networks, the data traffic is around Tbps and the launch power is around 20 dBm. In that sense, the recent work (Mao et al., 2018) demonstrate the possibility of coexistence of QKD with backbone network.

4. Chip-based QKD

Integrating QKD system has attracted more and more attention due to its advantage at compact size, low energy consumption and potential for low cost (Orieux and Diamanti, 2016). QKD is a complicated system including optics and electronics. Thus an integrated QKD system research should include integrating both optics and electronics. Fortunately, the Integrated circuits (IC) is already commercialized and integrated optics is also well developed in industry. In 2005, a commercial unbalanced Mach-Zahnder interferometer made of planar lightwave circuits (PLC) based on silica-on-silicon technology was exploited for the first time in a QKD system (Takesue et al., 2005) to replace the fiber based interferometer. Comparing to its fiber counterpart, PLC interferometer is more stable and can maintain its phase for several hours without any feedback (Nambu et al., 2008; Takesue et al., 2007).

Meanwhile, IC is exploited in a research towards compact and low cost QKD system (Duligall et al., 2006). As is shown in Fig. 26a. Alice module uses off-the-shelf IC components in a driver circuit to control four AlInGaP LEDs to emit four polarized BB84 states. The channel is a several-meter free space link, which is supposed to find application in a future quantum based Automated Teller Machine and even in a smart phone (Pizzi et al., 2012) according to the authors. Along this direction of research, Gwenaelle Vest et al. (Vest et al., 2015) provided a 2.5 cm long integrated QKD sender, as is shown in Fig. 26b. LEDs are changed into vertical cavity surface emitting lasers (VCSELs). Although the VCSEL is a bit expensive than LED, but it can be integrated in a wafer and modulated at a clock of 100 MHz, much higher than a LED. In the experiment, an array of four VCSELs emit synchronized picosecond optical pulses, which are coupled to micro-polarizers generating the polarization qubits. Then the qubits are combined in single-mode waveguides written in borosilicate glass. The final size of the QKD can be as small as $25mm \times 2mm \times 1mm$, which makes the system a strong candidate for short distance free-space QKD applications.

On the city fiber network side, many individual users in the network will trust a central relay station. This is so called Network-Centric structure (Hughes et al., 2013) or access network (Fröhlich et al., 2013). In such a structure, many users are all Alices and share only one central relay as Bob. In that sense, the receiving station can have more space and expensive and bulky detection system can be used. Therefore, the community concentrates more integration efforts in the sending side. Hughes et al. provided a QCard in their pioneering paper, as is shown in Fig. 26b. The QCard has a similar size as an electro-optic modulator or a normal key. It incorporates a distributed feedback laser and modulator. The laser is attenuated into single photon level and modulated into
BB84 polarization-state with decoy state. The repetition frequency is 10 MHz at the wavelength of 1550 nm, the telecom band.

Recently, the size of the QKD sender has reduced dramatically. In 2014, Zhang et al., put forward an on-chip LiNbO$_3$ polarization rotator and demonstrated the reference-frame-independent QKD protocol to overcome unstable fibre birefringence (Zhang et al., 2014a). In 2015, the same group from University of Bristol implemented integration of QKD based on an indium phosphide transmitter chip and a silicon oxynitride receiver chip (Sibson et al., 2017a). This chip is shown in Fig. 26d. The authors exploited the chips in three different QKD protocols, namely BB84, coherent-one-way and differential-phase-shift QKD.

Later, researchers from University of Toronto (Ma et al., 2016a) and Bristol (Sibson et al., 2017b) exploited Silicon photonics to build QKD sender system, respectively. As is shown in Fig. 26c, Ma et al. (Ma et al., 2016a) fabricated the QKD sender chip with a standard Si photonic foundry process and integrated two ring modulators, a variable optical attenuator and a polarization modulator in a 1.3mm × 3mm die area. The first ring modulator generates periodic nanosecond (ns) pulse trains, while the second ring modulates the intensity to create decoy and signal states. Output of the ring modulator is coupled into/out of the chip using on-chip adiabatic taper waveguide couplers and lensed fibers with a 2.5μm spot diameter. The chip was tested in a proof-of-concept demonstration of the BB84 QKD protocol over a 5 km long fiber link. Meanwhile, Sibson et al. (Sibson et al., 2017b) demonstrated coherent one-way QKD, polarization encoded BB84, and time-bin encoded BB84 in the paper with a 10 GHz bandwidth QKD modulation based on silicon photonic devices, respectively. The authors achieve estimated asymptotic secret key rates of up to 916 kbps and quantum bit error rates as low as 1.01% over 20 km of fiber. The clock rate of this experiment is much higher than previous one. However, this experiment only integrated the single modulator for different encoding states, while Ma et al. integrated more components on the chip, i.e., the whole QKD emitter.

Very recently, other research groups have demonstrated high-speed Silicon photonic chips for high dimensional QKD over multimode fiber (Ding et al., 2017), transceiver circuit (Cai et al., 2017) and metropolitan QKD (Bunandar et al., 2018). Moreover, CV-QKD is naturally suitable for photonic chip integration as its implementation is compatible with current telecom technologies (Diamanti and Leverrier, 2015; Weedbrook et al., 2012). In particular, CV-QKD essentially uses the same devices as classical coherent communication, and only homodyne detector is required rather than the dedicated single-photon detector. Si photonic chips integrating many functionalities of a CV-QKD setup have been reported in (Zhang et al., 2017; Ziebell et al., 2015).

## B. Other quantum cryptographic protocols

So far, QKD is the most developed and mature subfield of quantum cryptography. Meanwhile, quantum cryptography has many other protocols (Broadbent and Schaffner, 2016), which also have achieved quite remarkable progresses. A list of recent developments of other quantum cryptographic protocols is shown in Table V. We will review a few examples.

### 1. Quantum bit commitment

Bit commitment is another important and fundamental cryptographic task that guarantees a secure commitment between two mutually mistrustful parties. Alice first commits her to a particular bit value $b$. After a period of time, Alice reveal the bit value to Bob. A success bit commitment requires that Bob can not learn $b$ before Alice reveals it, which is called concealing criterion. Meanwhile, Alice should not change $b$ once she made the commitment. This is called binding criterion. Bit commitment is a building block for many cryptographic primitives, including coin tossing (Blum, 1983; Brassard and Crépeau, 1991), zero-knowledge proofs (Goldreich et al., 1986; Goldwasser et al., 1989), oblivious transfer (Benett et al., 1992b; Unruh, 2010) and secure two-party computation (Kilian, 1988).

In classical cryptography, bit commitment is based on computational complexity assumptions similar to public key exchange protocols and might be vulnerable to quantum attacks. Unfortunately, it has been proven that information-theoretically secure bit commitment is impossible even if Alice and Bob are allowed to use quantum resources (D’Ariano et al., 2007; Kitaev et al., 2004; Lo...
and Chau, 1998, 1997; Mayers, 1996, 1997). In the standard quantum circuit model by Mayers (Mayers, 1996, 1997) and by Lo and Chau (Lo and Chau, 1998, 1997) (Lo and Chau, 1998, 1997). Subsequently, such a no-go theorem has been further extended to case with superselection rules (Kitaev et al., 2004). For an re-examination of this result, see e.g. (D’Ariano et al., 2007). Furthermore, information-theoretic security of oblivious transfer and two-party secure computations are also proven to be impossible in (Lo, 1997).

Interestingly, if we take into account the signalling constraints implied by the Minkowski causality in a relativistic context, it has been shown that there are bit commitment protocols offering unconditional security (Kaniewski et al., 2013, Kent, 2011, 2012). In the secure relativistic protocol (Liu et al., 2014), both Alice and Bob have two agents A0, A1 and B0, B1 respectively. They are distributed in three locations which are almost aligned. First, Alice uses QKD to share two secret keys, $K_{A_0}$ and $K_{A_1}$, with A0 and A1. Then, Bob sends Alice N random BB84 polarization states. We denote as $t_0$ the time instant when Bob sends Alice his first signal. To commit to the bit value 0 (1), Alice measures all the incoming signals in the diagonal basis. We denote as $t_c$ the time instant when Alice completes all her measurements. Then, she announces publicly which signals she has detected. Also, she encodes her measurement results with the OTP method using $K_{A_0}$ and $K_{A_1}$, and sends them to A0 and A1. To unveil the commitment, A0 and A1 decode the measurement results received from Alice and send them to Bob’s agents B0 and B1, respectively. We denote as $t_{B0}$ and $t_{B1}$ the time instants when agents B0 and B1 receive the last signal from their counterparts.

To verify the commitment, Bob compares the results submitted by A0 and A1. If they are different, Bob rejects the commitment. Otherwise, he estimates a lower bound, $n_r$, for the number of single photons sent in the rectilinear basis and detected by Alice. Likewise, Bob does the same with the signals he sent in the diagonal basis. Let $n_{e,r}(n_{e,d})$ be the total number of errors in the rectilinear (diagonal) basis. Then, from the geographical distribution of his agents B0 and B1, together with the knowledge of $t_0$, $t_{B0}$ and $t_{B1}$, Bob estimates an upper bound, $t_{max}$, for $t_{commit}$. Only when both $n_r, n_d < N_{tot}$, $n_{e,r} < E_{tot}N_{tot}(n_{e,d} < E_{tot}N_{tot})$ and $t_{max} < t_{tol}$, Bob accepts the commitment as 0 (1), for some prefixed tolerated parameters $N_{tot}$, $E_{tot}$, and $t_{tol}$ previously agreed by Alice and Bob.

On experimental side, two groups implemented the secure relativistic quantum bit commitment simultaneously in 2013. One followed the original protocol and utilized decoy state method in free-space channel (Liu et al., 2014) and the other exploited a revised protocol with a plug and play system, in fiber link (Lunghi et al., 2013). Both experiments were secure against any quantum or classical attack. The committed time, however is limited to 21 ms if all attendees are located on Earth considering the relativistic constrains. Later, new protocols with weaker security but longer committed time was proposed (Chakraborty et al., 2015; Lunghi et al., 2015).

2. Quantum digital signature

Comparing to the previous two-party protocols, digital signature has one sender and multiple recipients, requiring that the messages cannot be forged or tampered with. Classical digital signature mainly exploits the Rivest-Shamir-Adleman protocol (Rivest et al., 1978), the security of which is based on the mathematical complexity of the integer factorization problem. Based on the quantum physics, quantum digital signature (QDS) protocol was provided, which could provided information-theoretical security (Guest, 2001). Although novel, this protocol needs nondestructive state comparison, long-time quantum memory, and a secure quantum channel for real application. Thereafter, QDS has attracted a great deal of interest in both theory (Andersson et al., 2006; Arrazola and Lütkenhaus, 2014; Arrazola et al., 2016; Dunjko et al., 2014; Wallden et al., 2015) and experiment (Amiri et al., 2016; Clarke et al., 2012; Collins et al., 2014; Croal et al., 2016; Donaldson et al., 2016; Yin et al., 2016b). All the three requirements have been fixed sequentially (Clarke et al., 2012; Collins et al., 2014; Donaldson et al., 2016). Later, more than 100 km QDS experiment has been demonstrated based on decoyed BB84 system (Yin et al., 2017a) and dps QKD (Collins et al., 2016), which are also secure against PNS attack. Very recently, measurement-device-independent (MDI) QDS have been implemented in both lab (Roberts et al., 2017) and field (Yin et al., 2017b).

3. Other protocols

QKD has been assuming that the eavesdropper has unlimited power as long as it is not violated quantum physics. A protocol is said to be information-theoretically secure if it allows an adversary (e.g. an eavesdropper) to have unlimited quantum computing power as long as it does not violate quantum mechanics. As noted in Section VII.B.1 above, information-theoretic security is not possible for quantum bit commitment, quantum oblivious transfer and two-party secure quantum computation. Naturally, restriction on adversary’s power can expand the territory of quantum cryptogra-
phy. Wehner et al. (Wehner et al., 2008) proposed one realistic assumption that quantum storage of qubits is noisy and demonstrated that an oblivious transfer protocol is unconditionally secure for any amount of quantum-storage noise (Damgård et al., 2008; König et al., 2012). Similar as bit commitment, oblivious transfer protocol is another primitive cryptograph protocol between two entrusted parties. The demonstration of the protocol was performed based on a modified entangled QKD system (Erven et al., 2014). The experiment exchanged a 1,366 bit random oblivious transfer string in 3 minutes and include a full security analysis under the noisy storage model, accounting for all experimental error rates and finite size effects.

Similar to bit commitment and oblivious transfer, a quantum protocol for coin flipping (Blum, 1981) can be unconditionally secure when considering relativistic constraints. This also means that without relativistic designs, no bias coin flipping could not be unconditionally secure (Lo and Chau, 1998). Nevertheless, a quantum protocol can limit the cheating probability strictly lower than $1/\sqrt{2}$ (Aharonov et al., 2000; Ambainis et al., 2004; Chailloux and Kerenidis, 2009; Kitaev, 1999; Nayak and Shor, 2003; Spekkens and Rudolph, 2002). The first experimental demonstration was provided with OAM qutrit entangled photon pairs, which shows the quantum advantage in coin flipping for the first time (Molina-Terriza et al., 2005). As a proof of principle demonstration, this experiment does not consider the channel loss. Theoretical and experimental efforts have been attempted towards this direction (Aharon et al., 2010; Berlín et al., 2009; Chailloux, 2010; Nguyen et al., 2008). Later, an implementation of the loss-tolerant protocol using an entangled-photon source was provided (Berlín et al., 2011). Recently, the secure distance has been extended to 15 km with a modified plug and play system (Pappa et al., 2014).

Quantum data locking (DiVincenzo et al., 2004) allows one to lock information in quantum states with an exponentially shorter key, presenting an efficient solution to many resource-limited secure applications. However, the original quantum data-locking scheme may suffer from significant qubit loss. In 2013, Fawzi, Hayden, and Sen (FHS) developed a loss-tolerant quantum data-locking scheme (Fawzi et al., 2013), in which the possible information leakage can be made arbitrarily small in a lossy environment while the unlocked information is significantly larger than the key size. This feature makes the protocol attractive also in secure communication (Lloyd, 2013; Lupo et al., 2014). Two groups have implemented the loss tolerant protocols respectively (Liu et al., 2016; Lum et al., 2016).

So far, we have given a brief review of other quantum crypto protocols for communication. Actually, in distributed quantum computing, quantum crypto protocols are still inevitable. Quantum computing is currently attracting tremendous interest from both academic and industry. However, due to its implementation complexity and cost, the future path of quantum computation is strongly believed to delegate computational tasks to powerful quantum servers on cloud. Universal blind quantum computing (UBQC) (Broadbent et al., 2009) is an effective method for a common user, who has limited or no quantum computational power, to delegate computation to an untrusted quantum server, without leaking any information about the user’s input and computational task. The security or blindness of the UBQC protocol is unconditional, i.e., the server cannot learn anything about user’s computation except its size. A proof of concept demonstration on UBQC was reported in 2012 (Barz et al., 2012). Recently, UBQC protocol with completely classical clients was proposed (Reichardt et al., 2013) and demonstrated in experiment (Huang et al., 2017). Overall, during the past few years, a number of UBQC protocols have been proposed in theory, and several experiments have been reported to demonstrate the feasibility of UBQC with photonic qubits. With the developments of the field of quantum computing, we expect that BQC will plan an important role in the future infrastructure of delegated quantum computation. See ref. (Fitzsimons, 2017) for a completed review of BQC.

VIII. CONCLUDING REMARKS

In this review, we have discussed the security aspects of practical QKD. These range from the security proofs of practical QKD (Section II), the practical vulnerabilities (Section IV), to the solutions of advanced QKD protocols (Sections VI, VII and VIII). Specifically, the decoy state QKD and the MDI-QKD provide viable solutions to realize practically secure QKD with current technology, which opens the way to the use of QKD technology for securing everyday interactions in the immediate future.

A. General questions to QKD

As a new technology stemming from the counterintuitive theory of quantum physics, QKD might not be easy to be understood and recognized by a general audience. For broad interest, we summarize a few frequently asked questions/concerns on practical QKD, together with our views on how they can be overcome.

1. Concern 1. Since RSA is secure under current computational power, we do not need QKD now.

Our view. Some important data such as government secrets and health data need to kept secret from decades, i.e., long-term security. RSA cannot guarantee long-term security, because one can record the encrypted information and later on decrypt it when the quantum computer comes up or
new advanced algorithm is discovered. In contrast, QKD can provide everlasting security, which is independent of all future hardware advances. Hence, QKD is required today for the transmission of top-secret data.

2. Concern 2. QKD vs post-quantum cryptography.

Our view. QKD and post-quantum cryptography are two parallel research directions. They go hand in hand with each other. It is not an “either-or” situation. Post-quantum cryptography has the advantages of being compatible with existing crypto infrastructure, but it has the drawback that its security cannot be proven or it is only secure against known quantum attacks. In contrast, QKD has the advantage of proven security based on the laws of quantum physics, but it is a symmetric-key algorithm, which can not replicate all the functionalities of public-key cryptography. In future, we believe that QKD is likely to be combined with the post-quantum cryptography to jointly form the infrastructure of quantum-safe encryption scheme.

3. Concern 3. QKD does not address large parts of the security problem.

Our view. The secure keys generated from QKD have widespread applications, such as encryption and authentication. Note that in QKD, authentication is only required in a short period, and once it is done, QKD can be employed for encryption in a rather long period\(^\text{16}\). Moreover, with the developments on high key-generation rate, QKD is also suitable for some of the future challenges such as securing the Internet of Things, big data, or cloud applications. Furthermore, as mentioned in Section VII.B.2, there exists quantum digital signature schemes with information-theoretical security.

4. Concern 4. Distance limitation.

Our view. In fiber, even without quantum repeater, the feasibility of QKD has been proved in experiments over long ranges of 400s-km (Boaron et al., 2018; Yin et al., 2016a). Using trusted relays, the distance has been extend to 2000 km fiber (Chen et al., 2019). Using quantum satellite, QKD has been demonstrated 7600-km (Liao et al., 2018, 2017a). Moreover, with the help of quantum repeaters (Briegel et al., 1998; Duan et al., 2001), QKD is feasible over arbitrarily long distance even with untrusted relay nodes. Important progress has been made in the developments of quantum repeaters (Chen et al., 2017; Kalb et al., 2017).

5. Concern 5. Cost limitation.

Our view. The recent developments of integrated QKD, such as compact transmitter (Hughes et al., 2013) and Si photonic chip-based QKD systems (Ma et al., 2016a; Sibson et al., 2017a), demonstrated already the possibility of low-cost hardware for QKD. Hence QKD is very likely to be cost-effective. See Section VII.A.4 for detail.

6. Concern 6. Point-to-point limitation.

Our view. Small-scale metropolitan QKD networks were intensively deployed in field by several countries (Chen et al., 2009; Elliott et al., 2005; Peev et al., 2009; Sasaki et al., 2011). Quantum access network was proposed and demonstrated (Fröhlich et al., 2013; Hughes et al., 2013). A large-scale network which covers a wide area was established lately (Chen et al., 2019). These networks already enable secure QKD for multiple users instead of point-to-point. Furthermore, the recent discovery of MDI-QKD protocols (Lo et al., 2012) and TF-QKD protocols (Lucamarini et al., 2018) works well in a star-type network setting (Xu et al., 2015a) by sharing a single detection system between multiple users. A prototype of MDI-QKD network has already been implemented in 2016 (Tang et al., 2016b). Therefore, these QKD networks and advanced QKD protocols enable QKD for network settings beyond point-to-point.

7. Concern 7. Trusted-relay limitation.

Our view. The discovery of MDI-QKD protocols (Lo et al., 2012) and TF-QKD protocols (Lucamarini et al., 2018) enables QKD with untrusted relays. Moreover, entanglement-based QKD works well with untrusted relays, and it has been demonstrated between two ground stations separated by a distance over 1100 kilometers (Yin et al., 2019). Furthermore, quantum repeaters (Briegel et al., 1998; Duan et al., 2001) enable secure QKD over arbitrarily long distance even with untrusted relay nodes. Hence trusted node is not a true limitation in QKD.

8. Concern 8. Hardware patches are expensive.

Our view. MDI-QKD already enables secure QKD with untrusted measurement devices, in which the expensive measurement devices do not need to be recalled/replaced once they are installed. Moreover, chip-based QKD makes the patches for hardware at a low-cost and simple manner. We believe

\(^{16}\) As an example, one can even use public key based authentication scheme in the initial authentication of a QKD session. Provided that the public key based authentication scheme is secure during the short time for initial authentication, the generated QKD key will be secure forever. Therefore, post-quantum cryptography and QKD may go hand in hand.
that a star-type of MDI-QKD network, together with chip-based transmitter, is promising to realize a future low-cost and practical QKD for applications.

9. Concern 9. Security loopholes in practical QKD.

Our view. Researchers in the filed of QKD have extensively understood and managed the security loopholes. All quantum attacks reported in the literature have been reviewed in Section IV. Those crucial loopholes have been eliminated by designing advanced countermeasures (Sections VI, VII and VIII). In particular, MDI-QKD has removed the weakest security link, i.e., the detection, in a standard QKD system (Lo et al., 2012). Secret sharing ideas have been proposed to foil covert channels and malicious classical post-processing units (Curty and Lo, 2019). Advanced technology in the future might make DI-QKD feasible (Hensen et al., 2015). Therefore, the gap between theory and practice of QKD has been reduced remarkably, and a number of loopholes have been completely removed. These achievements have made QKD a robust solution for secure communication.

10. Concern 10. Denial of service (DoS) attack.

Our view. One solution for DoS attack is to use alternative channel links by designing suitable network architectures. For instance, a circle type of QKD network has been implemented in the Beijing metropolitan network (see Fig. 2). The other solution is that the secure communication can be done offline. One can load the secret keys, generated from QKD, to USB or mobile phones. The secure communication via mobile phone will be immune to DoS attack. This method already finds commercial use, see e.g., the QUKey17.

B. The past and the future

During the past three decades, QKD has experienced extensive developments from theory to practice. These developments can be divided into several stages.

1. Stage 1. After the invention by Bennett-Brassard (Bennett and Brassard, 1984) and Ekert (Ekert, 1991), QKD was first demonstrated in the early 1990s (Bennett et al., 1992a), which started a series of theories and experiments (Franson and Jacobs, 1995; Muller et al., 1996; Townsend, 1994; Townsend et al., 1993) to prove the possibility of QKD.

2. Stage 2. The implementation of QKD was extended from laboratory to outdoor environments, and various technical difficulties were studied (Butler et al., 1998; Hughes et al., 2000; Ribordy et al., 2000; Townsend, 1997). See ref. (Gisin et al., 2002) for a review on the developments in early experiments. Meanwhile, on the theory side, the security proof of QKD was a major challenge until a few papers appeared and solved the problem (Bihm et al., 2000; Lo and Chau, 1999; Mayers, 2001; Shor and Preskill, 2000). These results put the security of QKD on a solid foundation.

3. Stage 3. With the security proofs for QKD under imperfect devices (Gottesman et al., 2004; Hwang, 2003; Lo et al., 2005; Wang, 2005), the feasibility of QKD was demonstrated from short range to long range, up to the scale of 100-km standard fiber (Peng et al., 2007; Rosenberg et al., 2007).

4. Stage 4. QKD was extensively deployed from point-to-point to small-scale metropolitan networks in field (Chen et al., 2009; Elliott et al., 2005; Peev et al., 2009; Sasaki et al., 2011). Meanwhile, the security loopholes in practical QKD systems were identified (Lydersen et al., 2010b; Makarov, 2009) and then removed by advanced QKD protocols (Lo et al., 2012).

5. Stage 5. The feasibility of QKD was extended to ultra-long distances and high rates, such as a scale of 400-km over low-loss fiber (Boaron et al., 2018; Yin et al., 2016a) and 1200-km over free space (Liao et al., 2017a), and a secret key rate of 1 Mbits/s (Lucamarini et al., 2013).

6. Stage 6. QKD was implemented from small scale to large scale that covers a wide area (Chen et al., 2019). See Fig. 2 for an example of the QKD network which has more than 150 user nodes and 700 QKD links, and covers more than 2,000 km area.

In future, towards the ultimate goal of a global QKD network, we expect that more and more QKD networks will be built in different countries. Besides physics, communities of computer science, engineering, optics, mathematics and so forth may work together to realize this goal. We do believe that a revolutionized global QKD network for secure communication stemming from quantum physics will be deployed and find widespread applications in the near future.

This review is concluded with a discussion on a few directions for future research.

1. Quantum repeaters. Quantum repeater can achieve an effective restoration of the quantum information without resorting to a direct measurement of the quantum state (Briegel et al., 1998; Duan et al.,

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17 [http://www.quantum-info.com/English/product/2017/1007/394.html](http://www.quantum-info.com/English/product/2017/1007/394.html)
enabling the realization of global quantum network in existing optical networks (Kimble, 2008). Quantum repeater has received intense research efforts in recent years (Pan et al., 2012; Sangouard et al., 2011; Wehner et al., 2018). Nonetheless, the limited performance of quantum memory is still a major obstacle in realizing practical quantum repeaters without a future experimental breakthrough (Sangouard et al., 2011; Yang et al., 2016). New recent approaches manage to reduce the need for a quantum memory by using all-photonic quantum repeaters (Azuma et al., 2015), but they require the resources of large-scale cluster states. Overall, we believe that quantum repeater is an important subject for future research. The first goal is to realize a practical quantum repeater that can beat the fundamental limits of direct quantum communication (Pirandola et al., 2017; Takeoka et al., 2014).

2. Standardization. Towards the widespread applications, the commercial standards for QKD should be established. Important progress has been made in this direction, such as the efforts of ETSI, ISO/IEC, CCSA and ITU by several countries. One important direction is to include the practical security into the standardization process, by defining the best practices to operate QKD systems and standardizing those countermeasures to guarantee the security of a QKD setup. We encourage future research to establish the commercial standards for QKD.

3. Battle-testing security. We have provided a review on the practical vulnerabilities in Section IV, together with the solutions of advanced countermeasures and QKD protocols. However, the practical security issue has not been perfectly solved. For instance, as discussed in Section VI.B, a security assumption in MDI-QKD is that the source should be trusted without loopholes. It is important to verify this assumption in practice. Hence, the research in analyzing the practical security of QKD setup should continue. This includes the developments of practically-secure QKD systems building on the experience gained from the research on practical vulnerabilities and advanced countermeasures. It is highly important to battle-test existing QKD implementations, quantify and validate the security claims of real-world QKD systems, and design real-life QKD systems with testable security assumptions.

4. Small-size and low-cost system. Recent developments of integrated QKD system have been reviewed in Section VII.A.4. These developments should continue to further reduce the costs and sizes of QKD, and to realize robust fully-integrated chip-based QKD systems. One important direction is to develop the star-type quantum access network (Fröhlich et al., 2013; Hughes et al., 2013), in which the expensive devices such as single-photon detectors can be placed in the central relay and many users share this relay. Each user requires only a low-cost transmitter such as a compact QCard (Hughes et al., 2013) or a simple Si chip (Ma et al., 2016a; Sibson et al., 2017b) which integrates a standard laser and modulators. Together with MDI-QKD, the central relay can be untrusted. Therefore, a chip-based MDI-QKD network will play an important role in the global quantum network.

5. QKD network with untrusted relays. The previously deployed networks were based on trusted relays (Chen et al., 2009, 2019; Elliott et al., 2005; Peev et al., 2009; Sasaki et al., 2011), which may raise the concern about the security properties of the relays. To remove this concern, it is important to develop QKD network with untrusted relays. In fact, MDI-QKD is naturally suitable for a star-type QKD network with untrusted relays. Tang et al., already put forward the first implementation of a MDI-QKD network (Tang et al., 2016b). We expect that metropolitan MDI-QKD networks will be built soon. Moreover, in entanglement-based QKD, the relay can be untrusted. A possible direction is to develop an entanglement-based QKD network, e.g., based on satellite (Yin et al., 2019). Furthermore, one can also realize QKD network with untrusted relays based on quantum repeater. With the technical improvements, quantum repeater assisted QKD network may be achieved in near future.

6. Satellite-based QKD. The reported satellite-based QKD was based on a low-earth-orbit (LEO) satellite of Micius (Liao et al., 2018, 2017a). To increase the coverage time and area for a more efficient satellite-based QKD network, one can launch higher-orbit quantum satellites and implement QKD in daytime. Important progress has been made in this direction (Liao et al., 2017b). An ultimate goal is to realize a satellite-constellation-based global quantum network.

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