TIME-SHIFT ATTACK IN PRACTICAL QUANTUM CRYPTOSYSTEMS

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Recently, a new type of attack, which exploits the efficiency mismatch of two single photon detectors (SPD) in a quantum key distribution (QKD) system, has been proposed. In this paper, we propose another “time-shift” attack that exploits the same imperfection. In our attack, Eve shifts the arrival time of either the signal pulse or the synchronization pulse or both between Alice and Bob. In particular, in a QKD system where Bob employs time-multiplexing technique to detect both bit “0” and bit “1” with the same SPD, Eve, in some circumstances, could acquire full information on the final key without introducing any error. In addition, we prove that if Alice and Bob are unaware of our attack, the final key they share is insecure. We emphasize that our attack is simple and feasible with current technology. Finally, we discuss some counter measures against our and earlier attacks.

1 Introduction

One of the most important practical application of quantum information is quantum key distribution (QKD), whose unconditional security is based on the fundamental law of quantum mechanics [1–6]. In principle, any eavesdropping attempt by a third party (Eve) will unavoidably introduce disturbance. So, it’s possible for the legitimate users (Alice and Bob) to upper bound the amount of information acquired by an eavesdropper from the measured quantum bit error rate (QBER). Alice and Bob can then distill a final secure key by performing error correction and privacy amplification. Unfortunately, a practical QKD system has imperfections and Eve may try to exploit these imperfections and launch specific attacks. One example is the photon number splitting (PNS) attack [7–10], where Eve takes advantage of the nonzero multi-photon emission probability of Alice’s laser source and the lossy nature
of a quantum channel. Security proofs for practical QKD systems exist [11, 12]. Recently, decoy state QKD [13–20] has also been proposed to substantially increase the distance and key generation rate of a practical QKD system when weak coherent-state sources are used.

Another critical device, which limits the performance of a long distance QKD system, is the single photon detector (SPD). Currently, many practical QKD systems use optical communication fibers as their quantum channels and work at the Telecom wavelengths of around either 1550nm or 1310nm. Single photon detection at these wavelengths is often performed by (thermoelectric) cooled InGaAs avalanche photo diodes (APDs) [21]. To minimize the dark count rate, this type of detector usually works in gated mode: it is activated by a suitable electrical gate signal for a narrow window (a few ns) only when a signal pulse (a few hundreds of ps) is expected to arrive. Outside of this time window, a detector has no response to the input photons. Obviously, in this design, the synchronization between Alice’s source and Bob’s detectors is critical.

Recently, an eavesdropping attack that exploits the efficiency mismatch of two single photon detectors in a practical QKD system has been proposed in [22]. In this attack, Eve intercepts and performs a complete von Neumann measurement on each quantum state sent out by Alice. She then generates a new time-shifted signal based on her measurement result. In the extreme case where there is complete detector efficiency mismatch (that is to say, there is a time window where the detector for the bit “0” is active while the detector for the bit “1” is completely inactive, and vice versa), Eve can acquire full information on the final key without introducing any error.

In this paper, we propose a simple attack that exploits the same imperfection. More specifically, in our attack, Eve does not measure the quantum state sent by Alice. Instead, Eve simply time-shifts each of Alice’s signal forward or backward as she wishes. It turns out that the security of some practical QKD systems, particularly those with time-multiplexed SPDs, could be totally compromised by this simple attack. We emphasize that our attack can be implemented with current technology.

This paper is organized as follows: In Section 2, we summarize the basic results in [22] and then propose our new eavesdropping strategy. This is followed by a comparison of these two attacks. In Section 3, we discuss the security loophole of QKD systems with a time-multiplexed SPD. Finally, in Section 4, we discuss some counter measures against our and earlier attacks.

2 Eavesdropping strategies exploiting detector efficiency mismatch

In a BB84 QKD system [1], typically, Bob uses two separate SPDs, which are labeled as SPD0 and SPD1, to detect bit “0” and bit “1” respectively. As we discussed in Section 1, to minimize the dark count rate, each of these two SPDs is only activated for a narrow time window when the signal is expected. Owing to the different responses of the two APDs and other imperfections in electronics, the time-dependent efficiencies of these two SPDs are not identical. Because the width of SPD’s open window (a few ns) is often substantially larger, or at least not shorter than the laser pulse duration (a few hundreds ps), Alice and Bob can synchronize the laser pulse with the center of SPD’s open window. This ensures that the small detector efficiency mismatch will not affect the normal operation of the QKD system.

Ref. [22] considers the time-dependent detector efficiency of the two detectors. Fig[1] shows
Fig. 1. The time-dependence efficiencies of SPDs. The dark (light) curve corresponds to the efficiency of SPD0 (SPD1). At time \( t_0 \), SPD0 is more sensitive to the incoming photon than SPD1.

A diagram of the time-dependent efficiency of the two SPDs: at time \( t_0 \), the efficiency of SPD0, \( \eta_0(t_0) \), is much higher than that of SPD1, \( \eta_1(t_0) \), while at time \( t_1 \), \( \eta_0(t_1) \ll \eta_1(t_1) \). Taking a symmetrical assumption [22], we can define

\[
r = \frac{\eta_1(t_0)}{\eta_0(t_0)} = \frac{\eta_0(t_1)}{\eta_1(t_1)} \quad (1)
\]

where \( r \in [0,1] \). In the extreme case favorable to Eve, \( r = 0 \), which means only SPD0 is active in time \( t_0 \), and only SPD1 is active at time \( t_1 \).

The intercept-resend attack described in [22] goes as follows:

1. Eve intercepts quantum states from Alice and measures each of them in a randomly chosen basis;

2. According to her measurement result, Eve prepares a new quantum state (faked state [23]) in a different basis with a different bit value. For example, if she measures in Z basis and gets bit “0” (labeled as \( Z_0 \)), then she prepares bit “1” in X basis (\( X_1 \));

3. According to her measurement result, Eve sends out her faked state at different time so that it arrives at Bob’s SPD at either time \( t_0 \) (corresponding to her measurement result “0”) or \( t_1 \) (corresponding to her measurement result “1”).

Assuming the intrinsic QBER in Alice and Bob’s system is zero, the QBER caused by this attack can be derived as [22]:

\[
QBER = \frac{2\eta_0(t_1) + 2\eta_1(t_0)}{\eta_0(t_0) + 3\eta_0(t_1) + 3\eta_1(t_0) + \eta_1(t_1)} \quad (2)
\]

In one extreme case when \( r = 0 \) (which corresponds to \( \eta_0(t_1) = \eta_1(t_0) = 0 \)), QBER=0. So Eve can acquire full information on the sifted key without introducing any errors. In the other extreme case, when \( r = 1 \) (the two SPDs are perfectly matched), Eve causes QBER=1/2. So,
Eve is only doing a random guess. This is worse than the standard intercept-resend attack (which causes QBER = 1/4, and requires exactly the same equipment capabilities from Eve). The attack [22] becomes more efficient than the standard intercept-resend attack for $r < 0.2$. In the intermediate case when $0 < r < 0.2$, the QBER calculated from (2) could be lower than the proven lower bound of standard BB84 system. In other words, a direct application of standard security proofs, e.g. GLLP [12], without taking into account of detector efficiency mismatch, is invalid.

Note that, to implement the attack in [22], Eve will need a complicated detection (similar to Bob’s system) and resend (similar to Alice’s system) system. If we assume that Eve builds her “practical” eavesdropping device based on today’s technology, she will also experience the problem of low detection efficiency and will introduce additional errors (even in the case of $r = 0$) due to the imperfections in her setup.

Here we propose a simple and practical attack that exploits the same imperfection. Fig. 2 shows the schematic diagram of the experimental system that implements our attack. Instead of measuring Alice’s quantum state, Eve just randomly shifts the time of Alice’s quantum state to make sure that it arrives at Bob’s detector at either time $t_0$ or at time $t_1$. If Eve chooses time $t_0$ (or $t_1$), whenever Bob detects a signal, with the probability of $1/(r + 1)$, the bit value will be “0” (“1”). [Here, we assume equal prior probability for the bit “0” and “1” emitted by Alice.] In the extreme case when $r = 0$, this probability is equal to one. Because the probability that Eve guesses Bob’s bit value wrong is $r/(r + 1)$, So Eve’s knowledge about the final key is given by:

$$I(B : E) = 1 - h(r/(r + 1)),$$

where $h(x) = -x \log_2(x) - (1 - x) \log_2(1 - x)$ is the binary Shannon entropy function. Note that in this attack, Eve does not measure Alice’s state. Therefore, Eve never introduces any errors.

We now show that whenever $I(B : E) > 0$, the final key shared between Alice and Bob is insecure if they are not aware of Eve’s attack. In order to show this, we compute an upper bound on the key generation rate under Eve’s attack. One upper bound is the conditional mutual information [24] given by

$$I(A : B|E) = h(r/(r + 1)).$$

Thus, if Alice and Bob are not aware of our attack, then they would generate keys at a rate equal to 1 since there are no bit errors! Therefore, whenever $h(r/(r + 1)) < 1$, or in other words, when Alice and Bob generate keys at a rate higher than the upper bound, the final key shared between them is insecure. To quantify this key rate upper bound, we may substitute in an experimental value of $r = 2$ observed in our experiment. This gives us an upper bound of $I(A : B|E) = h(2/3) = 0.9183$. Thus, our attack does cause a moderate decrease in the key rate upper bound in this case.

Comparing with the attack in [22], our attack is simpler and can be easily realized with today’s technology: Eve can use high speed optical switches to re-route Alice’s signal through either a long optical path or a short optical path to achieve the desired time shift. Another

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*In reality, due to the finiteness of the number of signals, Alice and Bob may choose the key generation rate to be $1 - h(\epsilon)$, where $\epsilon$ is some security parameter."
advantage of our attack is that Eve never introduces any errors. So, it is hard for Alice and Bob to detect Eve’s presence.

One drawback of our attack (from the point of view of Eve) is that Eve can’t get the full information (unless \( r = 0 \)) on the sifted key. So, it might still be possible for Alice and Bob to work out a secure key, provided that they can correctly upper bound Eve’s information.

In both the attack proposed in [22] and the one proposed here, Bob’s detection efficiency is lower than normal. In the previous case, Eve can compensate this decrease by using a stronger faked state, or by using a low-loss quantum channel, or by placing her intercept unit near Alice and resend unit near Bob to bypass the quantum channel [22], whereas in our attack, Eve has to use a low-loss channel. Another alternative to using a low-loss channel is for Eve to mask herself by introducing additional loss during the calibration phase. This can be done with current technology.

In next section, we will show that for some QKD design, where Bob uses the same SPD to detect both bit “0” and bit “1”, Eve could time-shift both the synchronization signal and quantum signal to acquire full information without introducing any errors. In other words, our attack is fatal there.

3 Security loophole of QKD system with a time-multiplexed SPD

In a standard design of BB84 QKD system, Alice sends out her quantum bit in a randomly chosen basis, while Bob also randomly chooses his measurement basis and uses two separate SPDs to detect bit “0” or bit “1”. In a modified system design [25, 26], Bob detects both bit “0” and bit “1” with the same SPD, by employing time-multiplexing technique.

In this design, the expected arrival time \( t_0 \) of bit “0” (to SPD) is different from the expected arrival time \( t_1 \) of bit “1”, with the time difference

\[
\Delta t = t_1 - t_0
\]

determined by the optical length difference \( n(L_1 - L_0) \), as shown in Fig. 3. Here, \( n \) is the
Fig. 4. Synchronization between Alice’s pulse and Bob’s SPDs: $S_1$-classical sync pulses, $S_2$-SPD’s gating signals, $S_3$-signal pulses without Eve, $S_4$-Eve shifts the signal pulses by $+\Delta t$.

effective refractive index of the fibers and we assume $t_1 > t_0$. So, it’s possible for Bob to distinguish bit “0” and bit “1” from the detection time information.

Besides the advantage of saving one SPD (which is a most expensive component in a QKD system), this specific design also helps to minimize the asymmetry between the detection efficiency of bit “0” and bit “1”. Unfortunately, as we will demonstrate below, this design may also open a loophole that will allow Eve to launch the “time-shift” attack that we discussed in Section 2.

Note that if Bob’s SPD works in a gated mode (as the case for most Telecommunication wavelength QKD), it has to be activated twice for each incoming pulse (at time $t_0$ and $t_1$). Since there is no overlap between these two open time windows, this is equivalent to the case $r = 0$ in Section 2. Therefore, Eve could acquire full information on the sifted key without introducing any error. Before we go into the details of this attack, we will first discuss the synchronization of Alice’s laser pulse with Bob’s detection window in a practical QKD system. This synchronization issue is crucial for our discussion.

A widely used synchronization method in a practical QKD system is by multiplexing a strong synchronizing laser pulse with the weak signal pulse by employing wavelength division multiplexing (WDM) technique [27,28]. In [28], Alice multiplexes each weak signal pulse ($1.55 \mu m$) with a strong timing pulse ($1.3 \mu m$) and sends them to Bob through the same optical fiber. On the receiver’s side, Bob first separates the timing pulse from the signal pulse with a WDM component, and then detects the timing pulse with an APD, which in turn produces two electrical gating signals to control the two SPDs (or in the case of time-multiplexed SPD, these two electrical gating signals activate the SPD twice for each signal pulse). The time relations of various signals are depicted in Fig. 4.

Eve’s eavesdropping strategy is quite similar to the one we proposed in Section 2: Eve doesn’t measure Alice’s quantum state. Instead, she flips the bit value first (for phase encoding BB84 protocol, this can easily be done by using a phase modulator to introduce an additional $\pi$ phase shift between the signal and reference pulses sent by Alice) and then randomly time-shifts the pulse (relative to the strong sync pulse) by an amount of either $-\Delta t$ or $+\Delta t$. Fig. 4 ($S_4$) shows the situation when Eve does the $+\Delta t$ shift. Obviously, in this case, Bob can only detect bit “1” or nothing; the bit “0” is blinded. Similarly, when Eve does the “$-\Delta t$” shift,
Bob can only detect bit “0” or nothing. So, whenever Bob has a detection event, Eve has full information about his bit value.

Table 1 summarizes all possible events when Alice sends out $Z_0$ and Bob measures in Z basis. The other three cases can be easily worked out by symmetry. Again, as we explained in Section 2, Eve’s attack does not introduce any error.

Note that if the time interval $\Delta t$ between the two open windows of Bob’s SPD is exactly equal to half of the laser pulse period $\Delta T$, as the case in [26], this attack cannot be applied [29]. The reason is the following: Owing to Eve’s shifting of the pulse, the arriving time of the “blinded” bit will overlap with one of the SPD’s two open windows for the successive signal. For example, suppose Eve does “$+\Delta t$” shift to the $k^{th}$ laser pulse, then with 50% chance, the incoming photon will be detected at the time corresponding to bit “0” for the $(k+1)^{th}$ pulse. It’s easy to see that QBER in this case is 25%.

Note that QKD systems with a long SPD gating period (larger than $3\Delta t$) may be immune to this kind of attack. In this case, Bob may monitor counts fall outside the predetermined “0” and “1” windows. For example, in [30], the SPD is gated with ~ 100ns pulse, while the time interval $\Delta t$ between bit “0” and bit “1” is a 6.2ns. In this case, the SPD is only activated once for each incoming signal, and Bob can distinguish bit “0” from bit “1” by measuring the time difference between the sync pulse and the detected photon.

### Discussion

The recently proposed eavesdropping strategy exploits the detector efficiency mismatch of SPDs [22]. In this paper, we propose a simple time-shifting attack that exploits the same imperfection. We emphasize that our attack is simple and feasible with current technology. In particular, we demonstrate a QKD system, where Bob employs time-multiplexing technique to detect both bit “0” and bit “1” with the same SPD, is especially vulnerable to this kind of attack.

People may ask that even there is a mismatch between the efficiencies of two SPDs, how Eve can know that. We remark that in quantum cryptography, if we cannot prove that Eve is incapable of getting this information, then we have to assume that this information is available to Eve. In fact, in this specific case, Eve, in principle, does have a way to acquire this information during the normal quantum key distribution process: she can randomly block a small fraction of the pulses from Alice and resend faked pulses to Bob (she only changes a small fraction, so the QBER does not change significantly). Each faked pulse is randomly prepared in one of the four states as in the BB84 protocol, and its delay time can be tuned by Eve. After the classical communication stage, Eve knows Bob’s basis choice for each detected
faked pulse. In the case when they (Eve and Bob) use the same basis, Eve knows for sure which SPD clicks. Let us assume that the properties of the two SPDs stay constant over a long period of time during an experiment. In this case, given a long enough time, Eve can simply repeat her attacks and thus gather enough statistical data to determine the efficiencies of both SPDs at various delay times. With this information, she can launch the time-shift attack we discussed in this paper. Another scenario where Eve can obtain the efficiency information is that Eve is actually the producer of the QKD system Alice and Bob use. Thus, in principle, Eve knows the efficiency mismatch between the two SPDs.

To counter Eve’s attack, Alice and Bob could develop various counter measures, such as those discussed in [22]. Other counter measures include: strict checks for detection rate and loss in the quantum channel; applying phase shift setting to Bob’s phase modulator for a narrower time period than $[-\Delta t, +\Delta t]$ relative to the normal pulse position; randomly shifting the gating window; and using a non-gating SPD.

We note that a recently proposed single SPD QKD system is also immune to this attack [31]. In a phase encoding BB84 version of this design, instead of randomly selecting from a set of two values, Bob’s phase modulation is randomly selected from a set of four values, which is identical to the set for Alice’s phase modulation. In this case, Bob not only randomly chooses his measuring basis for each incoming pulse, he also randomly determines which SPD (or which time window in the case of time-multiplexed SPD) is used for detecting bit “0” or bit “1”. Bob broadcasts his basis choice, but keeps his choice of detector (for the bit “0” or “1”) secret. In such a set-up, even if Eve has the information about which detector clicks, Eve still cannot work out Bob’s bit value because she does not know which detector corresponds to bit “0”. On another hand, the set-up in [31] may open up an unrelated security loophole. More concretely, Eve may try to read out Bob’s detector assignments by employing a strong external laser pulse, as described in [32].

We conclude with some general comments on the security of QKD. First, a security proof is only as good as its underlying assumptions. Once a security loophole has been discovered, it is often not too difficult to develop counter-measures that will plug the loophole and regain proofs of unconditional security of QKD. One example is the PNS attack that we mentioned in Section 1. However, the hard part is how to find out those security loopholes in the first place. A QKD system is a complicated system with many intrinsic imperfections. It is, thus, very important to conduct extensive research in those imperfections carefully to see if they are innocent or fatal for security. We need more quantum hackers in the field. The investigation of loopholes and counter-measures in practical QKD systems plays a complementary role to security proofs.

Second, implementing a countermeasure for some security loophole may open up new loopholes (such as the one mentioned above). Also, regarding countermeasures, in our opinion, there is a big difference between what Bob could do in principle and what Bob actually does in practice.

Third, it is important to construct a list of potential countermeasures, and to compare and contrast them. This task is specified in the ARDA’s quantum cryptography roadmap [33] as one of the major milestones. Such a study will help us to better understand the pros and cons of the various countermeasures and eventually lead to the identification of the best countermeasure in practice.
Fourth, given that a practical QKD system will always have imperfections, one might wonder if QKD systems offer any real advantage over conventional systems. Our answer is three-fold. First of all, implementation loopholes are a fact of life. Even conventional security systems such as smart cards suffer implementation loopholes. For instance, Eve may attempt to read off a private key from a smart card by using various techniques (including X-ray) to reverse-engineer the circuit embedded in a smart card. Second, QKD can be used in concatenation with a conventional system to ensure security [34]. By defending in depth, QKD can only increase security, not reduce it. Third, QKD has an important advantage of being future-proof: The signals are quantum. Once the transmission is done, there is no transcript for the transmission. For an eavesdropper to launch a quantum attack, she has to possess much of the quantum technology during the quantum transmission. In contrast, in a standard Diffie-Hellman public-key key exchange scheme, Eve has a complete transcript of the transmission and can save such a transcript for decades to wait for unexpected future advances in hardware and algorithms. Given that public key crypto-systems was itself an unexpected discovery made only three decades ago, our view is that it will be complacent to believe that our standard public key crypto-systems will be safe forever. Therefore, it pays to diversify one’s risk by defending in depth with a QKD system in concatenation with a conventional cryptosystem.

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