QKD Quantum Channel Authentication

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Abstract

Several simple yet secure protocols to authenticate the quantum channel of various QKD schemes, by coupling the photon sender’s knowledge of a shared secret and the QBER Bob observes, are presented. It is shown that Alice can encrypt certain portions of the information needed for the QKD protocols, using a sequence whose security is based on computational-complexity, without compromising all of the sequence’s entropy. It is then shown that after a Man-in-the-Middle attack on the quantum and classical channels, there is still enough entropy left in the sequence for Bob to detect the presence of Eve by monitoring the QBER. Finally, it is shown that the principles presented can be implemented to authenticate the quantum channel associated with any type of QKD scheme, and they can also be used for Alice to authenticate Bob.

1 Introduction

Quantum Key Distribution (QKD) has gained considerable interest in the academic and commercial sectors in recent years because of its ability to offer absolute security against all attacks that can be carried out on classical and quantum computers. This is in stark contrast to current classical public-key schemes that have been shown to be vulnerable to attacks on a quantum computer [1]. However, these same classical schemes do have a significant advantage in that they can be used to authenticate messages and eliminate Man-in-the-Middle attacks, at least when Eve (the adversary) is limited to a classical computer. In the absence of an authenticated public channel, most QKD protocols, such as BB84 [2], are not secure against Man-in-the-Middle attacks.

The current method to secure commercially viable QKD protocols against such an attack is to authenticate the classical communications between Alice and Bob. This prevents Eve from establishing key with either one because she would not be able to carry out the classical communications necessary for the protocols, and she would be limited to attacks that increase Bob’s observed quantum bit error rate (QBER). The Wegman-Carter authentication scheme [3] and variations thereof [4] seem to be the most commonly implemented methods to authenticate QKD public channels. They also seem to be sufficient to protect against Man-in-the-Middle attacks. However, these schemes do not actually authenticate the users of a quantum channel, and there could be situations where this is desired.

There have been several quantum authentication protocols developed for the purpose of authenticating quantum messages [5] [6] [7], with much of the focus being on the use of entanglement. A quantum message is a normal message sent over a quantum channel using quantum codes. On the other hand, only random bits are transmitted over the quantum channel in QKD, and all messages are sent over the classical channel. In many of the quantum message authentication schemes, a shared secret is used to encrypt a message that is transmitted using one of several quantum codes. An imposter is then detected by monitoring the errors in the code words. One problem these schemes have is the inherent structure in the codes and Eve’s ability to take advantage of possible correlations between two sequential bits, resulting from the structures of quantum codes. However, in QKD, there are no bit-to-bit correlations, assuming a perfectly random raw bit sequence, so it seems reasonable that QKD could be simpler to authenticate than a quantum message. In this article, it is shown that the quantum-based security of entanglement-based authentication may not be necessary, and that computational-complexity-based schemes are sufficient to authenticate the quantum channel of a QKD system.

Four protocols are presented, each of which requires only a shared secret and a key-expansion function, in addition to the standard QKD protocols, to detect an imposter. Through examples of Man-in-the-Middle attacks, it is shown that even though information about the shared secret will be leaked to Eve during a QKD session, as long as determining the shared secret (given the expanded key) requires more computation than is possible in a few seconds, there is enough entropy remaining in the expanded key for Bob to detect the presence of an imposter by monitoring the QBER. Finally, it is shown that the basic principles used for these protocols can be implemented to authenticate the quantum channel associated with any type of QKD scheme, and that these protocols can also be used for Alice to authenticate Bob.

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2 Protocols

Consider the situation where Alice and Bob are going to generate key using BB84 and have an n-bit shared secret $K$, where $n$ is chosen based on the level of desired security. Also suppose that Alice and Bob have agreed on a key expansion function $F()$, which need not be kept secret, that they consider secure from time-limited cryptographic attacks on both classical and quantum computers. The time it takes to determine $K$ given $F(K)$ needs to be longer than the time it takes to perform a QKD session.

For notational purposes, let $F(K)^i$ be the $i^{th}$ bit of the expanded sequence, which is synchronized with clocks at Alice and Bob. Let $x^t$ and $y^t$ be Alice’s bit and basis choice at time $t$, and let $z^t$ be Bob’s basis choice. Let the observable being used (phase, polarization, orbital angular momentum, ...) be represented by $\Gamma$, and let the two conjugate bases be denoted by $\Gamma_0$ and $\Gamma_1$. To put the notation into context, the quantum portion of BB84 is carried out when Alice sends $\Gamma_{y^t} = x^t$ and Bob measures $\Gamma_{z^t}$.

Each of the protocols below allow Bob, after Error Correction (EC), to conclude whether or not the photons originated with an impersonator, as well as whether or not he communicated with an impersonator during either sifting or EC, depending on the protocol. That is not to say that these protocols protect against the possibility that Eve is intercepting information, which is the purpose of the actual QKD protocol, but it does say that the information did not originate with Eve.

Note that $F(K)$, which is a pseudo-random bit sequence, will not be available to Eve for analysis until she has recovered the random bit stream with which it is combined, such as Alice’s bit or basis choices, because a random stream Xored with any stream produces a random stream. So, Eve will not even be able to begin working on the recovery of $K$ until after EC. It should also be noted that in the protocols below, 1a and 2a have timing limitations that $1b$ and $2b$ do not. Namely, 1a and 2a are only secure if Eve does not have the opportunity to complete the entire Alice-Eve session before starting Eve-Bob because Eve can simply omit sending a photon to Bob for the times that correspond to $j \in \{t\}$ for which he did not learn $F(K)^j$, and Bob would attribute a lack of detection events to attenuation of the photons. Conversely, $1b$ and $2b$ force Eve to use a continuous stream of $F(K)$ starting at $F(K)^0$, so she cannot avoid times for which she does not know $F(K)^j$. Also note that the timing requirement for the first two protocols is not unreasonable and can easily be met.

Protocol 1.a

1. (a) Alice sends a photon with $\Gamma_{y^t} = x^t \oplus F(K)^t$.
   (b) Bob measures $\Gamma_{z^t}$, and records $x'^t = \Gamma_{z^t} \oplus F(K)^t$.
   (c) This step continues until enough photons have been sent for Bob to accurately calculate the QBER.

2. Alice and Bob perform bit distillation. Alice publicly discloses the set of her basis choices, $\{y\}$. Bob then compares $\{y\}$ to $\{z\}$ and publicly discloses a list of the times that have valid bits. (Alice $\rightarrow$ Bob Sifting using $\{y\}$ and $\{z\}$)

3. Alice and Bob perform EC on the bits of $\{x\}$ and $\{x'\}$ retained after sifting, using some agreed-upon scheme such as CASCADE. There is a possibility that the error correction scheme used does not correct all of the errors, but corrects for some maximum error rate, $\Delta$, with a high degree of certainty. $\Delta$ could either be a limitation of the correction scheme or Alice’s unwillingness to correct more than a certain number of errors. For simplicity, suppose that $QBER \leq \Delta$ implies there will be no errors left after EC (with some degree of certainty) and $QBER > \Delta$ implies there will be about a $(QBER - \Delta)$ error rate after EC.

4. Bob makes a conclusion about the security of the error-corrected bits. If the QBER is too high, Bob concludes that either Eve has gained too much information concerning the key that he established with Alice (standard BB84 conclusion) or that Alice did not send the original photons (conclusion concerning the authenticity of the photons).

5. Either Alice and Bob perform privacy amplification to create final keys, or they start over.

6. Alice and Bob create a new $K$. Alice and Bob take $n$ secure bits, either pre-placed or established during a QKD session, and create a new $K$ to authenticate the next QKD session.

Protocol 1.b

1. (a) Alice sends a photon with $\Gamma_{y^t} = x^t$.
   (b) Bob measures $\Gamma_{z^t}$, and records $x'^t = \Gamma_{z^t}$.
   (c) This step continues until enough photons have been sent for Bob to accurately calculate the QBER.

2. Alice $\rightarrow$ Bob Sifting using $\{y\}$ and $\{z\}$. Bob and Alice then apply the stream $F(K)$ to the bits retained after sifting with a bit-wise Xor.

3. Alice and Bob perform EC on the bits of $F(K)$ applied to the bits of $\{x\}$ and $\{x'\}$ retained after sifting.

4. Bob makes a conclusion about the security of the error-corrected bits.
5. Either Alice and Bob perform privacy amplification to create final keys, or they start over.

6. Alice and Bob create a new $K$.

**Security of Protocol 1**

The QBER for these protocols is a function of $\Gamma$ being measured and any tampering that may occur on the quantum channel as well as the original sender’s knowledge of the $F(K)$ sequence. If the established QBER is sufficiently low, Bob concludes that the person he is communicating with for the EC, over the classical channel, has knowledge that only the sender of the photons would have as well as knowledge of $F(K)$, which only Alice has. Put another way, this protocol guarantees that Bob is communicating classically with the sender of the photons for the EC, and that the sender knows $F(K)$. Therefore, the original sender must be Alice.

To understand the security of these protocols, consider the following Man-in-the-Middle attack against Protocol 1.a, assuming the timing restrictions for Protocol 1.a, as noted above, have now been met.

1. (a) Alice sends a photon with $\Gamma_{\nu'} = x^t \oplus F(K)^t$.
   (b) Eve measures $\Gamma_{\nu'}$, and records $\chi^t = \Gamma_{\mu'}$.
   (c) Eve sends a photon with $\Psi_{\nu'} = \xi^t$, where $\Psi$ and $\Gamma$ are the same observable.
   (d) Bob measures $\Psi_{\nu'}$, and records $x^t = \Psi_{\nu'} \oplus F(K)^t$.
   (e) This step continues until enough photons have been sent for Bob to accurately calculate the QBER.

2. Alice and Eve perform bit distillation. Alice sends Eve the set of her basis choices, $\{y\}$. Eve then compares $\{y\}$ to $\{\mu\}$ and sends Alice a list of which bits to include, with about half of them being discarded. (Alice $\rightarrow$ Eve sifting)

3. Alice and Eve perform EC. Eve didn’t know $F(K)$, so she has a .50 error rate in her key, relative to Alice. After EC, Eve still has a $\alpha = \max\{0, (0.50 - \Delta)\}$ error rate for the bits retained after sifting. If $\Delta$ is sufficiently small, this could prevent Eve from establishing perfect keys with Alice, and could allow Alice to detect an imposter while Alice and Eve are communicating with the keys.

After EC, Eve’s $F(K)$, for the bits corresponding to events retained after sifting, has an error rate of $\alpha$, and her error rate for the complete $F(K)$ is then $(.25 + \frac{\alpha}{2})$.

4. Eve and Bob perform bit distillation. Eve sends Bob the set of her basis choices, $\{\nu\}$. Bob then compares $\{\nu\}$ to $\{z\}$ and sends Eve a list of which bits to include, with about half of them being discarded (Eve $\rightarrow$ Bob sifting). As long as Eve did not know $\{y\}$ prior to (Alice $\rightarrow$ Eve sifting) and did not know $\{z\}$ prior to (Eve $\rightarrow$ Bob sifting), about half of the bits retained by Bob and Eve will correspond to bits retained by Eve and Alice.

5. Eve and Bob perform EC. Eve’s total error rate of $F(K)$ is $(.25 + \frac{\alpha}{2})$, so her key will have a $(.25 + \frac{\alpha}{2})$ error rate relative to Bob’s key.

6. Bob will calculate a $0.25 \leq (QBER = .25 + \frac{\alpha}{2}) \leq 0.50$ and conclude that Eve must be involved.

An analogous Man-in-the-Middle attack carried out against 1.b would have similar results in practice, but without the timing restriction. Against 1.b the attack would, in theory, induce a $QBER = \alpha$ which implies $0 \leq QBER \leq 0.5$. However, keeping in mind that the most trivial attacks against QKD produce a $QBER = 0.25$, it is unlikely that Alice would allow $\Delta > 0.25$ and therefore, in practice, Bob will also calculate $0.25 < (QBER = \alpha) \leq 0.5$ with protocol 1.b. Also note that during attacks on 1.a and 1.b, through interactive EC with Bob, Eve can take advantage of some of the information she gains during the interaction to ensure that the QBER appears to be a little lower than it actually is. This threat can be eliminated by using forward error correction, during which no information is leaked by Bob back to Eve.

**Protocol 2.a**

1. (a) Alice sends a photon with $\Gamma_{\nu'\oplus F(K)^t} = x^t$.
   (b) Bob measures $\Gamma_{\nu'\oplus F(K)^t}$, and records $x'^t = \Gamma_{\xi'\oplus F(K)^t}$.
   (c) This step continues until enough photons have been sent for Bob to accurately calculate the QBER.

2. Alice $\rightarrow$ Bob Sifting using $\{y\}$ and $\{z\}$

3. Alice and Bob perform EC on the bits of $\{x\}$ and $\{x'\}$ retained after sifting.

4. Bob makes a conclusion about the security of the error-corrected bits.

5. Either Alice and Bob perform privacy amplification, or they start over.

6. Alice and Bob create a new $K$. 
Protocol 2.b

1. (a) Alice sends a photon with $\Gamma_{y^t} = x^t$.
   (b) Bob measures $\Gamma_{z^t}$, and records $x'' = \Gamma_{z^t}$.
   (c) This step continues until enough photons have been sent for Bob to accurately calculate the QBER.

2. Bob publicly discloses a list of the times for which he had a detection event. Alice and Bob remove their basis choices for times that do not correspond to detection events to create the sets $\{y\}'$ and $\{z\}'$ respectively. Alice $\rightarrow$ Bob Sifting using $\{y\}' \oplus F(K)$ and $\{z\}' \oplus F(K)$.

3. Alice and Bob perform EC on the bits of $\{x\}$ and $\{x''\}$ retained after sifting.

4. Bob makes a conclusion about the security of the error-corrected bits.

5. Either Alice and Bob perform privacy amplification, or they start over.

6. Alice and Bob create a new $K$.

Security of Protocol 2

These protocols offer similar assurances to Bob as Protocols 1.a and 1.b, except that they guarantee, after EC, that the person with which he performed sifting is someone that knows information that only the sender of the photon and Alice could know. In particular, after EC, Bob knows that he performed the sifting with someone who knew both $\{y\}$ and $F(K)$, otherwise, he would have randomly selected which bits to use for the EC and would have a substantial error rate. Therefore, the original sender must be Alice.

The QBER is a function of $\Gamma$ being measured and any tampering that may occur on the quantum channel, in addition to the original sender not knowing the correct $F(K)$ sequence that was XORed to Allice's basis stream. When Bob is trying to perform EC with a user that does not know $F(K)$, the error rate will be inflated because Bob would have randomly selected his bits from all of the bits, roughly half of which are in the wrong basis. Note that, unlike in Protocol 1, the knowledge Eve can gain during interactive EC will not help her reduce the QBER induced by her not knowing the correct basis during the sifting. So, for protocols 2.a and 2.b, Eve does not gain an advantage by performing interactive EC with Bob as opposed to forward EC.

To understand the security of these two protocols, consider the following Man-in-the-Middle attack against Protocol 2.a, assuming that the timing restrictions for Protocol 2.a, as noted above, have been met (similar security when carried out against Protocol 2.b, but without the timing restrictions).

Allow for the possibility that Alice-Eve EC is completed after Eve-Bob photon transmission, but before Eve-Bob sifting.

1. Eve creates a set of times $\{\tau\}$ that correspond to bits of $F(K)$ she intends to learn.

2. (a) Alice sends a photon with $\Gamma_{y^t} \oplus F(K)^t = x^t$.
   (b) Eve measures $\Gamma_{\mu^t}$, and records $x^t = \Gamma_{\mu^t}$.
   (c) Eve sends a photon with $\Psi_\nu = x^t$ if $t \in \{\tau\}$, where $\Psi$ and $\Gamma$ are the same observable.
   (d) Bob measures $\Psi_\nu \oplus F(K)^t$, and records $x'' = \Psi_\nu \oplus F(K)^t$ if $t \in \{\tau\}$.
   (e) This step continues until enough bits have been sent for Bob to accurately calculate the QBER.

3. Alice and Eve perform bit distillation. Alice sends Eve the set $\{y\}$. Eve tells Alice that they agreed on the basis selection for the times $t \in \{\tau\}$.

4. Alice and Eve perform EC. Eve didn’t know $F(K)$, so she has a .25 error rate in her key, relative to Alice. After EC, Eve still has a $(.25 - \Delta)$ error rate for the bits retained after sifting. Again, $\Delta$ could be chosen to prevent Eve from establishing perfect keys with Alice, and could allow Alice to detect the imposter while Alice and Eve are communicating with the keys as input to their encryption systems.

To understand what Eve knows after EC with Alice, consider the fact that Eve knows $y^t$ and $\mu^t$ for all $t$. Through EC she learns $y^t \oplus F(K)^t \neq \mu^t$, for some number of errors, which is sufficient to calculate $F(K)^t$ for these times. For the times that she had the correct bit value, Eve doesn’t know if $y^t \oplus F(K)^t = \mu^t$ or if $y^t \oplus F(K)^t \neq \mu^t$. Therefore, Eve’s copy of $\{F(K)^\gamma\}$, the bits of $F(K)$ that correspond to possible detection events at Bob, has a $(\gamma = \max\{\frac{\Delta}{2}, \frac{1-\Delta}{2}\})$ error rate.

5. Eve and Bob perform bit distillation. Eve sends Bob the set $\{\nu\} \oplus F(K')$, where $F(K')$ is Eve’s flawed version of $F(K)$. Bob then compares $\{\nu\} \oplus F(K')$ to $\{z\}$ and sends Eve a list of which bits to include. This set of events will be about half of the events included by Eve and Alice.

6. Eve and Bob perform EC. Eve’s error rate of $\{F(K')\}^\gamma$ is $\gamma$, so her key will have a ($\frac{\gamma}{2}$) error rate relative to Bob’s key.

7. Bob will calculate a $.1675 \leq QBER = \frac{\gamma}{2} \leq .25$ and conclude that Eve must be involved.
3 Conclusions

The security of the shared-secret authentication lies in Eve’s inability to predict the secret bits, so it is imperative that the secret bits be well protected until Bob has a chance to verify the sender’s identity. In each of the above protocols Alice leaks information about $F(K)$ to the person with whom she is performing EC, so $F(K)$ is not completely secure. However, as long as determining $K$ from $F(K)$ is a relatively computationally-intensive process, then there is enough entropy in the shared secret during the QKD session to prevent Eve from successfully carrying out a Man-in-the-Middle attack.

The significance of these protocols is that each of them could easily be implemented in current QKD systems and would only require minor software modifications. Each of the protocols can be used to authenticate the quantum channel of prepare-and-measure QKD systems, such as BB84. However, note that in Protocol 2.b, Alice only has to know her basis choice when she performs sifting and not when actually sending the photons. This feature allows 2.b to actually be used for any 2-Basis QKD schemes that require bit distillation and EC, even entanglement schemes. Similarly, Protocol 1.b only relies on Alice and Bob having a bit stream with errors and a shared secret, implying that it can be used with all QKD schemes, even no-switching QKD [9], as long as the QKD schemes require EC.

Suppose that the roles in the sifting and EC were reversed, such that Bob’s key prior to EC was assumed to be correct, and Bob helped Alice correct her bits that differed from Bob’s. Alice would then calculate the QBER, and they could use the protocols for Alice to verify that the photons were detected by someone who knows $F(K)$, Bob, and that she communicated with him for the sifting and EC. For example, Protocol 2.b would only differ in that Bob would send Alice $\{z\} \oplus F(K)$ for sifting, and they would change roles for EC. Therefore, Alice could also authenticate Bob’s identity, and they could adjust the protocols so that they can authenticate each other for every QKD session.

It should be noted that the protocols presented in this article belong to a more general class of authentication protocols that use a shared secret, a symmetric-key algorithm, and monitoring of the QBER to detect a Man-in-the-Middle attack. These four were chosen to represent the versatility and utility of the protocols, but were certainly not inclusive of all of the ways to use classical cryptography to authenticate a QKD quantum channel. Alternative protocols could be created by replacing the $F(K) \oplus (\text{Information})$ step by running the information through an algorithm such as AES, or varying where the encrypt/decrypt takes place, among other options. As was shown, the QBER induced by a Man-in-the-Middle attack would vary between the different protocols, but many of the possible protocols in this class are more than sufficient for authentication purposes.

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