# Quantum Cryptography

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Definition of the subject and its importance

Quantum cryptography is the synthesis of quantum mechanics with the art of code-making (cryptography). The idea was first conceived in an unpublished manuscript written by Stephen Wiesner around 1970 [4]. However, the subject received little attention until its resurrection by a classic paper published by Bennett and Brassard in 1984 [1]. The goal of quantum cryptography is to perform tasks that are impossible or intractable with conventional cryptography. Quantum cryptography makes use of the subtle properties of quantum mechanics such as the quantum no-cloning theorem and the Heisenberg uncertainty principle. Unlike conventional cryptography, whose security is often based on unproven computational assumptions, quantum cryptography has an important advantage in that its security is often based on the laws of physics. Thus far, proposed applications of quantum cryptography include quantum key distribution (abbreviated QKD), quantum bit commitment and quantum coin tossing. These applications have varying degrees of success. The most successful and important application—QKD—has been proven to be unconditionally secure. Moreover, experimental QKD has now been performed over hundreds of kilometers over both standard commercial telecom optical fibers and open-air. In fact, commercial QKD systems are currently available on the market.

On a wider context, quantum cryptography is a branch of quantum information processing, which includes quantum computing, quantum measurements, and quantum teleportation. Among all branches, quantum cryptography is the branch that is closest to real-life applications. Therefore, it can be a concrete avenue for the demonstrations of concepts in quantum information processing. On a more fundamental level, quantum cryptography is deeply related to the foundations of quantum mechanics, particularly the testing of Bell-inequalities and the detection efficiency loophole. On a technological level, quantum cryptography is related to technologies such as single-photon measurements and detection and single-photon sources.
TABLE I: Procedure of BB84 protocol.

| Alice's bit sequence | 0 1 1 1 0 1 0 0 0 1 |
|----------------------|---------------------|
| Alice's basis        | + × + × + × + × + × + × |
| Alice’s photon polarization | → \ ↑ ↑ ↑ / / / → \ |
| Bob's basis          | + + × + + × + + × + + × |
| Bob's measured polarization | → ↑ \ ↑ → / / / ↑ → \ |
| Bob's sifted measured polarization | → ↑ / → \ → \ |
| Bob’s data sequence  | 0 1 0 0 1 |

I. INTRODUCTION

The best-known application of quantum cryptography is quantum key distribution (QKD). The goal of QKD is to allow two distant participants, traditionally called Alice and Bob, to share a long random string of secret (commonly called the key) in the presence of an eavesdropper, traditionally called Eve. The key can subsequently be used to achieve a) perfectly secure communication (via one-time-pad, see below) and b) perfectly secure authentication (via Wigman-Carter authentication scheme), thus achieving two key goals in cryptography.

The best-known protocol for QKD is the Bennett and Brassard protocol (BB84) published in 1984 [1]. The procedure of BB84 is as follows (also shown in Table I).

1. Quantum communication phase

   (a) In BB84, Alice sends Bob a sequence of photons, each independently chosen from one of the four polarizations—vertical, horizontal, 45-degrees and 135-degrees.

   (b) For each photon, Bob randomly chooses one of the two measurement bases (rectilinear and diagonal) to perform a measurement.

   (c) Bob records his measurement bases and results. Bob publicly acknowledges his receipt of signals.

2. Public discussion phase

   (a) Alice broadcasts her bases of measurements. Bob broadcasts his bases of measurements.

   (b) Alice and Bob discard all events where they use different bases for a signal.

   (c) To test for tampering, Alice randomly chooses a fraction, \( p \), of all remaining events as test events. For those test events, she publicly broadcasts their positions and polarizations.
(d) Bob broadcasts the polarizations of the test events.

(e) Alice and Bob compute the error rate of the test events (i.e., the fraction of data for which their value disagree). If the computed error rate is larger than some prescribed threshold value, say 11%, they abort. Otherwise, they proceed to the next step.

(f) Alice and Bob each convert the polarization data of all remaining data into a binary string called a raw key (by, for example, mapping a vertical or 45-degrees photon to “0” and a horizontal or 135-degrees photon to “1”). They can perform classical post-processing such as error correction and privacy amplification to generate a final key.

Notice that it is important for the classical communication channel between Alice and Bob to be authenticated. Otherwise, Eve can easily launch a man-in-the-middle attack by disguising as Alice to Bob and as Bob to Alice. Fortunately, authentication of an m-bit classical message requires only logarithmic in m bit of an authentication key. Therefore, QKD provides an efficient way to expand a short initial authentication key into a long key. By repeating QKD many times, one can get an arbitrarily long secure key.

This article is organized as follows. In Section II, we will discuss the importance and foundations of QKD; in Section III, we will discuss the principles of different approaches to prove the unconditional security of QKD; in Section IV, we will introduce the history and some fundamental components of QKD implementations; in Section V, we will discuss the implementation of BB84 protocol in detail; in Section VI, we will discuss the proposals and implementations of other QKD protocols; in Section VII, we will introduce a very fresh and exciting area — quantum hacking — in both theory and experiments. In particular, we provide a catalogue of existing eavesdropping attacks; in Section VIII, we will discuss some topics other than QKD, including quantum bit commitment, quantum coin tossing, etc.; in Section IX, we will wrap up this article with prospectives of quantum cryptography in the future.

II. QUANTUM KEY DISTRIBUTION: MOTIVATION AND INTRODUCTION

Cryptography—the art of code-marking—has a long and distinguished history of military and diplomatic applications, dating back to ancient civilizations in Mesopotamia, Egypt, India and China. Moreover, in recent years cryptography has widespread applications in civilian applications such as electronics commerce and electronics businesses. Each time we go on-line to access our banking or credit card data, we should be deeply concerned with our data security.
A. Key Distribution Problem and One-time-pad

Secure communication is the best-known application of cryptography. The goal of secure communication is to allow two distant participants, traditionally called Alice and Bob, to communicate securely in the presence of an eavesdropper, Eve. See Figure 1. A simple example of an encryption scheme is the Caesar’s cipher. Alice simply shifts each letter in a message alphabetically by three letters. For instance, the word NOW is mapped to QRZ, because $N \rightarrow O \rightarrow P \rightarrow Q$, $O \rightarrow P \rightarrow Q \rightarrow R$, and $W \rightarrow X \rightarrow Y \rightarrow Z$. According to legends, Julius Caesar used Caesar’s cipher to communicate with his generals. An encryption by an alphabetical shift of a fixed but arbitrary number of positions is also called a Caesar’s cipher. Note that Caesar’s cipher is not that secure because an eavesdropper can simply exhaustively try all 26 possible combinations of the key to recover the original message.

In conventional cryptography, an unbreakable code does exist. It is called the one-time-pad and was invented by Gilbert Vernam in 1918. In the one-time-pad method, a message (traditionally called the plain text) is first converted by Alice into a binary form (a string consisting of “0”s and “1”s) by a publicly known method. A key is a binary string of the same length as the message. By combining each bit of the message with the respective bit of the key using XOR (i.e. addition modulo two), Alice converts the plain text into an encrypted form (called the cipher text). i.e. for each bit $c_i = m_i + k_i \mod 2$. Alice then transmits the cipher text to Bob via a broadcast channel. Anyone including an eavesdropper can get a copy of the cipher text. However, without
the knowledge of the key, the cipher text is totally random and gives no information whatsoever about the plain text. For decryption, Bob, who shares the same key with Alice, can perform another XOR (i.e. addition modulo two) between each bit of the cipher text with the respective bit of the key to recover the plain text. This is because $c_i + k_i \mod 2 = m_i + 2k_i \mod 2 = m_i \mod 2$.

Notice that it is important not to re-use a key in a one-time-pad scheme. Suppose the same key, $k$, is used for the encryption of two messages, $m_1$ and $m_2$, then the cipher texts are $c_1 = m_1 + k \mod 2$ and $c_2 = m_2 + k \mod 2$. Then, Eve can simply take the XOR of the two cipher texts to obtain $c_1 + c_2 \mod 2 = m_1 + m_2 + 2k \mod 2 = m_1 + m_2 \mod 2$, thus learning non-trivial information, namely the parity of the two messages.

The one-time-pad method is commonly used in top-secret communication. The one-time-pad method is unbreakable, but it has a serious drawback: it supposes that Alice and Bob initially share a random string of secret that is as long as the message. Therefore, the one-time-pad simply shifts the problem of secure communication to the problem of key distribution. This is the key distribution problem. In top-secret communication, the key distribution problem can be solved by trusted couriers. Unfortunately, trusted couriers can be bribed or compromised. Indeed, in conventional cryptography, a key is a classical string consisting of “0”s and “1”s. In classical physics, there is no fundamental physical principle that can prevent an eavesdropper from copying a key during the key distribution process.

A possible solution to the key distribution problem is public key cryptography. However, the security of public key cryptography is based on unproven computational assumptions. For example, the security of standard RSA crypto-system invented by Rivest-Shamir-Adlerman (RSA) is based on the presumed difficulty of factoring large integers. Therefore, public key distribution is vulnerable to unanticipated advances in hardware and algorithms. In fact, quantum computers—computers that operate on the principles of quantum mechanics—can break standard RSA crypto-system via the celebrated Shor’s quantum algorithm for efficient factoring [6].

B. Quantum no-cloning theorem and quantum key distribution (QKD)

Quantum mechanics can provide a solution to the key distribution problem. In quantum key distribution, an encryption key is generated randomly between Alice and Bob by using non-orthogonal quantum states. In contrast to classical physics, in quantum mechanics there is a quantum no-cloning theorem (see below), which states that it is fundamentally impossible for anyone including
an eavesdropper to make an additional copy of an unknown quantum state.

A big advantage of quantum cryptography is *forward security*. In conventional cryptography, an eavesdropper Eve has a transcript of all communications. Therefore, she can simply save it for many years and wait for breakthroughs such as the discovery of a new algorithm or new hardware. Indeed, if Eve can factor large integers in 2100, she can decrypt communications sent in 2008. We remark that Canadian census data are kept secret for 92 years on average. Therefore, factoring in the year 2100 may violate the security requirement of our government today! And, no one in his/her sane mind can guarantee the impossibility of efficient factoring in 2100 (except for the fact that he/she may not live that long). In contrast, quantum cryptography guarantees forward security. Thanks to the quantum no-cloning theorem, an eavesdropper does not have a transcript of all quantum signals sent by Alice to Bob.

For completeness, we include the statement and the proof of the quantum no-cloning theorem below.

**Quantum No-cloning theorem**: An unknown quantum state cannot be copied.

(a) The case without ancilla: Given an unknown state $|\alpha\rangle$, show that a quantum copying machine that can map $|\alpha\rangle|0\rangle \rightarrow |\alpha\rangle|\alpha\rangle$ does not exist.

(b) The general case: Given an unknown state $|\alpha\rangle$, show that a quantum copying machine that can map $|\alpha\rangle|0\rangle|0\rangle \rightarrow |\alpha\rangle|\alpha\rangle|u_\alpha\rangle$ does not exist.

Proof: (a) Suppose the contrary. Then, a quantum cloning machine exists. Consider two orthogonal input states $|0\rangle$ and $|1\rangle$ respectively. We have

$$|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle$$

and

$$|1\rangle|0\rangle \rightarrow |1\rangle|1\rangle.$$ 

Consider a general input $|\alpha\rangle = a|0\rangle + b|1\rangle$. Since a unitary transformation is linear, by linearity, we have

$$|\alpha\rangle|0\rangle = (a|0\rangle + b|1\rangle)|0\rangle$$

$$\rightarrow a|0\rangle|0\rangle + b|1\rangle|1\rangle.$$  

(1)

In contrast, for quantum cloning, we need:

$$|\alpha\rangle|0\rangle \rightarrow (a|0\rangle + b|1\rangle)(a|0\rangle + b|1\rangle)$$

$$= a^2|0\rangle|0\rangle + ab|0\rangle|1\rangle + ab|1\rangle|0\rangle + b^2|1\rangle|1\rangle.$$  

(2)
Clearly, if $ab \neq 0$, the two results shown in Eqs. (1) and (2) are different. Therefore, quantum cloning (without ancilla) is impossible.

(b): similar. □

More generally, for general quantum states, information gain implies disturbance.

**Theorem:** (Information Gain implies disturbance) Given one state chosen from one of the two distinct non-orthogonal states, $|u\rangle$ and $|v\rangle$ (i.e. $|\langle u|v \rangle| \neq 0$ or 1), any operation that can learn any information about its identity necessarily disturbs the state.

**Proof:** Given a system initially in state either $|u\rangle$ and $|v\rangle$. Suppose an experimentalist applies some operation on the system. The most general thing that she can try to do is to prepare some ancilla in some standard state $|0\rangle$ and couple it to the system. Therefore, we have:

$$|u\rangle|0\rangle \rightarrow |u\rangle|\phi_u\rangle \quad (3)$$

and

$$|v\rangle|0\rangle \rightarrow |v\rangle|\phi_v\rangle \quad (4)$$

for some states $|\phi_u\rangle$ and $|\phi_v\rangle$.

In the end, the experimentalist lets go of the system and keeps the ancilla. He/she may then perform a measurement on the ancilla to learn about the initial state of the system.

Recall that quantum evolution is unitary and as such it preserves the inner product. Now, taking the inner product between Eqs. (3) and (4), we get:

$$\langle u|v\rangle \langle 0|0 \rangle = \langle u|v\rangle \langle \phi_u|\phi_v \rangle$$

$$\langle u|v\rangle = \langle u|v\rangle \langle \phi_u|\phi_v \rangle$$

$$\langle u|v\rangle (1 - \langle \phi_u|\phi_v \rangle) = 0$$

$$1 - \langle \phi_u|\phi_v \rangle = 0$$

$$|\phi_u\rangle = |\phi_v\rangle,$$  

(5)

where in the fourth line, we have used the fact that $|\langle u|v \rangle| \neq 0$.

Now, the condition that $|\phi_u\rangle = |\phi_v\rangle$ means that the final state of the ancilla is independent of the initial state of the system. Therefore, a measurement on the ancilla will tell the experimentalist nothing about the initial state of the system. □

Therefore, any attempt by an eavesdropper to learn information about a key in a QKD process will lead to disturbance, which can be detected by Alice and Bob who can, for example, check the bit error rate of a random sample of the raw transmission data.
The standard BB84 protocol for QKD was discussed in Section I. In the BB84 protocol, Alice prepares a sequence of photons each randomly chosen in one of the four polarizations—vertical, horizontal, 45-degrees and 135-degrees. For each photon, Bob chooses one of the two polarization bases (rectilinear or diagonal) to perform a measurement. Intuitively, the security comes from the fact that the two polarization bases, rectilinear and diagonal, are conjugate observables. Just like position and momentum are conjugate observables in the standard Heisenberg uncertainty principle, no measurement by an eavesdropper Eve can determine the value of both observables simultaneously. In mathematics, two conjugate observables are represented by two non-commuting Hermitian matrices. Therefore, they cannot be simultaneously diagonalized. This impossibility of simultaneous diagonalization implies the impossibility of simultaneous measurements of two conjugate observables.

C. Example of a simple eavesdropper attack: intercept-resend attack

To illustrate the security of quantum cryptography, let us consider the simple example of an intercept-resend attack by an eavesdropper Eve, who measures each photon in a randomly chosen basis and then resends the resulting state to Bob. For instance, if Eve performs a rectilinear measurement, photons prepared by Alice in the diagonal bases will be disturbed by Eve’s measurement and give random answers. When Eve resends rectilinear photons to Bob, if Bob performs a diagonal measurement, then he will get random answers. Since the two bases are chosen randomly by each party, such an intercept-resend attack will give a bit error rate of $0.5 \times 0.5 + 0.5 \times 0 = 25\%$, which is readily detectable by Alice and Bob. Sophisticated attacks against QKD do exist. Fortunately, the security of QKD has now been proven. This subject will be discussed further in Section III.

D. Equivalence between phase and polarization encoding

Notice that the BB84 protocol can be implemented with any two-level quantum system (qubits). In Section I and the above discussion, we have described the BB84 protocol in terms of polarization encoding. This is just one of the many possible types of encodings. Indeed, it should be noted that other encoding method, particularly, phase encoding also exists. In phase encoding, a signal consists of a superposition of two time-separated pulses, known as the reference pulse and the signal pulse. See Figure 2 for an illustration of the phase encoding scheme. The information is encoded in the relative phase between two pulses. i.e., the four possible states used by Alice are
FIG. 2: Conceptual schematic for phase-coding BB84 QKD system. PM: Phase Modulator; BS: Beam Splitter; SPD: Single Photon Detector.

\[ \frac{1}{\sqrt{2}}(|R\rangle + |S\rangle), \frac{1}{\sqrt{2}}(|R\rangle - |S\rangle), \frac{1}{\sqrt{2}}(|R\rangle + i|S\rangle), \frac{1}{\sqrt{2}}(|R\rangle - i|S\rangle). \]

Notice that, mathematically the phase encoding scheme is equivalent to the polarization encoding scheme. They are simply different embodiments of the same BB84 protocol.

III. SECURITY PROOFS

“The most important question in quantum cryptography is to determine how secure it really is.” (Bennett and Brassard) Security proofs are very important because a) they provide the foundation of security to a QKD protocol, b) they provide a formula for the key generation rate of a QKD protocol and c) they may even provide a construction for the classical post-processing protocol (for error correction and privacy amplification) that is necessary for the generation of the final key. Without security proofs, a real-life QKD system is incomplete because we can never be sure about how to generate a secure key and how secure the final key really is.

A. Classification of Eavesdropping attacks

Before we discuss security proofs, let us first consider eavesdropping attacks. Notice that there are infinitely many eavesdropping strategies that an eavesdropper, Eve, can perform against a QKD protocol. They can be classified as follows:

**Individual attacks** In an individual attack, Eve performs an attack on each signal independently. The intercept-resend attack discussed in Section II C is an example of an individual attack.

**Collective attacks:** A more general class of attacks is collective attack where for each signal, Eve independently couples it with an ancillary quantum system, commonly called an ancilla, and evolves the combined signal/ancilla unitarily. She can send the resulting signals to Bob,
but keep all ancillas herself. Unlike the case of individual attacks, Eve postpones her choice of measurement. Only after hearing the public discussion between Alice and Bob, does Eve decide on what measurement to perform on her ancilla to extract information about the final key.

**Joint attacks:** The most general class of attacks is joint attack. In a joint attack, instead of interacting with each signal independently, Eve treats all the signals as a single quantum system. She then couples the signal system with her ancilla and evolves the combined signal and ancilla system unitarily. She hears the public discussion between Alice and Bob before deciding on which measurement to perform on her ancilla.

Proving the security of QKD against the most general attack was a very hard problem. It took more than 10 years, but the unconditional security of QKD was finally established in several papers in the 1990s. One approach by Mayers [7] was to prove the security of the BB84 directly. A simpler approach by Lo and Chau [8], made use of the idea of entanglement distillation by Bennett, DiVincenzo, Smolin and Wootters (BDSW) [9] and quantum privacy amplification by Deutsch et al. [10] to solve the security of an entanglement-based QKD protocol. The two approaches have been unified by the work of Shor and Preskill [11], who provided a simple proof of security of BB84 using entanglement distillation idea. Other early security proofs of QKD include Biham, Boyer, Boykin, Mor, and Roychowdhury [12], and Ben-Or [13].

**B. Approaches to security proofs**

There are several approaches to security proof. We will discuss them one by one.

1. Entanglement distillation

Entanglement distillation protocol (EDP) provides a simple approach to security proof [8, 10, 11]. The basic insight is that entanglement is a sufficient (but not necessary) condition for a secure key. Consider the noiseless case first. Suppose two distant parties, Alice and Bob, share a maximally entangled state of the form $|\phi\rangle_{AB} = 1/\sqrt{2}(|00\rangle_{AB} + |11\rangle_{AB})$. If each of Alice and Bob measure their systems, then they will both get "0"s or "1"s, which is a shared random key. Moreover, if we consider the combined system of the three parties—Alice, Bob and an eavesdropper, Eve, we can use a pure-state description (the “Church of Larger Hilbert space”) and consider a pure state $|\psi\rangle_{ABE}$. In this case, the von Neumann
entropy of Eve $S(\rho_E) = S(\rho_{AB}) = 0$. This means that Eve has absolutely no information on the final key. This is the consequence of the standard Holevo’s theorem. See, like. In the noisy case, Alice and Bob may share $N$ pairs of qubits, which are a noisy version of $N$ maximally entangled states. Now, using the idea of entanglement distillation protocol (EDP) discussed in BDSW, Alice and Bob may apply local operations and classical communications (LOCCs) to distill from the $N$ noisy pairs a smaller number, say $M$ almost perfect pairs i.e., a state close to $|\phi\rangle^M_{AB}$. Once such an EDP has been performed, Alice and Bob can measure their respective system to generate an $M$-bit final key.

One may ask: how can Alice and Bob be sure that their EDP will be successful? Whether an EDP will be successful or not depends on the initial state shared by Alice and Bob. In the above, we have skipped the discussion about the verification step. In practice, Alice and Bob can never be sure what initial state they possess. Therefore, it is useful for them to add a verification step. By, for example, randomly testing a fraction of their pairs, they have a pretty good idea about the properties (e.g., the bit-flip and phase error rates) of their remaining pairs and are pretty confident that their EDP will be successful.

The above description of EDP is for a quantum-computing protocol where we assume that Alice and Bob can perform local quantum computations. In practice, Alice and Bob do not have large-scale quantum computers at their disposal. Shor and Preskill made the important observation that the security proof of the standard BB84 protocol can be reduced to that of an EDP-based QKD protocol. The Shor-Preskill proof makes use of the Calderbank-Shor-Steane (CSS) code, which has the advantage of decoupling the quantum error correction procedure into two parts: bit-flip and phase error correction. They can go on to show that bit-flip error correction corresponds to standard error correction and phase error correction corresponds to privacy amplification (by random hashing).

2. Communication complexity/quantum memory.

The communication complexity/quantum memory approach to security proof was proposed by Ben-Or and subsequently by Renner and Koenig. See also. They provide a formula for secure key generation rate in terms of an eavesdropper’s quantum knowledge on the raw key: Let $Z$ be a random variable with range $Z$, let $\rho$ be a random state, and let $F$ be a two-universal function on $Z$ with range $S = \{0, 1\}^s$ which is independent of $Z$ and $\rho$. 
Then
\[
d(F(Z)|\{F\} \otimes \rho) \leq \frac{1}{2} 2^{-\frac{1}{2} (S_d((Z) \otimes \rho)) - S_0(\rho) - s)}.
\]

Incidentally, the quantum de Finetti’s theorem \cite{18} is often useful for simplifying security proofs of this type.

3. Twisted state approach.

What is a necessary and sufficient condition for secure key generation? From the entanglement distillation approach, we know that entanglement distillation a sufficient condition for secure key generation. For some time, it was hoped that entanglement distillation is also a necessary condition for secure key generation. However, such an idea was proven to be wrong in \cite{19, 20}, where it was found that a necessary and sufficient condition is the distillation of a private state, rather than a maximally entangled state. A private state is a “twisted” version of a maximally entangled state. They proved the following theorem in \cite{19}: a state is private in the above sense iff it is of the following form
\[
\gamma_m = U|\psi_{2^m}^+\rangle_{AB} \langle \psi_{2^m}^+| \otimes \varrho_{A'B'} U^\dagger
\]
where \(|\psi_d\rangle = \sum_{i=1}^d |ii\rangle\) and \(\varrho_{A'B'}\) is an arbitrary state on \(A',B'\). \(U\) is an arbitrary unitary controlled in the computational basis
\[
U = \sum_{i,j=1}^{2^m} |ij\rangle_{AB} \langle ij| \otimes U_{ij}^{A'B'}.
\]

The operation \(\text{(7)}\) will be called “twisting” (note that only \(U_{ij}^{A'B'}\) matter here, yet it will be useful to consider general twisting later).

Proof. (copied from \cite{19}) The authors of \cite{19} proved for \(m = 1\) (for higher \(m\), the proof is analogous). Start with an arbitrary state held by Alice and Bob, \(\rho_{AA'B'B'}\), and include its purification to write the total state in the decomposition
\[
\Psi_{ABA'B'E} = a|00\rangle_{AB}|\Psi_{00}\rangle_{A'B'E} + b|01\rangle_{AB}|\Psi_{01}\rangle_{A'B'E} + c|10\rangle_{AB}|\Psi_{10}\rangle_{A'B'E} + d|11\rangle_{AB}|\Psi_{11}\rangle_{A'B'E}
\]
with the states \(|ij\rangle\) on \(AB\) and \(\Psi_{ij}\) on \(A'B'E\). Since the key is unbiased and perfectly correlated, we must have \(b = c = 0\) and \(|a|^2 = |d|^2 = 1/2\). Depending on whether the key is \(|00\rangle\) or \(|11\rangle\), Eve will hold the states
\[
g_0 = Tr_{A'B'}|\Psi_{00}\rangle\langle \Psi_{00}|, \quad g_1 = Tr_{A'B'}|\Psi_{11}\rangle\langle \Psi_{11}|
\]
Perfect security requires \( \varrho_0 = \varrho_1 \). Thus there exists unitaries \( U_{00} \) and \( U_{11} \) on \( A'B' \) such that

\[
\begin{align*}
|\Psi_{00}\rangle &= \sum_i \sqrt{p_i} |U_0 \phi_i^{A'B'} \rangle |\varphi_i^E\rangle \\
|\Psi_{11}\rangle &= \sum_i \sqrt{p_i} |U_1 \phi_i^{A'B'} \rangle |\varphi_i^E\rangle.
\end{align*}
\]

(10)

After tracing out \( E \), we will thus get a state of the form Eq. (6), where \( \varrho_{A'B'} = \sum_i p_i |\phi_i \langle \phi_i| \). The main new ingredient of the above theorem is the introduction of a “shield” part to Alice and Bob’s system. That is, in addition to the systems \( A \) and \( B \) used by Alice and Bob for key generation, we assume that Alice and Bob also hold some ancillary systems, \( A' \) and \( B' \), often called the shield part. Since we assume that Eve has no access to the shield part, Eve is further limited in her ability to eavesdrop. Therefore, Alice and Bob can derive a higher key generation rate than the case when Eve does have access to the shield part.

An upshot is that even a bound entangled state can give a secure key. A bound state is one whose formation (via local operations and classical communications, LOCCs) requires entanglement, but which does not give any distillable entanglement. In other words, even though no entanglement can be distilled from a bound entangled state, private states (a twisted version of entangled states) can be distilled from a bound entangled state.

In summary, secure key generation is a more general theory than entanglement distillation.

4. Complementary principle

Another approach to security proof is to use the complementary principle of quantum mechanics. Such an approach is interesting because it shows the deep connection between the foundations of quantum mechanics and the security of QKD. In fact, both Mayers’ proof \[^7\] and Biham, Boyer, Boykin, Mør, and Roychowdhury’s proof \[^12\] make use of this complementary principle. A clear and rigorous discussion of the complementary principle approach to security proof has recently been achieved by Koashi \[^21\].

The key insight of Koashi’s proof is that Alice and Bob’s ability to generate a random secure key in the \( Z \)-basis (by a measurement of the Pauli spin matrix \( \sigma_Z \)) is equivalent to the ability for Bob to help Alice prepare an eigenstate in the complementary, i.e., \( X \)-basis (\( \sigma_X \)), with their help of the shield. The intuition is that an \( X \)-basis eigenstate, for example, \( |+\rangle_A = \frac{1}{\sqrt{2}} (|0\rangle_A + |1\rangle_A) \), when measured along the \( Z \)-basis, gives a random answer.

5. Other ideas for security proofs
Here we discuss two other ideas for security proofs, namely, a) device-independent security proofs and b) security from the causality constraint. Unfortunately, these ideas are still very much under development and so far a complete version of a proof of unconditional security of QKD based on these ideas with a finite key rate is still missing.

Let us start with a) device-independent security proofs So far we have assumed that Alice and Bob know what their devices are doing exactly. In practice, Alice and Bob may not know their devices for sure. Recently, there has been much interest in the idea of device-independent security proofs. In other words, how to prove security when Alice and Bob’s devices cannot be trusted. See, for example, [22]. The idea is to look only at the input and output variables. A handwaving argument goes as follows. Using their probability distribution, if one can demonstrate the violation of some Bell inequalities, then one cannot explain the data by a separable system. How to develop such a handwaving argument into a full proof of unconditional security is an important question.

The second idea b) security from the causality constraint is even more ambitious. The question that it tries to address is the following. How can one prove security when even quantum mechanics is wrong? In [23] and references cited therein, it was suggested that perhaps a more general physical principle such as the no-signaling requirement for space-like observables could be used to prove the security of QKD.

C. Classical Post-Processing Protocols

As noted in Section II after the quantum communication phase, Alice and Bob then proceed with the classical communication phase. In order to generate a secure key, Alice and Bob have to know what classical post-processing protocol to apply to the raw quantum data. This is a highly non-trivial question. Indeed, a priori, given a particular procedure for classical post-processing, it is very hard to know whether it will give a secure key or what secure key will be generated. In fact, it is sometimes said that in QKD, the optical part is easy, the electronics part is harder, but the hardest part is the classical post-processing protocol. Fortunately, security proofs often give Alice and Bob clear ideas on what classical post-processing protocol to use. This highlights the importance for QKD practitioners to study the security proofs of QKD.

Briefly stated, the classical post-processing protocol often consists of a) test for tampering and b) key generation. In a) test for tampering, Alice and Bob may randomly choose a fraction of the signals for testing. For example, by broadcasting the polarizations of those signals, they can work
out the bit error rate of the test signals. Since the test signals are randomly chosen, they have high confidence on the bit error rate of the remaining signals. If the bit error rate of the tested signal is higher than a prescribed threshold value, Alice and Bob abort. On the other hand, if the bit error rate is lower than or equal to the prescribed value, they proceed with the key generation step with the remaining signals. They first convert their polarization data into binary strings, the raw keys, in a prescribed manner. For example, they can map a vertical or 45-degrees photon to “0” and a horizontal or 135-degrees photon to “1”. As a result, Alice has a binary string $x$ and Bob has a binary string $y$. However, two problems remain. First, Alice’s string may differ from Bob’s string. Second, since the bit error rate is non-zero, Eve has some information about Alice’s and Bob’s string. The key generation step may be divided into the following stages:

1. Classical pre-processing

This is an optional step. Classical pre-processing has the advantage of achieving a higher key generation rate and tolerating a higher bit error rate \[24, 25, 26\].

Alice and Bob may pre-process their data by either a) some type of error detection algorithm or b) some random process. An example of an error detection algorithm is a B-step \[24\], where Alice randomly permutes all her bits and broadcasts the parity of each adjacent pair. In other words, starting from $\vec{x} = (x_1, x_2, \cdots, x_{2N-1}, x_{2N})$, Alice broadcasts a string $\vec{x_1} = (x_{\sigma(1)} + x_{\sigma(2)} \mod 2, x_{\sigma(3)} + x_{\sigma(4)} \mod 2, \cdots, x_{\sigma(2N-1)} + x_{\sigma(2N)} \mod 2)$, where $\sigma$ is a random permutation chosen by Alice. Moreover, Alice informs Bob which random permutation, $\sigma$, she has chosen. Similarly, starting from $\vec{y} = (y_1, y_2, \cdots, y_{2N-1}, y_{2N})$, Bob randomly permutes all his bits using the same $\sigma$ and broadcasts the parity bit of all adjacent pairs. I.e., Bob broadcasts $\vec{y_1} = (y_{\sigma(1)} + y_{\sigma(2)} \mod 2, y_{\sigma(3)} + y_{\sigma(4)} \mod 2, \cdots, y_{\sigma(2N-1)} + y_{\sigma(2N)} \mod 2)$. For each pair of bits, Alice and Bob keep the first bit iff their parities of the pair agree. For instance, if $x_{\sigma(2k-1)} + x_{\sigma(2k)} \mod 2 = y_{\sigma(2k-1)} + y_{\sigma(2k)} \mod 2$, then Alice keeps $x_{\sigma(2k-1)}$ and Bob keeps $y_{\sigma(2k-1)}$ as their new key bit. Otherwise, they drop the pair $(x_{\sigma(2k-1)}, x_{\sigma(2k)})$ and $(y_{\sigma(2k-1)}, y_{\sigma(2k)})$ completely.

Notice that the above protocol is an error detection protocol. To see this, let us regard the case where $x_i \neq y_i$ as an error during the quantum transmission stage. Suppose that for each bit, $i$, the event $x_i \neq y_i$ occurs with an independent probability $p$. For each $k$, the B step throws away the cases where a single error has occurred for the two locations $\sigma(2k-1)$ and $\sigma(2k)$ and keeps the cases when either no error or two errors has occurred. As a result, the error probability after the B-step is reduced from $O(p)$ to $O(p^2)$. The random permutation
of all the bit locations ensures that the error model can be well described by an independent identical distribution (i.i.d.).

An example of a random process is an adding noise protocol \[25\] where, for each bit \(x_i\), Alice randomly and independently chooses to keep it unchanged or flip it with probabilities, \(1 - q\) and \(q\) respectively, where the probability \(q\) is publicly known.

2. Error correction

Owing to noises in the quantum channel, Alice and Bob’s raw keys, \(x\) and \(y\), may be different. Therefore, it is necessary for them to reconcile their keys. One simple way of key reconciliation is forward key reconciliation, whose goal is for Alice to keep the same key \(x\) and Bob to change his key from \(y\) to \(x\). Forward key reconciliation can be done by either standard error correcting codes such as low-density-parity-check (LDPC) codes or specialized (one-way or interactive) protocols such as Cascade protocol \[27\].

3. Privacy amplification

To remove any residual information Eve may have about the key, Alice and Bob may apply some algorithm to compress their partially secure key into a shorter one that is almost perfectly secure. This is called privacy amplification. Random hashing and a class of two-universal hash functions are often suitable for privacy amplification. See for example \[28\] and \[17\] for discussion.

D. Composability

A key generated in QKD is seldom used in isolation. Indeed, one may concatenate a QKD process many times, using a small part of the key for authentication each time and the remaining key for other purposes such as encryption. It is important to show that using QKD as a sub-routine in a complicated cryptographic process does not create new security problems. This issue is called the composability of QKD and, fortunately, has been solved in \[29\].

Composability of QKD is not only of academic interest. It allows us to refine our definition of security \[29, 30\] and directly impacts on the parameters used in the classical post-processing protocol.
E. Security proofs of practical QKD systems

As will be discussed in Section IV, practical QKD systems suffer from real-life imperfections. Proving the security of QKD with practical systems is a hard problem. Fortunately, this has been done with semi-realistic models by Inamori, Lütkenhaus and Mayers [31] and in a more general setting by Gottesman, Lo, Lütkenhaus, and Preskill [32].

IV. EXPERIMENTAL FUNDAMENTALS

Quantum cryptography can ensure the secure communication between two or more legitimate parties. It is more than a beautiful idea. Conceptually, it is of great importance in the understandings of both information and quantum mechanics. Practically, it can provide an ultimate solution for confidential communications, thus making everyone’s life easier.

By implementing the quantum crypto-system in the real life, we can test it, analyze it, understand it, verify it, and even try to break it. Experimental quantum key distribution (QKD) has been performed since about 1989 and great progress has been made. Now, you can even buy QKD systems on the market.

A typical QKD set-up includes of three standard parts: the source (Alice), the channel, and the detection system (Bob).

A. A brief history

1. The first experiment

The proposal of BB84 protocol seemed to be simple. However, it took another five years before it was first experimentally demonstrated by Bennett, Bessette, Brassard, Salvail, and Smolin in 1989 [33]. This first demonstration was based on polarization coding. Heavily attenuated laser pulses instead of single photons were used as quantum signals, which were transmitted over 30cm open air at a repetition rate of 10Hz.

2. From centimeter to kilometer

30cm is not that appealing for practical communications. This short distance is largely due to the difficulty of optical alignment in free space. Switching the channel from open air to optical
fiber is a natural choice. In 1993, Townsend, Rarity, and Tapster demonstrated the feasibility of phase-coding fiber-based QKD over 10km telecom fiber and Muller, Breguet, and Gisin demonstrated the feasibility of polarization-coding fiber-based QKD over 1.1km telecom fiber. (Also, Jacobs and Franson demonstrated both free-space and fiber-based QKD.) These are both feasibility demonstrations by means that neither of them applied random basis choosing at Bob’s side. Townsend’s demonstration seemed to be more promising than Muller’s due to the following reasons.

1. The polarization dispersion in fibers is highly unpredictable and unstable. Therefore polarization coding requires much more controlling in the fiber than phase coding. In fiber-based QKD implementations, phase coding is in general more preferred than polarization coding.

2. Townsend et al. used 1310ns laser as the source, while Muller et al. used 800ns laser as the source. 1310nm is the second window wavelength of telecom fibers (the first window wavelength is 1550nm). The absorption coefficient of standard telecom fiber at 1310nm is 0.35dB/km, comparing to 3dB/km at 800nm. Therefore the fiber is more transparent to Townsend et al.’s set-up.

P. D. Townsend demonstrated QKD with Bob’s random basis selection in 1994. It was phase-coding and was over 10km fiber. The source repetition rate was 105MHz (which is quite high even by today’s standard) but the phase modulation rate was 1.05MHz. This mismatch brought a question mark on its security.

3. Getting out of the lab

It is crucial to test QKD technique in the field deployed fiber. Muller, Zbinden, and Gisin successfully demonstrated the first QKD experiment outside the labs with polarization coding in 1995. This demonstration was performed over 23km installed optical fiber under Lake Geneva. (Being under water, quantum communication in the optical fiber suffered less noise.)

There is less control over the field deployed fiber than fiber in the labs. Therefore its stabilization becomes challenging. To solve this problem, A. Muller et al. designed the “plug & play” structure in 1997. A first experiment of this scheme was demonstrated by H. Zbinden et al. in the same year. Stucki, Gisin, Guinnard, Robordy, and Zbinden later demonstrated a simplified version of the “plug & play” scheme under Lake Geneva over 67 km telecom fiber in 2002.
4. With a coherent laser source

The original BB84 proposal required a single photon source. However, most QKD implementations are based on faint lasers due to the great challenge to build the perfect single photon sources. In 2000, the security of coherent laser based QKD systems was analyzed first against individual attacks in 2000. Finally, the unconditional security of coherent laser based QKD systems was proven in 2001 and in a more general setting in 2002. Gobby, Yuan, and Shields demonstrated an experiment based on in 2005 (Note that this work was claimed to be unconditionally secure. However, due to the limit of this work, this is only true against individual attacks rather than the most general attack).

The security analysis in will severely limit the performance of unconditionally secure QKD systems. Fortunately, since 2003 the decoy state method has been proposed by Hwang and extensively analyzed by our group at the University of Toronto and by Wang. The first experimental demonstration of decoy state QKD was reported by us in 2006 over 15 km telecom fiber and later over 60 km telecom fiber. Subsequently, decoy state QKD was further demonstrated by several other groups. The readers may refer to Section VI B for details of decoy state protocols.

B. Sources

Single Photon Sources are demanded by the original BB84 proposal. Suggested by its name, the single photon sources are expected to generate exactly one photon on demand. The bottom line for a single photon source is that no more than one photon can be generated at one time. It is very hard to build a perfect single photon source (i.e., no multi-photon production). Despite tremendous effort made by many groups, perfect single photon source is still far from practical. Fortunately, the proposal and implementation of decoy state QKD (see Section VI B) make it unnecessary to use single photon sources in QKD.

Parametric Down-conversion (PDC) Sources are often used as the entanglement source. Its principle is that a high energy (∼400nm) photon propagates through a highly non-linear crystal (usually BBO), producing two entangled photons with frequency halved. PDC sources are usually used for entanglement-based QKD systems (e.g., Ekert91 protocol).

PDC sources are also used as “triggered single photon sources”, in which Alice possesses a PDC source and monitor one arm of its outputs. In case that Alice sees a detection, she
knows that there is one photon emitted from the other arm. Experimental demonstration of QKD with PDC sources is reported in [59].

**Attenuated Laser Sources** are the most commonly used sources in QKD experiments. They are essentially the same as the laser sources used in classical optical communication except for that heavy attenuation is applied on them. They are simple and reliable, and they can reach Gigahertz with little challenge. In BB84 system and differential-phase-shift-keying (DPSK) system (to be discussed in Subsection VI E), the laser source is usually attenuated to below 1 photon per pulse. In Gaussian-modulated coherent-state (GMCS) system (to be discussed in Subsection VI D), the laser source is usually attenuated to around 100 photons per pulse.

Attenuated laser sources used to be considered to be non-ideal for BB84 systems as they always have non-negligible probability of emitting multi-photon pulses regardless how heavily they are attenuated. However, the discovery and implementation of decoy method [46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57] made coherent laser source much more appealing. With decoy method, it is possible to make BB84 system with laser source secure without significant losses on the performance.

C. Channels

**Standard Optical Single-Mode Fiber (SMF)** is the most popular choice for now. It can connect two arbitrary points, and can easily be extended to networks. Moreover, it is deployed in most developed urban areas.

SMF has two “window wavelengths”: one is 1310nm and the other is 1550nm. The absorptions at these two wavelengths are particularly low (∼ 0.35dB/km at 1310nm, and ∼ 0.21dB/km at 1550nm). Nowadays most fiber-based QKD implementations use 1550nm photons as information carriers.

The main disadvantage of optical fiber is its birefringence. The strong polarization dispersion made it hard to implement polarization-coding system. Also it has strong spectral dispersion, which affects the high speed (10+ GHz) QKD systems heavily as the pulses are broadened and overlap with each other. For this reason, the loss in fibers (0.21dB/km at 1550nm) puts an limit on the longest distance that a fiber-based QKD system can reach.
**Free Space** is receiving more and more attention recently. It is ideal for the polarization coding. There is negligible dispersion on the polarization and the frequency. However, the alignment of optical beams can be challenging for long distances, particularly due to the atmospheric turbulence. Notice that open-air QKD requires a direct line of sight between Alice and Bob (unless some forms of mirrors are used). Buildings and mountains are serious obstacles for open-air QKD systems.

The greatest motivation for open-air QKD scheme is the hope for ground-to-satellite [61] and satellite-to-satellite quantum communication. As there is negligible optical absorption in the outer space, we may be able to achieve inter-continental quantum communication with free-space QKD.

### D. Detection systems

**InGaAs-APD Single Photon Detectors** are the most popular type of single-photon detectors in fiber-based QKD and they are commercially available. InGaAs-APD Single Photon Detectors utilize the avalanche effect of semiconductor diodes. A strong biased voltage is applied on the InGaAs diode. The incident photon will trigger the avalanche effect, generating a detectable voltage pulse. The narrow band gap of InGaAs made it possible to detect photons at telecom wavelengths (1550nm or 1310 nm).

InGaAs APD based single photon detectors have simple structure and commercially packaged. They are easy to calibrate and operate. The reliability of InGaAs APD is relatively high. They normally work at −50°C to −110°C to lower the dark count rate. This temperature can be easily achieved by thermal-electric coolers. The detection efficiency of InGaAs-APD based single photon detectors is usually $\sim 10\%$ [62].

In single photon detectors, a key parameter (besides detection efficiency) is the dark count rate. The dark count is the event that the detector generates a detection click while no actual photon hits it (i.e. “false alarm”). The dark count rate of InGaAs single photon detector is relatively high (10⁻⁵ per gate. The concept of gating will be introduced below.) even if it is cooled.

The after-pulse effect is that the dark count rate of the detector increases for a time period after a successful detection. This effect is serious for InGaAs single photon detectors. Therefore the blank circuit is often introduced to reduce this effect. The mechanism of the
blank circuit is that the detector is set to be deactivated for a time period, which is called the “dead time”, after a detection event. The dead time should be set to long enough so that when the detector is re-activated, the after-pulse effect is negligible. The dead time for InGaAs single photon detector is typically in the order of microseconds \[62\]. The long after pulse effect, together with the large timing jitter limits the InGaAs-APD based single photon detectors to work no faster than several megahertz. Moreover, the blank circuit reduces the detection efficiency of InGaAs-APD based single photon detectors.

An additional method to reduce the dark count rate is to apply the gating mode. i.e., the detectors are only activated when the photons are expected to hit them. Gating mode reduces the dark count rate by several orders and is thus used in most InGaAs-APD single photon detectors. However, it may open up a security loophole \[63, 64\].

There is a trade-off between the detection efficiency and the dark count rate. As the biased voltage on an APD increases, both the detection efficiency and the dark count rate increase. Recently, it has been reported that, by gating an InGaAs detector in a sinusoidal manner, it is possible to reduce the dead time and operate a QKD system at 500MHz. See \[65\]. This result seems to be an important development which could make InGaAs detectors competitive with newer single photon detector technologies such as SSPDs (to be introduced below).

**Si-APD Single Photon Detectors** are ideal for detection of visible photons (say 800nm). They have negligible dark count rate and can work at room temperature. They are very compact in size. More importantly, they have high detection efficiency (> 60%) and can work at gigahertz. These detectors are ideal for free space QKD systems. However, the band gap of silicon is too large to detect photons at telecom wavelength (1550nm or 1310nm), and the strong attenuation of telecom fiber on visible wavelengths makes it impractical to use visible photons in long distance fiber-based QKD systems.

**Parametric Up-conversion Single Photon Detectors** try to use Si-APD to detect telecom wavelength photons. It uses periodically poled lithium niobate (PPLN) waveguide and a pumping light to up-convert the incoming telecom frequency photons into visible frequency, and uses Si-APD to detect these visible photons. The high speed and low timing-jitter of Si-APDs make it possible to perform GHz QKD on fiber-based system with up-conversion single photon detectors \[66, 67\].
The efficiency of up-conversion detectors is similar to that of InGaAs APD single photon detectors. There is also a trade-off between the detection efficiency and the dark count rate. When increasing the power of the pumping light, the conversion efficiency will increase, improving the detection efficiency. Meanwhile, more pumping photons and up-converted pumping photons (with frequency doubled) will pass through the filter and enter the Si-APD, thus increasing the dark count rate [67].

Transiting-edge Sensor (TES) is based on critical state superconductor rather than semiconductor APDs. It uses squared superconductor (typically tungsten) thin film as “calorimeter” to measure the electron temperature. A biased voltage is applied on the thin film to keep it in critical state. Once one or more photons are absorbed by the sensor, the electron temperature will change, leading to a change of the current. This current change can be detected by a superconductive quantum-interference device (SQUID) array [68].

The TES single photon detectors can achieve very high detection efficiency (up to 89%) at telecom wavelength. The dark count rate is negligible. Moreover, TES detectors can resolve photon numbers. This is because the electron temperature change is proportional to the number of photons that have been absorbed.

The thermal nature of TES detectors limits their counting rates. Once some photons were absorbed by the sensor, it would take a few microseconds before the heat is dissipated to the substrate. This long relaxation time limits the counting rate of TES detector to no more than a few megahertz [68]. This is a major drawback of TES.

The bandwidth of TES detector is extremely wide. The detector is sensitive to all the wavelengths. Even the black body radiation from the fiber or the environment can trigger the detection event, thus increasing the dark count rate. To reduce the dark counts caused by other wavelengths, a spectral filter is necessary. However, this will increase the internal loss and thus reduce the detection efficiency.

One of the greatest disadvantage of TES detector is its working temperature: 100mK. This temperature probably requires complicated cooling devices [68].

Superconductive Single Photon Detectors (SSPDs) also use superconductor thin film to detect incoming photons. However, instead of using a piece of plain thin film, a pattern of zigzag superconductor (typically NbN) wire is formed. The superconductive wire is set to critical state by applying critical current through it. Once a photon hits the wire, it heats
a spot on the wire and makes the spot over-critical (i.e., non-superconductive.). As the current is the same as before, the current density in the areas around this hot-spot increases, thus making these areas non-superconductive. As a result, a section of the wire becomes non-superconductive, and a voltage spike can be observed as the current is kept constant.

The SSPD can achieve very high (up to 10GHz) counting rate. This is because the superconductor wire used in SSPD can dissipate the heat in tens of picoseconds. It also has very low dark count rate (around 10Hz) due to the superconductive nature. The SSPDs should be able to resolve the incident photon number in principle. However, photon number resolving SSPDs have never been reported yet.

The efficiency of SSPD is lower than that of TES. This is because only part (∼50%) of the sensing area is covered by the wire. The fabrication of such complicated zigzag superconductor wire with smooth edge is also very challenging.

The working temperature of SSPD (∼3K) is significantly higher than that of TES. SSPDs can work in closed-cycle refrigerator. Moreover, this relatively high working temperature significantly reduces the relaxation time.

Homodyne Detectors are used to count the photon number of a very weak pulse (∼100 photons). The principle is to use a very strong pulse (often called the local oscillator) to interfere with the weak pulse. Then use two photo diodes to convert the two resulting optical pulses into electrical signals, and make a substraction between the two electrical signals.

The homodyne detectors are in general very efficient as there is always some detection result given some inputting signals. However, the noise of the detectors as well as in the electronics is very significant. Moreover, the two photo diodes in the homodyne detector have to be identical, which is hard to meet in practice.

The homodyne detectors are commonly used in GMCS QKD systems, and they are so far the only choice for GMCS QKD systems. Recently, homodyne detectors have also been used to implement the BB84 protocol.

E. Truly quantum random number generators

An important but often under-appreciated requirement for QKD is a high data-rate truly quantum random number generator (RNG). An RNG is needed because most QKD protocols (with...
the exception of a passive choice of bases in an entanglement-based QKD protocol) require Alice to choose actively random bases/signals. Given the high repetition rate of QKD, such a RNG must have a high data-rate. To achieve unconditional security, a standard software-based pseudo-random number generator cannot be used because it is actually deterministic. So, a high data rate quantum RNG is a natural choice. Incidentally, some firms such id Quantique do offer commercial quantum RNGs. Unfortunately, it is very hard to generate RNG by quantum means at high-speed. In practice, some imperfections/bias in the numbers generated by a quantum RNG are inevitable. The theoretical foundation of QKD is at risk because existing security proofs all assume the existence of perfect RNGs and do not apply to imperfect RNGs.

V. EXPERIMENTAL IMPLEMENTATION OF BB84 PROTOCOL

In this section, we will focus mainly on the optical layer. We will skip several important layers. In practice, the control/electronics layer is equally important. Moreover, it is extremely challenging to implement the classical post-processing layer in real-time, if one chooses block sizes of codes to be long enough to achieve unconditional security.

A. Optical Layer: Polarization Coding

Polarization coding usually uses four laser sources generating the four polarization states of BB84 protocol. A conceptual schematic is shown in Figure 3. Note that due to polarization dispersion of fiber, usually people need some compensating like the waveplates.

The polarization compensation should be implemented dynamically as the polarization dispersion in the fiber changes frequently. This is solved by introducing the electrical polarization controller in [57].
B. Optical Layer: Phase Coding

Original Scheme is basically a big interferometer as shown in Figure 2. However it is not practical as the stability of such a huge interferometer is extremely poor.

Double Mach-Zehnder Interferometer Scheme is an improved version of the original proposal. It has two interferometers and there is only one channel connecting Alice and Bob (comparing to the two channels in the original proposal). A conceptual set-up is shown in Figure 4. We can see that the two signals travel through the same channel. They only propagate through different paths locally in the two Mach-Zehnder interferometers. Therefore people only need to compensate the phase drift of the local interferometers (the polarization drift in the channel still needs to be compensated). This is a great improvement over the original proposal. However, the local compensation has to be implemented in real time. This is quite challenging. An example set-up that implemented the real time compensation of both polarization and phase drifting is reported in [69].

Faraday-Michelson Scheme is an improved version of the double Mach-Zehnder interferometer scheme. It still has two Mach-Zehnder interferometers but each interferometer has only one beam splitter. The light propagates through the same section of fiber twice due to the Faraday mirror. The schematic is shown in Figure 5. We can see that the polarization drift is self-compensated. This is a great advance in uni-directional QKD implementation and is
First proposed and implemented in [70]. Nonetheless, the phase drift of local interferometers still needs compensation. Due to the fast fluctuation of phase drift (a drift of $2\pi$ usually takes a few seconds), this compensation should be done in real-time. A Faraday-Michelson decoy state QKD implementation over 123.6km has been reported in [58].

**Plug & Play Scheme** is another improved version of the double Mach-Zehnder interferometer scheme. It has only one Mach-Zehnder interferometer and the light propagates through the same channel and interferometer twice due to the faraday mirror on Alice’s side. A conceptual set-up is shown in Figure 6. We can see that both the polarization drift and the phase drift are automatically compensated. A ‘Plug & Play” scheme based decoy state QKD implementation over 60km has been reported in [53]. Nonetheless, the bi-directional design brings complications to security as Eve can make sophisticated operations on the bright pulses sent from Bob to Alice. This is often called the “Trojan horse” attack [71]. Recently, the security of ”Plug and Play” QKD system has been proven in [72].

**Sagnac Loop Scheme.** Another bi-directional optical layer design is to use a Sagnac loop where
the quantum signal is encoded in the relative phase between the clockwise and counterclockwise pulses that go through the loop. The typical schematic is shown in Figure 7.

Sagnac loop QKD is simple to set up and can be easily used in a network setting with a loop topology. However, its security analysis is highly non-trivial.

VI. OTHER QUANTUM KEY DISTRIBUTION PROTOCOLS

Given the popularity of the BB84 protocol, why should people be interested in other protocols? There are at least three answers to this question. First, to better understand the foundations of QKD and its generality, it is useful to have more than one protocol. Second, different QKD protocols may have advantages and disadvantages. They may require different technologies to implement. Having different protocols allow us to compare and contrast them. Third, while it is possible to implement standard BB84 protocol with attenuated laser pulses, its performance in terms of key generation rate and distance is somewhat limited. Therefore, we have to study other protocols. Since, from a practical standpoint, the third reason is the most important one. We will elaborate on it in the following paragraph.

The original BB84 [1] proposal requires a single photon source. However, most QKD implementations are based on faint lasers due to the great challenge to build perfect single photon sources. Faint laser pulses are weak coherent states that follow Poisson distribution for the photon number. The existence of multi-photon signals opens up new attacks such as photon-number-splitting attack. The basic idea of a photon-number-splitting attack is that Eve can introduce a photon-number-dependent transmittance. In other words, she can selectively suppress single-photon signals and transmit multi-photon signals to Bob. Notice that, for each multi-photon signal, Eve can beamsplit it and keep one copy for herself, thus allowing her to gain a lot of information about the raw key.

The security of coherent laser based QKD systems was analyzed first against individual attacks in 2000 [44], then eventually for a general attack in 2001 [31] and 2002 [32]. Unfortunately, unconditionally secure QKD based on conventional BB84 protocol [31, 32] will severely limit the performance of QKD systems. Basically, Alice has to attenuate her source so that the expected number \( \mu \) of photon is of the same order as the transmittance, \( \eta \). As a result, the key generation rate will scale only quadratically with the transmittance of the channel.

Some of the protocols discussed in the following subsections may dramatically improve the performance of QKD over standard BB84 protocol. For instance, the decoy state protocol has been proven to provide a key generation rate that scales linearly with the transmittance of the
channel and has been successfully implemented in experiments.

We conclude with some simple alternative QKD protocols. In 1992, Bennett proposed a protocol (B92) that makes use of only two non-orthogonal states \(2\). A six-state QKD protocol was first noted by Bennett and co-workers \(73\) and some years later by Bruss \(74\). It has an advantage of being symmetric. Even QKD protocols with orthogonal states have been proposed \(75\). Efficient BB84 and six-state QKD protocols have been proposed and proven to be secure by Lo, Chau and Ardehali \(76\). A Singaporean protocol has also been proposed. Recently, Gisin and co-workers proposed a one-way coherent QKD scheme \(77\).

A. Entanglement-based Protocols

1. Proposals

In 1991, Ekert proposed the first entanglement based QKD protocol, commonly called E91 \(3\). The basic idea is to test the security of QKD by using the violation of Bell’s inequality. Note that one can also implement the BB84 protocol by using an entanglement source. Imagine Eve prepares an entangled state of a pair of qubits and sends one qubit to Alice and the second qubit to Bob. Each of Alice and Bob randomly chooses one of the two conjugate bases to perform a measurement.

2. Implementations

The key part of entanglement-based quantum cryptography is to distribute an entangled pair (usually EPR pair) to two distant parties, Alice and Bob.

Polarization entanglement is preferred in QKD as it is easy to measure the polarization (typically via polarizing beam splitter). The air has negligible birefringence and thus is the perfect channel for polarization-entanglement QKD.

In free-space QKD, atomspherical turbulence may shift the light beam. Therefore the collection of incident photon is challenging. Usually large diameter optical telescope is needed to increase the collection efficiency.

A standard approach is to put the entanglement source right in the middle of Alice and Bob. See Figure \(8\). Once an entangled pair is generated, the two particles are directed to different destinations. Alice and Bob measure the particles locally, and keep the result as the bit value. This approach has potential in the ground-satellite intercontinental entanglement distribution, in which the entanglement source is carried by the satellite and the entangled photons are sent to two distant
ground stations. A recent source-in-the-middle entanglement-based quantum communication work over 13km and is reported in [78].

A simpler version is to include the entanglement source in Alice’s side locally. See Figure 9. Once Alice generates an entangled pair, she keeps one particle and send the other to Bob. Both Alice and Bob measure the particle locally and keep the result as the bit value. This approach is significant simpler than the above design because only Bob needs the telescope and compensating parts. A recent experiment of source-in-Alice entanglement-based quantum communication over 144km open air is reported in [79].

B. Decoy State Protocols

1. Proposals

Recall that BB84 implemented with weak coherent state has a key generation rate that scales only quadratically with the transmittance. The decoy state protocol can dramatically increase the key generation rate so that it scales linearly with the transmittance. In a decoy state protocol,
Alice prepares some decoy states in addition to signal states. The decoy states are the same as the signal state, except for the expected photon number. For instance, if the signal state has an average photon number $\mu$ of order 1 (e.g. $0.5$), the decoy states have an average photon number $\nu_1$, $\nu_2$, etc. The decoy state idea was first proposed by Hwang\cite{46}, who suggested using a large $\nu$ (e.g. 2) as a decoy state. Our group provided a rigorous proof of security to decoy state QKD\cite{47,48}. Our numerical simulations showed clearly that decoy states provide a dramatic improvement over non-decoy protocols. In the limit of infinitely many decoy states, Alice and Bob can effectively limit Eve’s attack to a simple beam-splitting attack. Moreover, we proposed practical protocols. Instead of using a large $\nu$ as a decoy state, we proposed using small $\nu$’s as decoy states\cite{47}. For instance, we proposed using a vacuum state as the decoy state to test the background and a weak $\nu$ to test the single-photon contribution. We and Wang analyzed the performance of practical protocols in detail \cite{49,50,51}.

Notice that the decoy state is a rather general idea that can be applied to other QKD sources. For instance, decoy state protocols have recently been proposed in \cite{80,81,82} for parametric down conversion sources. For a comparison of those protocols, see \cite{83}.

2. Implementations

The first experimental demonstration of decoy state QKD was reported by our group in 2006 first over 15 km telecom \cite{52} fiber and later over 60 km telecom fiber \cite{53}. Subsequently, the decoy state QKD was further demonstrated experimentally by several groups worldwide \cite{54,55,56,57}.

The implementation of decoy state QKD is straightforward. The key part is to prepare signals with different intensities. A simple solution is to use an amplitude modulator to modulate the intensities of each signal to the desired level. See Figure \ref{fig:11}. Decoy state QKD implementations using amplitude modulator to prepare different states are reported in \cite{52,53,54,55,56}.
The amplitude modulator has the disadvantage that the preparation of vacuum state is quite challenging. An alternative solution is to use laser diodes of different intensities to generate different states. This solution requires multiple laser diodes and high-speed optical switch, and is thus more complicated than the amplitude modulator solution. Nonetheless, perfect vacuum states can be easily prepared in this way. Decoy state QKD implementations using multiple laser diodes are reported in [57, 58]. Decoy state with a parametric down conversion source has been experimentally implemented in [84].

C. Strong Reference Pulse Protocols

1. Proposals

The proposal of strong reference pulse QKD dated back to Bennett’s 1992 paper [2]. The idea is to add a strong reference pulse, in addition to the signal pulse. The quantum state is encoded in the relative pulse between the reference pulse and the signal pulse. Bob decodes by splitting a part of the strong reference pulse and interfering it with the signal pulse. The strong reference pulse implementation can counter the photon number splitting attack by Eve because it removes the neutral signal in the QKD system. Recall that in the photon number splitting attack, Eve suppresses single photon signals by sending a vacuum. This works because the vacuum is a neutral signal that leads to no detection. In contrast, in a strong reference pulse implementation of QKD, a vacuum signal is not a neutral signal. Indeed, if Eve replaces the signal pulse by a vacuum and keeps the strong reference pulse unchanged, then the interference experiment by Bob will give non-zero detection probability and a random outcome of ”0” or ”1”. On the other hand, if Eve removes both the signal and the reference pulses, then Bob may detect Eve’s attack by monitoring
the intensity of the reference pulse, which is supposed to be strong.

In some recent papers, the unconditional security of B92 QKD with strong reference pulse has been rigorously proven. However, those proofs require Bob’s system to have certain properties and do not apply to standard threshold detectors.

2. Implementations

The B92 protocol is simpler to implement than BB84 protocol. However, its weakness in security limits people’s interest on its implementation. A recent implementation of B92 protocol over 200m fiber is reported in [85].

D. Gaussian-modulated Coherent State (GMCS) Protocol

1. Proposals

Instead of using discrete qubit states as in the BB84 protocol, one may also use continuous variables for QKD. Early proposals of continuous variables QKD use squeezed states, which are experimentally challenging. More recently, gaussian-modulated coherent states have also been proposed for QKD. Since a laser naturally emits a coherent state, compared to a squeezed state QKD proposal, a GMCS QKD protocol is experimentally more feasible. In GMCS QKD, Alice sends Bob a sequence of coherent state signals. For each signal, Alice draws two random numbers $X_A$ and $P_A$ from a set of Gaussian random number with a mean of zero and a variance of $V_A N_0$ and sends a coherent state $|X_A + iP_A\rangle$ to Bob. Bob randomly chooses to measure either the $X$ quadrature of the $P$ quadrature with a phase modulator and a homodyne detector. After performing his measurement, Bob informs Alice which quadrature he has performed for each pulse, through an authenticated public classical channel. Alice drops the irrelevant data and keeps only
the quadrature that Bob has measured. Alice and Bob now share a set of correlated Gaussian variables which they regard as the raw key. Alice and Bob randomly select a subset of their signals and publicly broadcast their data to evaluate the excess noise and the transmission efficiency of the quantum channel. If the excess noise is higher than some prescribed level, they abort. Otherwise, Alice and Bob perform key generation by some prescribed protocol.

An advantage of a GMCS QKD is that every signal can be used to generate a key, whereas in qubit-based QKD such as the BB84 protocol losses can substantially reduce the key generation rate. Therefore, it is commonly believed that for short-distance (say < 15 km) applications, GMCS QKD may give a higher key generation rate.

GMCS QKD has been proven to be secure only against individual attacks. The security of GMCS QKD against the most general type of attack—joint attack—remains an open question.

### 2. Implementations

GMCS protocol has significant advantage over the BB84 protocol at short distances. It was first implemented by F. Grosshans et al. in 2003. It was shown to be working with channel loss up to 3.1dB, which is equivalent to the loss of 15km telecom fiber. Nonetheless, the strong spectral and polarization dispersion of telecom fiber made it challenging to build up a fiber-based GMCS system. Lodewyck, Debuisschert, Tualle-Brouri, and Grangier built the first fiber-based GMCS system in 2005 but only over a few meters. This distance was largely extended to 14km by Legré, Zbinden, and Gisin in 2006 with the introduction of the “plug & play” design, which brought questions on its security. The uni-directional GMCS QKD has been later implemented over 5km optical fiber by Qi, Huang, Qian, and Lo in 2007 and over 25km optical fiber by J. Lodewyck et al. in 2007.

GMCS QKD requires dual-encoding on both amplitude quadrature and phase quadrature, and homodyne detection for decoding. See Figure 12. Its implementation is in general more challenging than that of BB84 protocol.

### E. Differential-phase-shift-keying (DPSK) Protocols

#### 1. Proposals

In DPSK protocol, a sequence of weak coherent state pulses is sent from Alice to Bob. The key bit is encoded in the relative phase of the adjacent pulses. Therefore, each pulse belongs
FIG. 13: Conceptual schematic for differential phase shift keying QKD system. PM: Phase Modulator; BS: Beam Splitter; SPD: Single Photon Detector.

to two signals. DPSK protocol also defeats the photon number splitting attack by removing the neutral signal. Eve may attack a finite train of signals by measuring its total photon number and then splitting off one photon, whenever the photon number is larger than one. But, since each pulse belongs to two signals, the pulses in the boundary of the train will interfere with the pulses immediately outside the boundary. Therefore, Eve’s attack does not allow her to gain full information about all the bit values associated with the train. Moreover, by splitting the signal, Eve has reduced the amplitude of the pulses at the boundary of the train. Therefore, Bob will detect Eve’s presence by the higher bit error rates for the bit values between the pulses at the boundary and those just outside the boundary.

While DPSK protocol is simpler to implement than BB84, a proof of its unconditional security is still missing. Therefore, it is hard to quantify its secure key generation rate and perform a fair comparison with, for example, decoy state BB84 protocol. Attacks against DPSK has been studied in, for example, [91, 92].

2. Implementations

DPSK protocol is simpler in hardware design than the BB84 protocol as it requires only one Mach-Zehnder interferometer. See Figure 13. It also has the potential in high-speed applications. Honjo, Inoue, and Takahashi experimentally demonstrated this protocol with a planar light-wave circuit over 20km fiber in 2004 [93]. This distance was soon extended to 105km [94] in 2005. In 2007, DPSK scored both the longest and the fastest records in QKD implementations: H. Takesue et al. reported an experimental demonstration of DPSK-QKD over 200km optical fiber at 10GHz [60]. However, since a proof of unconditional security is still missing (see last two paragraphs), it is unclear whether the existing experiments generate any secure key. Indeed, the attacks described in [91, 92] showed that with only one-way classical post-processing, all existing DPSK experiments
are insecure.

VII. QUANTUM HACKING

Since practical QKD systems exist and commercial QKD systems are on the market, it is important to understand how secure they really are. We remark that there is still a big gap between the theory and practice of QKD. Even though the unconditional security of practical QKD systems with semi-realistic models have been proven [31, 32], practical QKD systems may still contain fatal security loopholes. From a historical standpoint, Bennett and Brassard mentioned that the first QKD system [33] was unconditionally secure to any eavesdropper who happened to be deaf! This was because the system made different sounds depending on whether the source was sending a “0” or a “1”. Just by listening the sounds, an eavesdropper can learn the value of the final key. This example highlights the existence of side channels in QKD and how easy an eavesdropper might be able to break the security of a QKD system, despite the existence of security proofs.

In this section, we will sketch a few cleverly proposed quantum hacking strategies that are outside standard security proofs and their experimental implementations. We will conclude countermeasures and future outlook. Notice that we will skip eavesdropping attacks that have already been covered by standard security proofs.

A. Attacks

1) Large Pulse Attack. In a large pulse attack, Eve sends in a strong pulse of laser signal to, for example, Alice laboratory to try to read off Alice’s phase modulator setting from a reflected pulse. See Ref. [95]. As a result, Eve may learn which BB84 state Alice is sending to Bob.

A simple counter-measure to the large pulse attack is to install an isolator in Alice’s system.

2) Faked State Attack. Standard InGaAs detectors suffer from detection efficiency mismatch. More concretely, as noted in Section [IV.D] InGaAs detectors are often operated in a gated mode. Therefore, the detection efficiency of each detector is time-dependent. Refer to Figure [14] for a schematic diagram of the detection efficiencies of two detectors (one for “0” and one for “1”) as functions of time. At the expected arrival time, the detection efficiency of the two detectors are similar. However, if the signal is chosen to arrive at some unexpected times, it is possible that the detector efficiencies of the two detectors differ greatly.

The faked state attack proposed by Makarov and co-workers [96] is an intercept-resend attack.
In a faked state attack, for each signal, Eve randomly chooses one of the two BB84 bases to perform a measurement. Eve then sends to Bob a wrong bit in the wrong basis at a time when the detector for the wrong bit has a low detection efficiency. For instance, if Eve has chosen the rectilinear basis and has found a "0" in the bit value, she then prepares a state "1" in the diagonal basis and sends it to Bob at the arrival time where detector efficiency of the detector for "0" is much higher than that of detector for "1".

Now, should Eve have chosen the wrong basis in her measurement, notice that the detection probability by Bob is greatly suppressed. For instance, in our example, if the correct basis is the diagonal basis, let us consider when happens when Bob measures the signal in the correct basis. Since the bit value resent by Eve is "1" in the diagonal basis and Bob’s detector for "1" has a low detection efficiency, most likely Bob will not detect any signal. On the other hand, should Eve have chosen the correct basis in her measurement, Bob has a significant detection efficiency. For instance, in our example, if the correct basis is in fact the rectilinear basis, let us consider what happens when Bob measures in the correct basis. In this case, a bit "1" in the diagonal basis sent by Eve can be re-written as a superposition of a bit "0" and a bit "1" in the rectilinear basis. Since the detector for "0" has a much higher detection efficiency than the detector for "1", most likely Bob will detect a "0". Since "0" was exactly what was originally sent by Alice, Bob will find a rather low bit error rate, despite Eve’s intercept-resend attack.

The faked state attack, while conceptually interesting, is hard to implement in practice. 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. For this reason, the faked state attack has never been implemented in practice.

3) Time-shift Attack. The time-shift attack was proposed by Qi, Fung, Lo, and Ma[97]. It
also utilizes the detection efficiency mismatch in the time domain, but is much easier to implement than the faked states attack.

As we mentioned in the above section, typical InGaAs-APD detectors usually operate in a gated mode. That is, if the photon hits the detector at an unexpected time, the two detectors may have substantially different efficiency. Therefore, Eve can simply shift the arrival time of each signal, creating large efficiency mismatch between “0”s and “1”s.

Let’s take a specific example to illustrate this attack: suppose detector 0 has higher efficiency than detector 1 if the signal arrives earlier than the expected time, and lower efficiency than detector 1 if the signal arrives later than expected. Eve can simply shift the arrival time of each bit by sending it through a longer path or a shorter one. Consider the case in which Eve sends bit $i$ through a shorter path. In this case bit $i$ will hit the detector earlier than expected, thus detector 0 has much higher efficiency. If Bob reports a detection event for the $i$th bit, Eve can make a guess that this bit is a “0” with high probability of success.

Furthermore, Eve can carefully set how many bits should be shifted forward and how many should be shifted backward so that Bob gets similar counts of “0”s and “1”s. In this way, Bob cannot observe a mismatch between the numbers of “0”s and “1”s.

Note that the time-shift attack does not make any measurement on the qubits. Therefore, quantum information is not destroyed. That is, Eve does not change the polarization, the phase, or the frequency of any bit. This means the time-shift attack will not increase the bit error rate of the system in principle. Moreover, since Eve does not need to make any measurement or state preparation, the time-shift attack is practically feasible even with current technology.

The time-shift attack will introduce some loss as the overall detection efficiency is lower if the photon hits the detector at an unexpected time. Nonetheless, Eve can compensate this loss by making the channel more transparent. Notice that, since the quantum channel between Alice and Bob may contain many lossy components such as splices and couplers, it may not be too hard for Eve to make a channel more transparent.

The time-shift attack has been successfully implemented on a commercial QKD system by Zhao, Fung, Qi, Chen, and Lo [98] in 2007. This is the first and so far the only experimentally successful demonstration of quantum hacking on commercial QKD system. It is shown that the system has no-negligible probability to be vulnerable to the time-shift attack. Quantitative analysis shows that the final key shared by Alice and Bob (after the error correction and the privacy amplification of the most general security analysis) has been compromised by Eve.

The success of the time-shift attack in [98] is rather surprising as QKD has been widely believed
to be unconditionally secure. The experimental success in quantum hacking highlighted the limit of the whole research program of device-independent security proofs \[22\] by showing that device-independent security proofs, even if they are found to exist in future, do not apply to a practical QKD system. The success of time-shift attack is not due to some technical imperfection. It is deeply connected with the detection efficiency loophole in the verification of Bell-inequalities. So far the InGaAs detectors have only \( \sim 10\% \) detection efficiencies, and the channel connecting Alice and Bob usually has quite large attenuation for long distance communication. The low overall detection efficiency fails the device-independent security proof.

Notice that even non-gated detectors have dead times and generally suffer from detection efficiency loophole. The detection efficiency mismatch is also discussed in \[99\].

4) Phase remapping attack. In a bi-directional implementation of QKD such as the "Plug and Play" set-up, Eve may attempt to tamper with Alice’s preparation process so that Alice prepares four wrong states, instead of the four standard BB84 state. This is called the phase remapping attack and was proposed in \[100\].

In a "Plug and Play" QKD system, Alice receives a strong pulse from Bob and she then attenuates it to a single-photon level and encodes one of the BB84 state on it. For instance, Alice may encode her state by using a phase modulator. In a phase modulator, the encoded phase is proportional to the voltage applied. In practice, a phase modulator has a finite rise time. For each BB84 setting, one may thus model the applied voltage (and thus the encoded phase) as a trapezium. Ideally, Bob’s strong pulse should arrive at the plateau region of the phase modulation, thus getting maximal phase modulation by Alice’s phase modulator. Now, imagine that Eve applies a time-shift to Bob’s strong pulse so that it arrives in the rise region of the phase modulation graph instead of the plateau region. In this case, Alice has wrongly encoded her phase only partially.

If we assume that the four settings of Alice’s encoding (for the four BB84 states) have the same rise region, then by time-shifting Bob’s strong pulse, Eve can force Alice to prepare the four state with phase \( 0, a, 2a, 3a \), rather than \( 0, \pi/2, \pi, 3\pi/2 \). In general, these four states are more distinguishable than the standard BB84 state. Therefore, Eve may subsequently apply an intercept-resend attack to the signal sent out by Alice.

It was proven in \[100\] that in principle Eve can break the security of the QKD system, without alerting Alice and Bob.

5) Attack by passive listening to side channels. The attack by listening to the sounds made by the source in the first QKD experiment is an example of an attack by passive listening to side channels. Another example is \[101\]. A counter-measure is to carefully locate all possible side
channels and to eliminate them one by one.

6) Saturation Attack: In a recent preprint [102], Makarov studied experimentally how by sending a moderately bright pulse, Eve can blind Bob’s InGaAs detector. A simple counter-measure would be for Bob to measure the intensity of the incoming signal.

7) High Power Damage Attack: In Makarov’s thesis, it was proposed that Eve may try to make controlled changes in Alice’s and Bob’s system by using high power laser damage through sending a very strong laser pulse. Again, a simple counter-measure would be for Alice and Bob to measure the intensity of the incoming signals and monitor the properties of various components from time to time to ensure that they perform properly.

B. Counter-measures

Once an attack is known, there are often simple counter-measures. For instance, for the large pulse attack, a simple counter-measure would be to add a circulator in Alice’s laboratory. As for the faked state attack and time-shift attack, a simple counter-measure would be for Bob to use a four-state setting in his phase modulator. Other counter-measures include Bob applying a random time-shift to his received signals. However, the most dangerous attacks are the unanticipated ones.

Notice that it is not enough to say that a counter-measure to an attack exists. It is necessary to actually implement a counter-measure experimentally in order to see how effective and convenient it really is. This will allow Alice and Bob to select a useful counter-measure. Moreover, notice that the implementation of a counter-measure may itself open up new loopholes. For instance, if Bob implements a four-state setting as a counter-measure to a time-shift attack, Eve may still combine a large pulse attack with the time-shift attack to break a QKD system.

C. Importance of quantum hacking

As noted in Section III, there has been a lot of theoretical interest on the connection between the security of QKD and fundamental physical principles such as the violation of Bell’s inequality. An ultimate goal of such investigations, which has not been realized yet, is to construct a device-independent security proof [22]. Even if such a goal is achieved in future, would any of these theoretical security proofs applies to a quantum key distribution system in practice? Unfortunately, the answer is no. As is well-known, the experimental testing of Bell-inequalities often suffers from the detection efficiency loophole [22]. The low detection efficiency of practical detectors not only
nullifies security proofs based on Bell-inequality violation, but also gives an eavesdropper a powerful handle to break the security of a practical QKD system. Therefore, the detection efficiency loophole is of both theoretical and practical interest.

A practical QKD system often consists of two or more detectors. In practice, it is very hard to construct detectors of identical characteristics. As a result, two detectors can generally exhibit different detector efficiencies as functions of either one or a combination of variables in the time, frequency, polarization or spatial domains. Now, if an eavesdropper could manipulate a signal in these variables, then she could effectively exploit the detection efficiency loophole to break the security of a QKD system. In fact, she could even violate a Bell-inequality with only a classical source. In time-shift attack, one consider an eavesdropper’s manipulation of the time variable. However, the generality of detection efficiency loophole and detector efficiency mismatch should not be lost.

We should remark that, for eavesdropping attacks, the sky is the limit. The more imaginative one is, the more new attacks one comes up. Indeed, what people have done so far are just scratching the surface of the subject. Much more work needs to be done in the battle-testing of QKD systems and security proofs with testable assumptions. See Section on Future Directions.

VIII. BEYOND QUANTUM KEY DISTRIBUTION

Besides QKD, many other applications of quantum cryptography have been proposed. Consider, for instance, the millionaires’ problem. Two millionaires, Alice and Bob, would like to determine who is richer without disclosing the actual amount of money each has to each other. More generally, in a secure two-party computation, two distant parties, Alice and Bob, with private inputs, x and y respectively, would like to compute a prescribed function \( f(x, y) \) in such a way that at the end, they learn the outcome \( f(x, y) \), but nothing about the other party’s input, other than what can be logically be deduced from the value of \( f(x, y) \) and his/her input. There are many possible functions \( f(x, y) \). Instead of implementing them one by one, it is useful to construct some cryptographic primitives, which if available, can be used to implement the secure computation of any function \( f(x, y) \). In classical cryptography, to implement secure two-party computation of a general function will require making additional assumptions such as a trusted third party or computational assumptions. The question is whether we can do unconditionally secure quantum secure two-party computations.

Two important cryptographic primitives are namely quantum bit commitment (QBC) and one-
out-of-two quantum oblivious transfer (QOT). In particular, it was shown by Kilian \cite{103} that in classical cryptography, oblivious transfer can be used to implement a general two-party secure computation of any function $f(x, y)$. Moreover, in quantum cryptography, it was proven by Yao \cite{104} that a secure QBC scheme can be used to implement QOT securely. For a long time back in the early 1990’s, there was high hope that QBC and QOT could be done with unconditional security. In fact, in a paper \cite{105} it was claimed that QBC can be made unconditionally secure. The sky fell around 1996 when Mayers \cite{106} and subsequently, Lo and Chau \cite{107}, proved that, contrary to widespread belief at that time, unconditionally secure QBC is, in fact, impossible. Subsequently, Lo \cite{108} proved explicitly that unconditionally secure one-out-of-two QOT is also impossible. Mayers and Lo-Chau’s result was a big step backwards and thus a big disappointment for quantum security.

After the fall of QBC and QOT, people turned their attention to quantum coin tossing (QCT). Suppose Alice and Bob are having a divorce and they would like to determine by a coin toss who is going to keep their kid. They do not trust each other. However, they live far away from each other and have to do a coin toss remotely. How can they do so without trusting each other? Classically, coin tossing will require either a trusted third party or making computational assumptions. As shown by Lo and Chau, ideal quantum coin tossing is impossible \cite{109}. Even for the non-ideal case, Kitaev has proven that a strong version of QCT (called strong QCT) cannot be unconditionally secure. However, despite numerous papers on the subject (See, for example, \cite{110} and references therein), whether non-ideal weak QCT is possible remains an open question.

Other QKD protocols are also of interest. For instance, the sharing of quantum secrets has been proposed in \cite{111}. It is an important primitive for building other protocols such as secure multiparty quantum computation \cite{112}. There are also protocols for quantum digital signatures \cite{113}, quantum fingerprinting and unclonable encryption. Incidentally, quantum mechanics can also be used for the quantum sharing of classical secrets \cite{114}, conference key agreement and third-man cryptography.

For QKD, so far we have only discussed a point-to-point configuration. In real-life applications, it will be interesting to study QKD in a network setting \cite{115}. Note that the multiplexing of several QKD channels in the single fiber has been successful performed. So has the multiplexing of a classical channel together with a QKD channel. However, much work remains to be done on the design of both the key management structure and the optical layer of a QKD network.
IX. FUTURE DIRECTIONS

The subject of quantum cryptography is still in a state of flux. We will conclude with a few examples of future directions.

A. Quantum Repeaters

Losses in quantum channels greatly limit the distance and key generation rate of QKD. To achieve secure QKD over long distances without trusting the intermediate nodes, it is highly desirable to have quantum repeaters. Briefly stated, quantum repeaters are primitive quantum computers that can perform some form of quantum error correction, thus preserving the quantum signals used in QKD. In more detail, quantum repeaters often rely on the concept of entanglement distillation, whose goal is, given a large number $M$ of noisy entangled states, two parties, Alice and Bob, perform local operations and classical communications to distill out a smaller number (say $N$) but less noisy entangled states.

The experimental development of a quantum repeater will probably involve the development of quantum memories together with the interface between flying qubits and qubits in a quantum memory.

B. Ground to satellite QKD

Another method to extend the distance of QKD is to perform QKD between a satellite and a ground station. If one trusts a satellite, one can even build a global QKD network via a satellite relay. Basically, a satellite can perform QKD with Alice first, when it has a line of sight with Alice. Afterwards, it moves in orbit until it has a line of sight with Bob. Then, the satellite performs a separate QKD with Bob. By broadcasting the XOR of the two keys, Alice and Bob will share the same key. Satellite to ground QKD appears to be feasible with current or near-future technology, for a discussion, see, for example, [61].

With an untrusted satellite, one can still achieve secure QKD between two ground stations by putting an entangled source at the satellite and sending one half of each entangled pair to each of Alice and Bob.
C. Calculation of the quantum key capacity

Given a specific theoretical model, so far it is not known how to calculate the actual secure key generation rate in a noisy channel. All is known is how to calculate some upper bounds and lower bounds. This is a highly unsatisfactory situation because we do not really know the actual fundamental limit of the system. Our ignorance can be highlighted by a simple open question: what is the highest tolerable bit error rate of BB84 that will still allow the generation of a secure key?

While lower bounds are known \[24, 25, 26\] and 25 percent is an upper bound set by a simple intercept-resend attack, we do not know the answer to this simple question.

Notice that this question is of both fundamental and practical interests. Without knowing the fundamental limit of the key generation rate, we do not know what the most efficient procedure for generating a key in a practical setting is.

D. Multi-party quantum key distribution and entanglement

Besides its technological interest, QKD is of fundamental interest because it is deeply related to the theory of entanglement, which is the essence of quantum mechanics. So far there have been limited studies on multi-party QKD. Notice that there are many deep unresolved problems in multi-party entanglement. It would be interesting to study more deeply multi-party QKD and understand better its connection to multi-party entanglement. Hopefully, this will shed some light on the mysterious nature of multi-party entanglement.

E. Security proofs with testable assumptions

The surprising success of quantum hacking highlights the big gap between the theory and practice of QKD. In our opinion, it is important to work on security proofs with testable assumptions. Every assumption in a security proof should be written down and experimentally verified. This is a long-term research program.

F. Battle-testing QKD systems

Only through battle-testing can we gain confidence about the security of a real-life QKD system. Traditionally, breaking a cryptographic systems is as important as building one. Therefore, we need
to re-double our efforts on the study of eavesdropping attacks and their counter-measures.

As stated before, quantum cryptography enjoys forward security. Thanks to the quantum no-cloning theorem, an eavesdropper Eve does not have a transcript of all quantum signals sent by Alice to Bob. Therefore, once a QKD process has been performed, the information is gone and it will be too late for Eve to go back to eavesdrop. Therefore, for Eve to break a real-life QKD system today, it is imperative for Eve to invest in technologies for eavesdropping now, rather than in future.

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$$ S(\rho) = - \sum_i \lambda_i \log_2 \lambda_i = - \text{tr} \rho \log_2 \rho $$

where $\lambda_i$'s are eigenvalues of the density matrix $\rho$.

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