Will Quantum Cryptography ever become a successful technology in the marketplace?

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(July 2, 2021)

We assess the potential of quantum cryptography as a technology. We highlight the fact that academia and real world have rather different perspectives and interests. Then, we describe the various real life forces (different types of users, vendors of crypto-systems, conventional cryptographers, governments) behind the decision of the adoption (or rejection) of quantum cryptography and their different interests. Various roadblocks to the widespread application of quantum cryptography are discussed. Those roadblocks can be fundamental, technological, psychological, commercial or political and many of them have nothing to do with the security of quantum key distribution. We argue that the future success of quantum cryptography as a technology in the marketplace lies in our ability to appreciate and to overcome those roadblocks and to answer real world criticisms on the subject.

PACS Numbers:

I. INTRODUCTION

In this quantum cryptography workshop† we have heard many interesting talks. From an academic point of view, it is quite clear that quantum cryptography is a very active research area. Now, from the technological point of view, it is natural to ask about the potential of quantum cryptography as a technology. In other words, will quantum cryptography ever be widely used in future?

Given the immense progress in both the theoretical and experimental sides in the last few years, some of us in the audience may be tempted to say ‘yes’. However, ultimately the answer to this question does not depend on the subjective opinions of research scientists, but on the complex social and economic forces behind it as well as future advancements in the quantum technology.

On the question of whether quantum cryptography will ever be widely used in future, I certainly do not claim to have a full answer. In this talk, I will simply share with you some of my thoughts on the subject. None of the viewpoints expressed here are original. Nor are they sophisticated. They are just my personal simplifications and understandings/misunderstandings of what is well known to people in other walks of life. However, those viewpoints may not be commonly known to quantum cryptographers.

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II. ACADEMIA VS REAL WORLD

A. Technology focussed vs solution focussed

Let me begin by saying that the academic world and the real world have very different perspectives. In academia, we often deal with curiosity driven research. Even in quantum technology, our main focus is technology. That is to say the technological aspects of a subject. For instance, in this workshop many talks deal with the fundamental and technical issues of the security of quantum cryptographic systems. Important as they are, those subjects are so esoteric that they are quite beyond the understanding of even the most sophisticated developers and customers of conventional cryptography. More importantly, those subjects do not necessarily address their real world concerns.

In the real world, customers (users of cryptography) generally have problems and they look for solutions, not technology. It does not matter whether it is high-tech or low-tech, so long as it can solve their problem, they will take it. For instance, putting an eraser on top of a pencil is a trivial idea from the technological point of view. From the users’ point of view, this can be regarded as a major invention that offers convenience and added value to the individual eraser and the pencil. As another example, nuclear power generators may be a high-tech solution. But, it must compete with low-tech alternatives like oil and coal in a competitive commodity market—electricity generation.

Clearly, customer acceptance is very important to the success of a technology in the marketplace. Beside cus-

*This paper is an extended version of a talk to be presented in NEC Princeton workshop on quantum cryptography, Dec. 13-15.
tomers, there are many other players in the development/adoption of new technologies. Different players have different interests and concerns, some of which may be regarded as irrational by outsiders. Whether we like it or not, the only way to assure that a technology is adopted is to better understand the diverse interests and concerns of different players in the field.

B. Players in the Quantum Game

Let me introduce the interested parties in the development/adoption of cryptographic/security systems one by one and describe their main concerns.

1. Academia

(A) Quantum Cryptographers Type I (Particularly Theorists): The main interest of theoreticians in quantum cryptography is to design cryptographic protocols with perfect security \[1\].

(B) Quantum Cryptographers Type II (Particularly Experimentalists): The main interest of experimental quantum cryptographers is to design and implement quantum cryptographic schemes that are feasible with current (or near future) technology and secure against realistic attacks \[2\].

(C) Conventional Cryptographers? Some people may argue that many conventional cryptographers live in the same academic world as quantum cryptographers. I have no comment on this argument.

2. Real World

(A) Users Type 1 (individuals): The main interest of individual customers in using cryptographic/security product is often the peace of mind. If the users voluntarily use the product, this peace of mind may be due to the perceived security offered by the product. If the users are forced to use the products by others, the peace of mind may arise because they make their employers happy.

Cost and transparency are two other major concerns of the individual customer. Someone working on information security once told me that the general feeling in the community is that security does not sell. (i.e., While customers worry about security, they are unwilling to pay for a higher-price product for the sole reason of its being more secure.) The acceptable additional cost of a more secure product is essentially zero. People are interested in a solution (say a payment scheme) that is offered as a complete package: versatility, convenience of use, reliability, cost and security. "Security" is just a small term in the whole equation. Here, I have put security in a quotation mark because it is perceived security that counts. A layman generally does not understand real security. Besides, it appears to me that there is no logical consistence in users behaviors when many of them seem perfectly happy in giving out their credit card numbers over the phone, but not over the Internet.

Transparency of the operation of encryption is also a plus. While a layman can intuitively appreciate the security offered by an encrypted file which looks garbled even to the unsophisticated eye, the same cannot be said for quantum cryptography.

(B) Users Type II (businesses): A notable motivation for many businesses such as the banking industry to employ cryptographic products for its customers is to limit its financial and legal liability. Businesses generally accept a certain degree of financial losses due to insecure products as parts of their normal operating cost in doing businesses. Therefore, non-perfect security of conventional cryptographic systems is not a bad thing, but a fact of life. The important things are to have risk management and to have risk factors that are well understood. Employing industrial standards is very useful in reducing businesses’ financial and legal liability. Employing a non-standard disruptive technology like quantum cryptography is much more risky.

Securing long distance communication is an important concern in businesses. As international companies are now getting more and more global and tremendous amount of data are passed between different offices of the same company or different companies, there is an increasing need in securing those massive transcontinental communications. Besides, there is an increasing need for post-Cold-War type of applications like authentication and signatures.

(C) Vendors of Crypto Products: Like any other businesses, the main concern of vendors of crypto products is to make money in the long run. Besides, vendors have vested interests in deciding which technology to employ. For instance, a vendor with a large number of patents and products in the elliptic curve crypto-systems might be tempted to emphasize the strengths of elliptic curve crypto products compared to products based on other principles.

(D) Conventional Cryptographers and Security Experts: Because of their own background and experience, conventional cryptographers and security experts are keen to use something that they can understand and trust such as the one-way function hypothesis. If you ask them whether they believe in quantum mechanics or one-way hypothesis more, their answer is clear.

(E) Governments: Different departments in a government have different interests. For instance, the military and the foreign office are certainly interested in having perfect security for their communications. On the other hand, for agencies such as the FBI, the ability to wiretap communications of the criminals is very important. From this point of view, perfect security might threaten national security and should be discouraged or controlled by laws. I am not up to date with the current US regulations. However, until recently, cryptography has been regarded as ammunition in the US laws, subject to the strictest control in its usage and export.
III. ROADBLOCKS

Having introduced the different players and their interests in cryptography, it is the time to discuss the major roadblocks to the future deployment of quantum cryptographic systems. For ease of discussion, I will divide those roadblocks into different classes. However, my division is somewhat subjective.

A. Fundamental roadblocks

Quantum cryptography is a fundamentally limited technology.

(A) Impossibility of unconditional security for many applications
First, it has a limited range of applications. The fundamental appeal of quantum cryptography has been perfect or unconditional security (i.e., security guaranteed by the laws of quantum mechanics only and without making any computational assumptions). However, the unconditional security of a number of important basic protocols such as bit commitment [3], one-out-of-two oblivious transfer [4] and one-way identification (and more generally, one-sided two-party secure computations) [4] have been shown to be impossible in a series of no-go theorems. What it means that all such protocols must require quantum computational assumptions.

(B) Lack of public key based quantum cryptographic schemes
Second, quantum cryptography has made no significant contribution to public key cryptography. Many real life cryptographic applications such as signature and authentication schemes in the Internet age involve public key cryptography. However, very little (if anything) has been done on quantum cryptographic signature and authentication schemes that are public-key based.

B. Technological roadblocks

(C) Limited distance in current quantum key distribution experiments
Experimental quantum key distribution has been performed over tens of kilometers. However, a major market for secure communication is, in fact, transcontinental communications. Until the distance achieved in experimental quantum key distribution increases by two order of magnitude, quantum key distribution is not a feasible technology for this major market sector.

(D) Limited data rate
The current data rate for experimental quantum key distribution is of the order kbits for second. (Worse still, the post-processing including error correction and privacy amplification is quite massive.) In contrast, the current world record for a single mode optical fiber communication is 160 Gbits for second [5]. “Multiplying 160 gigabits over additional wavelengths, we expect to be able to scale up to many trillions of bits a second in the foreseeable future.” says Alastair Glass, director of Bell Labs Photonics Research Labs. If quantum key distribution is ever going to be widely used for one-time pad application for the massive data being transmitted in commercial optical fibers, there is probably a ten order of magnitude gap in data rate to be closed in the foreseeable future.

C. Commercial roadblocks

(E) Equipment size is too big.
Ideally, cryptographic applications should be done either by a software or a very small hardware component such as a smart card or a CD. Unfortunately, current quantum cryptographic systems are quite big. Shrinking a quantum cryptographic system to the size of a briefcase is already a big challenge. Shrinking it to the size of a smart card requires much ingenuity and development.

(F) Cost is too high.
The acceptable additional cost of a more secure cryptographic product for individual consumers is essentially zero while the components of existing quantum cryptographic system cost hundreds or even thousands of dollars.

(G) Integration with existing infrastructure in information technology requires further developments.
Except for niche markets, we cannot expect an optical fiber to be solely dedicated to quantum communications for any substantial period of time. The integration of quantum technology with conventional and existing infrastructure in information technology requires much further work.

D. Security roadblocks

(H) Known loopholes in current implementations
While quantum cryptography claims to offer perfect security in theory, in practice current experimental implementations contain quite a number of security loopholes. It has been argued that essentially none of the existing implementations is actually secure [3]. Plugging those known loopholes is a highly non-trivial experimental and theoretical design problem.

(I) Hidden loopholes in implementations
All security analyses of quantum cryptographic systems involve idealizations. It is highly probably that many other fatal security loopholes in the implementations of quantum cryptography remain to be discovered.
Given the slippery nature of the subject, quantum cryptography hardly inspires the confidence of potential users. The best way to construct a secure cryptographic system is to try hard to break it. Unfortunately, until recently very few people worked on breaking quantum cryptographic systems. Without an army of people trying to break them, the security of quantum cryptographic systems are largely untested.

E. Psychological/ Vested Interest roadblocks

(1) Conventional cryptographers have no confidence in quantum mechanics.

Most conventional cryptographers do not understand quantum mechanics. Nor are they familiar with its many applications. In any case, the burden of proof of the usefulness of a new technology lies on its own practitioners, not conventional cryptographers. In contrast, from their point of view, things like the one-way function hypothesis, the hardness of factoring are well-tested principles and something that they understand well. It is wishful thinking to ask them to take a leap of faith by abandoning their well cherished philosophy and taking up a black box philosophy for no apparent good reason.

Moreover, Neal Koblitz remarked in Crypto’97 (the most important international conference in fundamental research in cryptography) that many cryptographers hate quantum computation because if it flies, it will put many of them out of business. Indeed, if a quantum computer is ever built, many public key cryptographic schemes that are widely used today will be totally unsafe. This could potentially kill public key cryptography and throw cryptography back to the “dark age”\footnote{[Discussion of the possibility that public key cryptography may actually survive quantum attacks]} — a nightmare scenario for electronic commerce and data security. [See, however,\footnote{[For a discussion of the possibility that public key cryptography may actually survive quantum attacks]} for a discussion of the possibility that public key cryptography may actually survive quantum attacks.]

Since quantum cryptography is a part of quantum information processing, it is only natural that conventional cryptographers may not like it neither.

(K) Vendors of conventional cryptographic products have vested interests in promoting and preserving conventional technologies.

If this is what conventional cryptographers might think as individual researchers, you can imagine what existing crypto-system vendors might think about quantum cryptography: Quantum cryptography is far more likely to be seen as an unwelcome threat rather than a potential opportunity.

In the history of technological developments, disruptive technologies are often made possible by new firms rather than existing firms that have large stakes in the dominant existing technology.

F. Political/Legal roadblocks

(1) Quantum cryptography may be limited by governmental crypto control policies.

As mentioned earlier, in the US, usage/export of strong cryptography is subject to stringent governmental control. Any future usage/export of quantum cryptographic systems will be subject to the same stringent set of regulations. How to reconcile the main selling point of quantum cryptography (strong security) and cryptography control (limitation on the employment of strong cryptography) is a subject that deserves future investigations.

IV. FUTURE DIRECTIONS

Having discussed the various roadblocks to the future widespread applications of quantum cryptography, I hope that you will agree that the issue of commercial feasibility is much more complicated than a research scientist may naively think. Certainly, my own grasp of the problem is limited. If there is a lesson in this talk, it is the following: To better understand the issue of commercial feasibility, it is best for quantum cryptographers to engage more in constructive conversations with people in the real world (users, vendors, conventional cryptographers, government officials, etc). While we do not have to agree with what they say, it is important for us to understand their views clearly. The future adoption of quantum cryptography relies on their acceptance.

On the more technical side, I offer the following subjective list of future directions.

1. Develop new applications for quantum cryptography:

In my opinion, it is important to develop new applications of quantum cryptography such as signature and authentication schemes, quantum voting, etc. Since various no-go theorems have ruled out the possibility of a number of cryptographic primitives, future quantum cryptographic systems may well be based on quantum computational assumptions\footnote{[Therefore, it would be of practical interest to invent a ”quantum one-way trapdoor function”and public key based quantum cryptographic systems.\}.

One possible viewpoint to take is to regard quantum cryptography as a natural extension (rather than a replacement) of conventional cryptography and put its foundation on computational assumptions on both conventional cryptography and quantum mechanics. How to combine the advantages offered by quantum mechanics and public key infrastructure is a big issue. It would be of particular interest to construct a public-key based quantum encryption scheme and show rigorously that breaking it will require the simultaneous breaking of widely accepted assumptions in both conventional cryptography (such as cracking the Diffie-Hellman key exchange
scheme) and quantum computation (such as the ability to achieve quantum computation/measurement involving more than $N$ qubits). Such an encryption scheme will convince people in both conventional and quantum cryptographic communities that it is secure against any realistic attacks.

[Brassard] has emphasized the possibility that conventional public key cryptography may actually survive quantum attacks. According to [7], it has been argued in [9] that quantum resistant one-way function that can be computed efficiently with classical computers but cannot be inverted efficiently even with a quantum computer may well exist. That would be bad news for quantum cryptographers, though.

2. Use teleportation to plug security loopholes [11].

A major criticism on quantum cryptography is that it may contain many hidden security loopholes. For instance, while it is often assumed that a photon source emits single photons, in real life perfect single photon sources are notoriously hard to make. Besides, experimental systems generally contain higher energy levels whose occupancy is totally ignored in most security analysis. Indeed, as emphasized by, for example, John Smolin [12], it is even conceivable in principle that an eavesdropper can hide a quantum robot in the quantum signals received by the two users. Owing to this quantum Trojan Horse problem, quantum cryptographic systems seem inherently unsafe.

Nonetheless, one can argue that by using teleportation, quantum cryptographic systems can be made no more unsafe than conventional ones [11]. One can reduce the quantum Trojan Horse problem to a conventional Trojan Horse problem. This is done by the following method. Instead of receiving any untrusted quantum signals from a quantum channel, each user insists that any signal should be teleported to him/her. For instance, Bob prepares locally an EPR pair and sends a member to a laboratory outside his door. Any incoming quantum signal will be teleported to him by his doorman outside his door. What he receives are just classical messages. Note that teleportation provides an exact counting of the number of dimensions of Hilbert space of the reconstructed state. This is so even if the original EPR pair that Bob prepares is imperfect and contains hidden dimensions.

Of course, the problem of classical Trojan Horse attack remains. But, this is inevitable. Since Bob’s goal is to receive classical communications from Alice through an untrusted channel, if receiving untrusted classical messages is a problem, the whole enterprise of secure communication is simply hopeless.

3. Use quantum repeaters to extend the range of secure quantum key distribution.

This is crucial if quantum key distribution is ever to make any impact on intercontinental communication.

4. Increase data rate for quantum key distribution.

Existing schemes for quantum key distribution such as BB84 and Ekert’s scheme are based on two-level quantum systems and as such their data rates are limited. If quantum cryptography is ever widely used as one-time pad for encrypting massive data in communications, higher level systems and particularly continuous variable quantum cryptography are a way to go forward. This would mean that many of the current investigations may become obsolete in the near future.

5. Miniaturization.

The ultimate goal is to reduce the size of quantum cryptographic systems to that of a smart card or a compact disc.

6. Integration with existing infrastructure in information technology.

It may be hard to justify the cost of construction of an entirely new infrastructure dedicated to the long-distance transmission of quantum signals. Integration of quantum technology with existing infrastructure (including optical fibers) in information technology is, therefore, an important subject.

7. Towards an international standard for quantum cryptography.

Ultimately, some form of international standards will be needed for the widespread deployment of quantum cryptography.

8. We need quantum hackers.

We have seen encouraging signs that researchers are finally taking a critical look at the security of current experimental implementations of quantum cryptographic systems [4]. In order to better understand the real risk of employing quantum cryptography, much more should be done on the subject.

An attacker should attack a Chinese Wall from its weakest point. The weakest point of a cryptographic system often lies in the blindspot of its designers. A cryptographer may regard a cryptographic system as a mathematical black box function which provides an output for each input. However, in real life the box is never black to begin with. (Private keys embedded in a smart card circuitry may be read out by illuminating the smart card with various wavelengths of electromagnetic radiations.) The black box also gives out timing information, power consumption information, etc. The inputs to the black box include also its power supply, something that is subject to manipulations by malicious parties. The designer of the black box may try to cheat by designing a black box that leaks information in a subtle encrypted way that can be read by only the designer.

Indeed, in conventional cryptography, it is often the case that the most powerful attacks against a system has little to do with the fundamental design or mathematical equations underlying the design. The devil is in the actual implementation, rather than the fundamental design. If we are really interested in the future of quantum
technology, we must face up to those subtle loopholes in implementations. A way to do so is to become a quantum hacker and devise innovative methods of cracking experimental quantum cryptographic system.

9. Crypto control of quantum cryptography?

The issue of cryptography control of quantum cryptography remains to be addressed. I have no particular suggestion.

V. ACKNOWLEDGMENT

I have greatly benefitted from helpful discussions with many colleagues, collaborators, and experts in both conventional cryptography/security systems and quantum cryptography. I would like to thank them all and apologize for any misrepresentations of their ideas/observations in this talk.

[1] See, for example, H.-K. Lo and H. F. Chau, Science 283, 2050 (1999) and supplementary material at www.sciencemag.org/feature/data/984035.sht and D. Mayers, Los Alamos preprint archive (LANL) quant-ph/9802022 version 4.

[2] See, for example, G. Brassard et al., Los Alamos preprint archive quant-ph/9911054.

[3] D. Mayers, Phys. Rev. Lett. 78, 3414 (1997) [also in Los Alamos preprint archive (LANL) quant-ph/9605047]; H.-K. Lo and H. F. Chau, Phys. Rev. Lett. 78, 3410 (1997) [also in LANL quant-ph/9603004]. For a review, see, for example, H. F. Chau and H.-K. Lo, Fortsch. Phys. 46, 507 (1998) [also in LANL quant-ph/9709053].

[4] H.-K. Lo, Phys. Rev. A56, 1154 (1997).

[5] http://www.bell-labs.com/news/1999/november/10/3.html

[6] Such a viewpoint has been relayed to me by Nigel Smart, private communications.

[7] G. Brassard, in Advances in Cryptology—Crypto 97, Springer-Verlag, LNCS 1294, p. 337 (1999).

[8] C. H. Bennett, private communications.

[9] C. H. Bennett, E. Bernstein, G. Brassard and U. Vazirani, SIAM Journal on Computing, ?.

[10] C. H. Bennett et al., Phys. Rev. Lett. 70, 1895 (1993).

[11] See H.-K. Lo and H. F. Chau, Note 21 of Ref. [1].

[12] J. Smolin, private communications.

[13] See, for example, H.-J. Briegel, W. Dür, S. J. van Enk, J. I. Cirac and P. Zoller, Philos. Trans. R. Soc. London Series A356, 1713 (1998).