Considerations on Quantum-Based Methods for Communication Security

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Abstract—In this paper we provide an intuitive-level discussion of the challenges and opportunities offered by quantum-based methods for securing communications, e.g., over a network. The goal is to distill down to the most fundamental issues and concepts in order to provide a clear foundation for assessing the potential value of quantum-based technologies relative to classical alternatives. It is hoped that this form of exposition can provide greater clarity of perspective than is typically offered by mathematically-focused treatments of the topic. It is also hoped that this clarity extends to more general applications of quantum information science such as quantum computing and quantum sensing.

Index Terms—Communication Security; Cryptography; One-Time Pad; Quantum Computing; Quantum Information; Quantum-Key Distribution; Quantum Networks; Quantum Sensing; QKD.

I. INTRODUCTION

Quantum-based technologies exploit physical phenomena that cannot be efficiently exhibited or simulated using technologies that exploit purely classical physics. For example, a quantum sensor may use quantum phenomena to probe a system to discern classical and/or quantum properties of the system that cannot be directly measured by classical sensing technologies. Quantum computing, by contrast, generalizes the classical unit of information, the bit, in the form of a quantum bit or qubit, and exploits quantum computational operators that cannot be efficiently simulated using classical Boolean-based operators.

Secure quantum-based communication protocols have emerged as among the first practical technologies for which advantages over classical alternatives have been rigorously demonstrated. As will be discussed, however, these advantages rely on a set of assumptions about the capabilities of potential adversaries (hackers) as well as those of the communicating parties. Because the quantum advantage can be lost if these assumptions are relaxed, the utility of quantum-based communication must be assessed based on the assumed scenario in which it will be applied.

In the next section we discuss scenarios in which classical cryptography can facilitate unconditionally secure communications. We then discuss a more general class of communication scenarios in which classical methods cannot provide unconditional guarantees of security but may offer practically sufficient ones. We then provide a high-level description of how special properties of quantum systems can be exploited to enlarge the range of scenarios for which unconditional communication security can be achieved. This provides context for realistically examining how the tantalizing theoretical features of quantum-based approaches to communication security may translate to practical advantages over classical alternatives.

II. SECURE COMMUNICATIONS

Suppose two parties, Alice and Bob, know they will have need for unconditionally secure communications at various times in the future. If they determine that they are unlikely to communicate more than a total of $n$ bits before the next time they meet then they can create a sequence of random bits, referred to as a one-time pad (OTP), and each keep a copy for use to mask their messages.

For example, a week later Alice can contact Bob using whatever unsecure communication medium she chooses, e.g., phone or email, and then send her $k$-bit private message encrypted by performing an exclusive-or (XOR) of it with the first $k$ bits of the OTP. Upon receipt of the encrypted $k$-bit message, Bob will simply invert the mask by applying the same XOR operation using the first $k$ bits of the OTP.

Even if an eavesdropper, Eve, is able to monitor all communications between Alice and Bob, she will not be able to access the private information (i.e., original plain-text messages) without a copy of their OTP. Thus, the OTP protocol offers unconditional security against eavesdropping, but its use is limited to parties who have previously established a shared OTP. The question is whether a secure protocol can be established between two parties who have never communicated before.

III. PUBLIC KEY ENCRYPTION

At first glance it appears that there is no way for Alice and Bob to communicate for the first time in a way that is secure against an eavesdropper who has access to every bit of information they exchange. However, a commonly-used analogy can quickly convey how this might be done.

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The exclusive-or function of two bits $a$ and $b$ is $0$ if they are the same and $1$ if they differ.
Suppose Alice wishes to mail a piece of paper containing a secret message to Bob. To ensure security during transport she places the paper in a box and applies a lock before sending. When Bob receives the box he of course can’t open it because of the lock, but he can apply his own lock and send the box back to Alice. Upon receipt, Alice removes her lock and sends the box back to Bob, who can now open it and read the message.

If it is assumed that the box and locks can’t be compromised then this protocol is secure even if Eve is able to gain physical access to the box during transport. An analogous protocol can be applied to digital information if it is possible for Alice and Bob to sequentially encrypt a given message and then sequentially decrypt it. To do so, however, Alice must be able to remove her encryption mask after Bob has applied his. In other words, their respective encryption operations must commute and not be invertible by Eve.

It turns out that no classical protocol can satisfy the necessary properties for unconditional security. However, a practical equivalent of unconditional security can potentially be achieved in the sense that Eve may be able to invert the encryption – but only if she expends thousand years of computation time. Under the assumption that security of the message will be irrelevant at that point in the distant future, the protocol can be regarded as unconditionally secure for all practical purposes.

At present there are technically no protocols that provably require such large amounts of computational effort, but some do if certain widely-believed conjectures (relating to one-way functions) are true. Assuming that these conjectures are in fact true, classical public-key protocols would seem to offer practically the same level of security as a one-time pad but will essentially be erased in the process.

On the other hand... estimating the expected amount of time necessary to break a classical public-key protocol is very difficult. Even if it is assumed that the amount of work required by Eve grows exponentially with the length of a critical parameter, a particular value for that parameter must be chosen. For all existing protocols the value of this parameter introduces an overhead coefficient (both in computational time and space) which may not be exponential but may grow such that the protocol becomes impractical in most real-world contexts.

Suppose the parameter is selected based on a tradeoff between practical constraints and a minimum acceptable level of security, e.g., that it would take Eve 500 years to break the encryption using the fastest existing supercomputer. What if Eve can apply 1000 supercomputers and break it in six months? Or what if she develops an optimized implementation of the algorithm that is 1000 times faster? Breaking the code may still require time that is exponential in the value of the parameter, but the real question is how to estimate the range of parameter values that are at risk if Eve applies all available resources to crack a given message.

As an example, in 1977 it was estimated that the time required to break a message encrypted with the RSA public-key protocol using a particular parameter value would be on the order of many quadrillion years. However, improved algorithms and computing resources permitted messages of this kind to be broken only four years later, and by 2005 it was demonstrated that the same could be done in only a day.

The difficulty of making predictions, especially about the future, raises significant doubts about the extent to which any particular classical public-key scheme truly provides a desired level of security for all practical purposes, and it is this nagging concern that motivates interest in quantum-based protocols that offer true unconditional security, at least in theory.

IV. Quantum Key Distribution (QKD)

Quantum-based public-key protocols have been developed that provide unconditional security guaranteed by the laws of physics. In the case of Quantum Key Distribution (QKD) its security is achieved by exploiting properties that only hold for qubits. The first is the no-cloning theorem, which says that the complete quantum state of a qubit cannot be copied. The second is that a pair of qubits can be generated with an entangled states such that the classical binary value measured for one by a particular measurement process using parameter value $\Theta$ will be identical to what is measured for the other using the same parameter value, but not necessarily if the second measurement is performed with a different parameter value $\Theta' \neq \Theta$.

The no-cloning theorem is clearly non-classical in the sense that a qubit stored in one variable can’t be copied into a different variable the way the content of a classical binary variable can be copied into another variable or to many other variables. For example, if the state of a given qubit is somehow placed into a different qubit then the state of the original qubit will essentially be erased in the process. In other words, the state of the qubit should not be viewed as having been copied but rather teleported from the first qubit to the second qubit. If it is simply measured, however, then its state collapses to a classical bit and all subsequent measurements will obtain the same result.

Based on these properties, the following simple quantum communication protocol can be defined:

1) Alice and Bob begin by agreeing on a set of $k$ distinct measurement parameter values $\Theta = \{\Theta_1, \Theta_2, ..., \Theta_k\}$. This is done openly without encryption, i.e., Eve sees everything.

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2The theoretical physics explaining why quantum states can’t be cloned, and the details of how qubits are prepared and manipulated, are not important in the present context for the same reason that details of how classical bits are implemented in semiconductor devices are not relevant to discussions of algorithmic issues.

3This toy protocol is intended only to illuminate the key concepts in a way that links to classical one-time pad (variations can be found in [7]). Much more complete expositions of the general theory and practice of quantum cryptography can be found in [1], [4]–[6].
2) Alice and Bob each separately choose one of the $k$ parameter values but do not communicate their choices, thus Eve has no knowledge of them.

3) Alice generates a pair of entangled qubits. She measures one and sends the other to Bob.

4) Bob reports his measured value. If Alice sees that it is not the same as hers then she chooses a different parameter and repeats the process. She does this for each parameter value until only one is found that always (for a sufficiently large number of cases) yields the same measured value as Bob but does not give results expected for different $\Theta$ values.

5) At this point Alice and Bob have established a shared parameter value that is unknown to Eve. The process can now be repeated to create a shared sequence of random bits that can be used like an ordinary one-time pad. In fact, subsequent communications can be conducted securely using classical bits.

The security of the above protocol derives from the fact that Eve cannot clone $k$ copies of a given qubit to measure with each $\Theta_k$, and simply measuring transmitted qubits will prevent Alice and Bob from identifying a unique shared measurement parameter. In other words, Eve may corrupt the communication channel but cannot compromise its information. At this point Alice and Bob can create a shared OTP (which they can verify are identical by using a checksum or other indicator) and communicate with a level of security beyond what is possible for any classical public-key protocol.

V. The Authentication Challenge

For research purposes it is natural to introduce simplifying assumptions to make a challenging problem more tractable. The hope is that a solution to the simplified problem will provide insights for solving the more complex variants that arise in real-world applications. This was true of the lockbox example in which it was assumed that Eve might obtain physical access to the locked box but is not able to dismantle and reassemble the box, or pick the lock, to access the message inside. The secure digital communication problem as posed in this paper also has such assumptions.

Up to now it has been assumed that Eve has enormous computational resources at her disposal sufficient to overcome the exponential computational complexity demanded to break classical protocols. Despite these resources, it has also been assumed that she is only able to passively monitor the channel between Alice and Bob. This is necessary because otherwise she could insert herself and pretend to be Alice when communicating with Bob and pretend to be Bob when communicating with Alice. This is referred to as a Man-In-The-Middle (MITM) attack, which exploits what is known as the authentication problem.

To appreciate why there can be no general countermeasure to MITM attacks, consider the case of Eve monitoring all of Alice’s outgoing communications. At some point Eve sees that Alice is trying to achieve first-time communication with a guy named Bob. Eve can intercept the messages intended for Bob and pretend to be Bob as the two initiate a secure quantum-based protocol. Pretending to be Alice, Eve does the same with Bob. Now all unconditionally secure communications involve Eve as a hidden go-between agent.

In many respects it might seem easier to actively tap into a physical channel (e.g., optical fiber or copper wire) than to passively extract information from a bundle of fibers or wires within an encased conduit, but of course it’s possible to add physical countermeasures to limit Eve’s ability to penetrate that conduit. On the other hand, if that can be done then it might seem possible to do something similar to thwart passive monitoring.

Ultimately no quantum public-key protocol can be unconditionally secure without a solution to the authentication problem. Many schemes have been developed in this regard, but ultimately they all rely on additional assumptions and/or restrictions or else involve mechanisms that potentially could facilitate a comparable level of security using purely classical protocols.

As an example, suppose a company called Amasoft Lexicon (AL) creates a service in which customers can login and communicate with other registered customers such that AL serves as a trusted intermediary to manage all issues relating to authentication. This may involve use of passwords, confirmation emails or text messages to phones, etc., but ultimately it must rely on information that was privately established at some point between itself and each of its customers, e.g., Alice and Bob.

Suppose each customer is required to set up a strong password. Initially, how is that information exchanged securely with AL? One option might be to require the customer to physically visit a local provider so that the person’s identity can be verified, and a secure password can be established, without having to go through an unsecure channel. Okay, but how long must the password be? If it is to be repeatedly used then it would become increasingly vulnerable as Eve monitors more and more messages.

To avoid repeated use of a short password, AL could give Alice a drive containing 4TB of random bits for an OTP that would be shared only by her and AL. The same would be done using a different OTP when Bob registers. Now Alice can initiate unconditionally secure communicates with AL, and AL can do the same with Bob, and therefore Alice and Bob can communicate with unconditional security via AL.

Regardless of whether communications through AL involve a quantum component, the security of the overall system depends on the trusted security of AL – and on the security practices of its customers in maintaining the integrity of their individual OTPs. The situation can be viewed as one of replacing one point of vulnerability with a different one. For example, what prevents Eve from seeking employment at AL? Are there sufficient internal safeguards to protect against nefarious actions of AL employees?
VI. THE COMPLEXITY CHALLENGE

Complexity is a double-edged sword in the context of communication security. On the one hand it can be used to increase the computational burden on Eve. On the other hand, it can introduce more points of vulnerability for her to exploit as the scale of the implementation (amount of needed software and hardware) increases.

In the case of quantum-based protocols there is need for highly complex infrastructure to support the transmission of qubits and the preservation of entangled states. The details are beyond the scope of this paper, but it is safe to say that as implementation details become more concretely specified the number of identified practical vulnerabilities grows.

An argument can be made that as long as the theory is solid the engineering challenges will eventually be surmounted. This may be verified at some point in the indefinite future, but it is worthwhile to consider the number of practical security challenges that still exist in current web browsers, operating systems, etc., despite the recognized commercial and regulatory interests in addressing them.

The critical question is whether the investment in quantum-based infrastructure to support quantum-based secure communication protocols is analogous to a homeowner wanting to improve his security by installing a titanium front door with sophisticated intruder detection sensors but not making any changes to windows and other doors.

The natural response to the titanium door analogy is to agree that quantum-based technologies represent only one part of the overall security solution and that of course there are many other vulnerabilities which also must be addressed. However, this raises a new question: Is it possible that a complete solution can be developed that doesn’t require any quantum-based components?

It may turn out that it is only feasible to guarantee practically sufficient levels of security (as opposed to unconditional) and only for specialized infrastructure and protocols tailored to specific use-cases. If the scope of a given use-case is sufficiently narrow (e.g., communications of financial information among a fixed number of banks) then the prospects for confidently establishing a desired level of security are greatly improved. In other words, relative simplicity tends to enhance trust in the properties of a system because it is difficult to be fully confident about anything that is too complicated to be fully understood.

VII. DISCUSSION

The foregoing considerations on the status of quantum-based approaches for secure communications have leaned strongly toward a sober, devil’s-advocate perspective. This was intentional to firmly temper some of the overly-enthusiastic depictions found in the popular media. For example, the following is from media coverage of an announcement in May of 2017 about the launch of a quantum-based “unhackable” fiber network in China:

“The particles cannot be destroyed or duplicated. Any eavesdropper will disrupt the entanglement and alert the authorities,” a researcher at the Chinese Academy of Sciences is quoted as saying.

Hopefully our discussion thus far clarifies the extent to which there is a factual basis for this quote and how the implicit conclusion (i.e., that the network is “unhackable”) goes somewhat beyond that basis. One conclusion that cannot be doubted is that remarkable progress has been made toward implementing practical systems based on theoretically-proposed quantum techniques. Another equally-important conclusion that can be drawn is that China is presently leading this progress.

In many respects the situation is similar to the early days of radar when it was touted as a sensing modality that could not be evaded by any aircraft or missile because it had the means “to see through clouds and darkness.” While this claimed capability was not inaccurate, that power motivated the development of increasingly sophisticated countermeasures to mask the visibility of aircraft to enemy radar, thus motivating the development of increasingly more sophisticated technologies to counter those countermeasures. The lesson from this is that every powerful technology will demand continuing research and development to meet new challenges and to support new applications.

It is likely that the real value of future quantum fiber networks will not be communication security but rather to support the needs of distributed quantum sensing applications. More specifically, quantum information from quantum-based sensors and related technologies can only be transmitted via special channels that are implemented to preserve entangled quantum states. The future is quantum, so the development of infrastructure to manage and transmit quantum information has to be among the highest of priorities.

VIII. CONCLUSION

In retrospect it seems almost ludicrous to suggest that any technology could ever offer something as unequivocally absolute as “unconditional guaranteed security,” but that doesn’t mean quantum-based technologies don’t represent the future state-of-the-art for maximizing network communication security. More importantly, surmounting the theoretical and practical challenges required to realize this state-of-the-art will have much more profound implications than simply supporting the privacy concerns of Alice and Bob.

See the appendices for more succinct expressions of arguments considered in this paper.
Appendix A

Devil’s Advocate Arguments

• “The theoretical guarantees provided by QKD are only satisfied under certain assumptions. It may be that those assumptions can’t be satisfied in any practical implementation and thus QKD provides no theoretical advantages over classical alternatives.”
• “If it’s possible to implement the highly-complex infrastructure needed to support QKD, and to provide physical security against MITM attacks, then it should also be possible to implement physical security against passive monitoring. If that can be achieved then there is no need for QKD.”
• “The complexity associated with QKD may make it less secure than simpler classical alternatives. Just consider the number of security challenges that still exist in current web browsers, operating systems, etc., despite the recognized commercial and regulatory interests in addressing them.”
• “Progress on the development of classical protocols (e.g., based on elliptic curve cryptography) may very well lead to rigorous guarantees about the asymmetric computational burden imposed on Eve. If so, this would provide essentially unconditional security for all practical purposes.”
• “The need for provable unconditional security may be limited to only a few relatively narrow contexts in which classical alternatives are sufficient. For example, communications of financial information among a fixed number of banks could potentially be supported using classical one-time pads that are jointly established at regular intervals.”
• “QKD assumptions on what the physical infrastructure is required to support, and on what Eve is and is not able to do, seem to evolve over time purely to conform to the limits of what the theoretical approach can accommodate. This raises further doubts about QKD’s true scope of practical applicability.”
• “Implementing quantum infrastructure to support QKD is analogous to a homeowner wanting to improve security by installing a titanium front door but not making any changes to windows and other doors. In the case of Alice and Bob, for example, it’s probably much easier for Eve to place malware on their computers, or place sensors at their homes, than to identify and compromise a network link somewhere between them.”

Appendix B

Replies to the Devil’s Advocate:

• “People can assume responsibility for their local security but have no choice but to trust the security of infrastructure outside their control.”
• “A network that supports quantum information is unquestionably more powerful than one that does not. It is impossible to foresee the many ways this power will be exploited down the road, but it is hard to imagine that enhanced security will not be included.”

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