On the Foundations of Quantum Key Distribution — Reply to Renner and Beyond*

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Abstract

In a recent note (arXiv:1209.2423) Renner claims that the criticisms of Hirota and Yuen on the security foundation of quantum key distribution arose from a logical mistake. In this paper it is shown that Renner misrepresents the claims of Yuen and also Hirota while adopting one main theorem of Yuen in lieu of his own previous error. This leads to his incoherent position which ignores quantitative security criterion levels that undermine the current security claims, a main point of the Yuen and Hirota criticisms. This security criterion issue has never been properly addressed in the literature and is here fully discussed, as are several common misconceptions on QKD security. Other foundational issues are touched upon to bring out further the present precarious state of quantum key distribution security proofs.

I INTRODUCTION

In this paper we will respond to the recent Reply paper by Renner [1] that the criticisms of Yuen [2-5] and Hirota [6] on the security of quantum key distribution (QKD) protocols are derived from a logical error. While Hirota could speak for himself, some related points in his paper would be included in our discussion. Renner explicitly attributes an equivocal claim to us, and by an incorrect argument in a footnote, claims to produce a counter-example to our conclusion. In truth, the precise form of our claim has been repeatedly given in [2-5]. Rather, Renner made a fundamental error in [7-8] which has become the standard interpretation of the trace distance criterion d widely employed in QKD. This incorrect interpretation leads to the current prevalent QKD security claim that the generated key K has a probability $p \geq 1 - d$ of being ideal [9-11]. In actuality, K is not ideal with probability 1 for $d > 0$ and may have a probability d of being found in total by an attacker Eve [2-5]. As brought out in detail in section III, the correct meaning of d gives a much weaker security guarantee than the wrong interpretation in general. It is the consequence of this error in concrete QKD protocols that Yuen and Hirota pointed out, which is beyond rational dispute as will be shown in this paper.

Security is a quantitative issue. The exact level one has for a given l-bit key K is crucially important. In [1] l is taken to be 10^6 and $d = 10^{-20}$. There are two sorts of security, "raw security" [3] before K is used and composition security where Eve has additional information about it when K is used, for example from a known-plaintext attack. In raw security, the ideal situation occurs when K has the uniform distribution U to Eve. Since the earlier days of QKD [12], "unconditional security" means the security result holds against all attacks allowed by the laws of quantum physics, with quantitative information theoretic security level that can be made arbitrarily close to ideal through a *security parameter*. If d is the maximum failure probability with "failure" meaning the key is not ideal [7-11], security would be perfect with a large probability $p \geq 1 - d$, but that is false. When K has a distribution P to Eve, its quality is often measured by a single-number security criterion, say the variational distance $\delta(P, U)$ between P and U.

Since δ or d is not a bound on $1 - p$, operational security meaning has to be given to them through Eve's probabilities of success in estimating various portions of K and through Eve's average bit error rate (BER) [2-5].

This paper would provide the details to elaborate on the following:

(1) **What Renner Claimed Before The Reply** —
The trace distance d is defined in (TD) of [1] with (TD) meaning $d \leq \epsilon$, equation (1) of [1] says

$$(\text{TD}) \rightarrow (\text{UC } secrecy) \qquad (1)$$

In [7-11] before this Reply paper [1], UC secrecy (of level at least ϵ, or "ϵ-secrecy") means the generated K is ideal with probability $p \geq 1 - \epsilon$. This is often phrased in terms of the "failure probability" $1 - p$ being less than ϵ. Thus, with d interpreted as the maximum failure probability [7-11], (1) is obtained to guarantee ϵ-secrecy when the level of d is bounded by ϵ.

(2) **What Yuen And Hirota Claimed** —
It was shown [2-5] that Renner's interpretation of d is incorrect and in fact K is not uniform with probability 1 when $d > 0$, i.e., $p = 0$. Furthermore, the levels of d obtained in concrete protocols, in theory [13] not to say in experiment [14], imply K is very poor compared to U [2-6], for both raw and known-plaintext attack security and for both Eve's sequence success probabilities and BER.

(3) **What Renner Claimed In His Reply** —
The meaning of (1) is now equivocal in [1]. In paragraph two, UC secrecy is still claimed to be "ϵ-secret" with a failure probability $\leq \epsilon$, but the explanation of failure probability in footnote [14] is given in terms of the correct sequence probability meaning of d first described in [5] but with no reference. The BER meaning is not given. These two interpretations of UC secrecy in [1] are contradictory, as indicated in point (2) above. By an arbitrary stipulation in footnote [15], it is declared in [1] that $d = 10^{-20}$ for an $l = 10^6$ bit key is sufficiently secure. Together with distorting our correct claim that the condition (HY) means the key is near-uniform to that it is necessary for security, a "logical error" on Yuen and Hirota is manufactured in [1] through a counter-example in footnote [19]. This counter-example itself is infused with error and confusion, including the *same* conceptual confusion that leads to the error described in (1) above.

(4) **What Is Wrong With The Security Claim In [1]** —
In addition to the above point (2) there are fundamental problems on the claims in [1] for $d = 10^{-20}$ and $l = 10^6$. Since K is then far from uniform, it cannot be used to subtract for $leak_{EC}$, Eve's information gain from error correction, that is employed in all recent security proofs. Also, why is such d level "sufficient" for security? When K is not near-uniform, *only* the users in a specific application can decide whether a given d level is sufficient. It *cannot* be prescribed in advance at $d = 10^{-20}$. It is the responsibility of the security analyst to spell out clearly the key rate and security level tradeoff. Note that according to the most up to date theoretical analysis of single-photon BB84 in [13], $d = 10^{-20}$ is nowhere to be found. Already in their presented results the key rate is reduced to effectively zero at $d = 10^{-14}$, with a one-bit K generated before message authentication bits are accounted for.

When the average guarantee in the security proofs is converted to individual guarantee necessary for security claim on an individual system, the level is reduced from d to $d^{1/3}$ for Eve's sequence success probabilities [4]. Thus, $d = 10^{-20}$ [1] reduces to $d^{1/3} > 10^{-7}$. For $d = 10^{-14}$ [13], $d^{1/3} > 10^{-5}$ and for $d = 10^{-6}$ [14], $d^{1/3} = 10^{-2}$. These are poor to very poor security guarantees for any application, and they remain so even under the wrong interpretation. Such quantitative issues are among the main claims of [2-6] not addressed in [1].

(5) **What Are The Other QKD Security Foundation Issues** —
There are many other basic problems in the known QKD security proofs that have been raised additionally in [15-19] but not touched upon in [1] despite its title and references. There are also several common but fundamental misconceptions in QKD security that should be clarified. A most significant misconception is that there is a security parameter in QKD protocols that can bring security to an arbitrarily good level if the key rate is below a certain threshold.

In this paper, we will explain points (1)-(5) in detail. In section II we will explain the above criterion issue to settle the matter once for all. We will start by dispelling a common misconception that QKD security is guaranteed by the laws of quantum physics, either no-cloning or whatever Uncertainty Relation.

The *necessary condition* for operational quantitative security will be given. We will describe the severe reduction of the guaranteed d level to $d^{1/3}$, and the importance of bringing Eve's BER on K close to $1/2$. While many details on the points about d itself can be found from [2-5], in section III we will make just one basic point on the error of interpreting d as maximum failure probability, namely a new fundamental argument on why the 'proof' of such an interpretation given in [7-8] involving a joint distribution is not only invalid but is in fact irrelevant to the issue. All the security points raised in [1] will be addressed. In section IV various security proof issues concerning BB84 type protocols will be touched upon. We will bring out the inevitable exchange of key rate and security level in QKD systems, with the important consequence that there is *no* security parameter in QKD protocols that would render it arbitrarily secure for a fixed key rate. We will point out the incorrect step of subtracting $leak_{EC}$ to account for information leak due to error correction. Some common misconceptions about QKD security are summarized in section V.

The upshot is that the security foundation of QKD is indeed very much shaken. General security cannot be established by experiments and can only be proved theoretically. The present predicament is that it is *not* clear why and how a concrete QKD protocol can be proved secure in principle.

II QKD SECURITY CRITE-RION AND NECESSARY SECURITY CONDITIONS

In a QKD protocol of the BB84 type [20] two users A and B try to establish a sequence of secret bits, the generated key K, between themselves that no eavesdropper Eve can know even with any active attack. The security is often claimed to be based on the laws of quantum physics as if the latter have to be violated in order for Eve to succeed. It is clear that quantum no-cloning is a necessary but far from sufficient condition for security. In particular, the possibility of approximate cloning shows the issue is a more complicated quantitative one. The more prevalent intuitive security idea is quantum disturbance-information trade-off, that the users could tell the presence of Eve by monitoring the system disturbance level if she gains an amount of "information" on K exceeding a given design level. Indeed, intrusion level estimation is a key part of all the typical QKD approaches. Henceforth the term QKD is used with the understanding that intrusion level estimation is involved.

To get sizable disturbance relative to the signal that can be readily estimated in QKD, the signal level needs to be low, say a single photon in BB84. Thus, the disturbance induced by Eve is easily masked by other unavoidable disturbance in a concrete realistic system even when such imperfection is small for other purposes. Furthermore, in an active attack Eve could in principle transform the quantum signals in many different ways and the users have to estimate her information gain under a given level of tolerable disturbance. It is now clear that security is a *quantitative* and *complicated* matter, and that there is no simple intuitive reason why any net key bits can be generated in QKD with whatever security, especially when the bits used for message authentication necessary for defending against man-in-the-middle attack are counted.

What security criterion should one use to measure the quantitative security level and why? In the literature this issue has *never* been correctly addressed. The mutual (accessible) information was used from the beginning but was found to contain a major loophole [21,22] and is by now largely abandoned. The trace distance criterion d [23,7-8] is at present nearly universally employed in QKD security analysis which is cited in [1] as the criterion that leads to "UC secrecy".

What is the level of d needed for UC secrecy? While one can distinguish perfect secrecy from UC secrecy, adequate UC security cannot be established by mere terminology or definition. It appears that the QKD security criterion is often thought to be a matter of choice by the designer, a wrong conception as we show presently. In [5] the following criteria are given in terms of Eve's optimal probabilities p_1 of successfully estimating various subsets of K from her attack. For raw security [3] where Eve only has information from the key generation process, the conditions are, with K^* being any subset of K and for any value k^* of K^*,

$$p_1(k^*) \leq 2^{-|K^*|} + \epsilon' \qquad (2)$$

for some chosen level ϵ' [5]. Under known-plaintext attack where Eve knows a subset segment $K_1 = k_1$ of K and estimates a subset K_2^* in the rest of K, the condition is, for some level of ϵ'',

$$p_1(k_2^*|K_1 = k_1) \leq 2^{-|K_2^*|} + \epsilon'' \qquad (3)$$

These probabilities have direct operational meaning in contrast to theoretical entities such as d or mutual information. The users have to decide what the ϵ' and

ϵ'' are for the cryptosystem to be sufficiently secure operationally in a particular application. In particular, if these levels cannot be guaranteed it means Eve may be able to guess the key portion K^* or K_2^* with a probability exceeding the prescribed level chosen by the users, thus the cryptosystem is *not* proven secure to its operational specification! Hence (2)-(3) are *necessary conditions* for security. They are not sufficient for one-time pad use of K, as discussed later.

Among different composition security situations, known-plaintext attacks have to be included in QKD security proofs. As discussed in [3], the raw security of conventional symmetric-key ciphers is far better than that of concrete QKD systems.

As explained in [2], Eve derives from her probe measurement a whole distribution P on all the 2^l possible K values. A single-number criterion merely expresses a constraint on P, but P itself should be compared to U for operational security guarantees. In particular, one has the form given in the left sides of (2)-(3) above for Eve's sequence success probabilities. In the ideal case, $\epsilon' = \epsilon'' = 0$ in (2)-(3). The levels ϵ' and ϵ'' can be stipulated by the system designer for different security needs. Under a $d \leq \epsilon$ guarantee, (2)-(3) hold only when averaged over all relevant key values [5] with $\epsilon' = \epsilon'' = \epsilon$.

From Markov inequality [24] such average guarantee can be converted into the individual guarantees (2)-(3) for *proper comparison with U* [25]. Operationally, average guarantee is *not* sufficient also because "failure probability" of some sort is required in the quality control of individual items in any production system. Thus, we have (2)-(3) with

$$\epsilon' = \epsilon'' = d^{1/3} \tag{4}$$

due to averaging of d with respect to the possible K values and the privacy amplification codes given in security proofs [4,5].

Our averaged conditions [5] are obtained for the classical variational distance [24] which is bounded by d upon measurement from Eve. They do not seem to have appeared before [26] in either the classical or quantum literature other than deterministic bit leak in raw security brought up in [3]. Probabilistic bit leaks of any level are covered in (2)-(3), and such leaks must also be guaranteed by quantitative bounds. Note that equality can be achieved for these bounds, i.e., there are Eve's distributions on K compatible with the $d \leq \epsilon$ guarantee which satisfy (2)-(3) with equality [2-5]. This shows they can be used with equality to measure the quantitative security guarantee on K.

What would be a sufficient condition for security? If ϵ' and ϵ'' are not small in the right scale with respect to l, (2)-(3) may *not* be sufficient depending on the application. Recall that the comparison reference of the distribution P of K is U. When K is used in one-time pad form, in addition to (2)-(3) Eve's average BER p_b in her estimate of the K bits has to be close to $1/2$ for security. (Note that p_b accounts for the correlation between the bits in K from its definition [4].) This is well known in data communications and is easily seen, that an incorrect sequence estimate on K may nevertheless produce a preponderance of correctlyy estimated key bits similar to what one may get from a biased a priori distribution of K that is different from U. It turns out that [4] only

$$\frac{1}{2} - p_b \leq d^{\frac{1}{4}}/2\sqrt{\log_2 e} \tag{5}$$

can be guaranteed for the whole K in raw security, there is no subset guarantee for either raw or known-plaintext attack security. However, if $d \sim 2^{-l}$ for $l \gg 1$ so that K is near-uniform, it appears K should be quantitatively secure for all conceivable applications as stated in [15]. Note that no composition security argument from the mere form of d [23] can guarantee p_b under known-plaintext attacks [4], while the wrong interpretation can [11], because K is U with a high probability $p \geq 1 - d$.

III THE INCORRECT INTERPRETATION OF d AND CLASSICAL CRYPTOGRAPHY

The prevalent interpretation is that d gives the probability that K is different from U with Eve's probe disconnected from K and thus giving composition security also [7-11]. This interpretation has repeatedly been pointed out to be incorrect in [2-5] to no avail, until the appearance of [1], which no longer cites such an interpretation but instead the correct one! The origin of the error comes from the interpretation of the variational distance $\delta(P, Q)$,

$$\delta(P, Q) = \frac{1}{2} \sum_i |P_i - Q_i| \tag{6}$$

between two classical probability distributions P and Q which is given to Proposition 2.1.1 in [7], that "the two settings described by P and P', respectively, cannot differ with probability more than ϵ." In our present notation or that of [8], $P' = Q$, and d is interpreted equivalently from Lemma 1 of [8] as the "probability that two random experiments described

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by P and Q, respectively, are different". We would not repeat the reasons and simple counter-examples [2-5] on why this interpretation is wrong. It does not follow from the mathematical statement of his Proposition 2.1.1, or the equivalent Lemma 1 of [8], through a joint distribution which gives P and Q as marginals, but rather from conceptual and verbal confusions. Instead, we point out here that any such joint distribution is irrelevant to the meaning of $\delta(P,Q)$. This is simply because the marginal distribution is just P regardless of what the underlying space of P is joined to. P does not suddenly become Q with a probablity $\delta(P,Q)$ in the presence of the given joint distribution. The wrong interpretation arose from basic conceptual confusions about the relation of probability concepts to the real world. It is amazing that it has perpetuated as far and as long as it has.

The variational distance is a well studied concept and nowhere else could one find such a strong interpretation as given in [7-8]. In particular, d is not so interpreted in [23]. Indeed, it is shown in [3] and easily seen from (6) that when $d > 0$, the distribution of K is *not* U with probability 1 (no probability issue here really) instead of d. Subtle and equivocal words in [1] may suggest that the wrong and correct interpretations of d (equivalently δ) are similar. Although the two interpretations quantitatively contradict each other, one may perhaps think they are numerically close. In particular, since "failure" includes the event where the whole K is compromised, it is important to understand the difference between the two interpretations precisely, as follows.

Prior to ref [5], which correctly proves known-plaintext attack security under $d \leq \epsilon$ for the first time, in the literature there are two incorrect/incomplete proofs of universal composition security. One of them [11] is invalid since it utilizes the wrong interpretation of d. With (3) from [5], known-plaintext attack security is established for Eve's sequence success probabilities but there is *no* similar guarantee for Eve's BER. In contrast, under the wrong interpretation Eve's BER $p_b = \frac{1}{2}$ with a probability $\geq 1-d$ for every k, on which counter-examples are easily constructed. In general, each different composition situation has to be treated under the correct meaning of d for quantitative guarantee, which cannot be given by just d or δ since they are not operational criteria. This fact alone shows the composition security claim on d in [23] in incomplete or invalid, since mathematical representation of operation security is lacking.

A further difference is that if K is not at least near uniform, one cannot use it to subtract for the bits $leak_{EC}$, given by (8) in section IV, while such bits need to be used in the middle of a valid security proof. Another difference is that Markov inequality needs to be applied only once under the wrong interpretation since there is no K-average needed, which results in $d^{1/2}$ instead of $d^{1/3}$ in (4).

Even *assuming* the wrong interpretation is true, the relatively large value of d that can be obtained is quite worrysome. For $d = 10^{-20}$, the operational guarantee (2)-(3) for a 10^6 bit key is not better than that of a 66 bit key! An arbitrary reason of system imperfection level given in footnote [15] of [1] is used to justify such numerical values. But why is $d = 10^{-20}$ sufficient for UC secrecy? In fact, the raw security operational guarantee (1)-(2) for $d = 10^{-20}$ is much worse than that obtained in conventional symmetric key ciphers [3].

Furthermore, there is no hint that such a d level of 10^{-20} can be obtained in a concrete protocol. If one takes into account Markov inequality for individual guarantee as discussed in section II, only an effective $d^{1/3} > 10^{-7}$ is obtained for $d = 10^{-20}$ after the K value average and privacy amplification code average are accounted for [4]. The effective $d^{1/3}$ value of $> 10^{-7}$ for $d = 10^{-20}$ is already very large for $l = 10^3$, not to say $l = 10^6$. The *only* concrete experimental protocol with quantified security level is given in [14,27] with effectively $d = 10^{-6}$. Then $d^{1/3} = 10^{-2}$ from [14] may entail a very drastic breach of security. Note that the $d = 10^{-20}$ level cannot even be achieved for a positive key rate in a "tight finite-key" analysis of single-photon BB84 [13], for which the best $d = 10^{-14}$ is obtained for $l = 1$! It should be emphasized that these effective $d^{1/3}$ values give *poor* security guarantee even according to the wrong interpretation. The corresponding BER guarantee of (5) is similarly poor.

In this connection, it is important to note that the size of d should be measured with respect to 2^{-l} according to the correct interpretation (2)-(3), not with respect to 1 according to the incorrect interpretation. This has been a major source of confusion, that since the system is evidently secure or ideal when a criterion takes the value zero hence it should be secure for a small value of the criterion. Yes, this is correct if "smallness" is measured in the correct scale, but 1 is not always the scale, an elementary point that is often forgotten when relative dimensional measure is ignored.

Similarly, the criterion d as "distinguishability advantage" is used to justify d as a security criterion in [23], which is also the justification for using variational distance in some classical cryptography work brought up in the last paragraph of [1]. While the distinguishability advantage was only established for

binary decisions, it is now established [5] for N-ary decisions for N between 2 and 2^l. However, the relevant point in this connection is that the required level ϵ in $d \leq \epsilon$ depends on what N in the N-ary decision is. A value good compared to $\frac{1}{2}$ for N=2 may be very inadequate relative to 1/N for N $= 2^l$, as we just discussed. This N-ary issue is another reason why composition security proof has to be spelled out precisely and quantitatively. Security is a quantitative issue through and through. Further discussion of such d meaning is given in [4].

The quantitative counter-example in [1] is irrelevant to begin with since we never deny (1) in its correct sense and we only insist (HY) is necessary for a near-uniform K when l is large. It may be mentioned that the counter-example uses a very strict meaning for his vague condition (HY) that neither Yuen nor Hirota ever indicated. The construction in the counter-example betrays the *same confusion* which underlies the erroneous interpretation of d [7-8]. In the counter-example, δ or d or ϵ is fixed at 2^{-l} and there is *no room* for another $\epsilon = 10^{-20}$ "by construction"! This is one conspicuous example of the several incoherences in [1].

In classical cryptography practice, encryption security is based on complexity, search for known-plaintext attacks on symmetric key ciphers and other computational ones in asymmetric key ciphers. The information theoretic security we talk about here for QKD plays no role except for one-time pad. Thus, the claim of [1] that classical cryptography is compromised without a small enough d is false, for this and the following reasons.

The bound storage model [28] with controllable information theoretic security is not used in practice while it has a criterion related to d, but there is a security parameter in [28] that could make it arbitrarily small which is not available in QKD. In particular, the key length l itself is not such a parameter once the proper criterion is employed in QKD [2], a point that will be elaborated in the next section IV. On the other hand, security is not fully established in [28] unless the criterion value goes to zero, precisely because N-ary decisions as well as Eve's bit error rate are not treated. In fact, security under known-plaintext attacks, which is the real issue for symmetric key ciphers [3], is also not treated in [28].

In public key cryptography the variational distance criterion from complexity consideration plays no role in practice. In fact the probabilistic encryption schemes that utilize such theory is not used due to its slow speed. Similar to [28], security for public key is not established in principle for N-ary decisions, Eve's bit error rate, and for known-plaintext attacks.

The actual situation is that other than one-time pad, no protocol in classical cryptography has been proven secure, information theoretically or computationally. Cryptography is still very much an art. Quantum cryptography aspires to provable security, a lofty goal that has been repeatedly claimed to be achieved from numerous errors of reasoning. Since security is a serious matter and cannot be established experimentally, we should examine all the security proof steps more carefully. A concise discussion of such steps and the state of QKD security proofs is given next.

IV   QKD SECURITY PROOF STATUS

There are five main steps involved in the general security proof of a BB84-type QKD protocol, assuming the physical modelling is complete and correct:

(i) Pick a security criterion and establish its operational guarantee is adequate;

(ii) Measure the quantum bit error rate (QBER) on the checked qubits and transfer it with proper statistical margin to the sifted key K'';

(iii) Bound Eve's relevant information on K'' under an arbitrary joint attack;

(iv) Apply an open error correcting code (EEC) and bound Eve's information on the corrected key K';

(v) Apply an open privacy amplification code (PAC) to generate the final key K and bound Eve's information on K according to the chosen criterion to obtain its quantitative level of security.

Each of these five steps has been treated incorrectly since the early days of QKD security proofs. At present, step (i) is almost resolved (apart from Eve's general bit error rate) in one way through the criterion d via (2)-(5) above. Step (v) can be resolved by the classical Leftover Hash Lemma [29]. We will discuss the other three steps in turn, the main impediment to progress in security proof is from steps (iii) and (iv).

Historically the Shor-Preskill proof [30] is most influential and widely quoted, but it is incomplete/incorrect for all five steps. Here it will be used as a representative and the other security approaches and proofs other than [13] will not be discussed. The Shor-Preskill proof employs the mutual accessible information criterion I_a without insisting it be small

enough. (In contrast to the impression from [21,22], the I_a criterion is actually fine if its level is at or below 2^{-l} for an l-bit key K [31].) The transfer of QBER is later amended in [32] for general joint attacks, which is still incorrect because it involves classical counting instead of qubit counting. It appears that correct quantum counting can be developed [33], which gives wider fluctuation or lower security level with a factor of two reduction in the exponent.

The major difficulty in QKD security proof arises from the correlation between key bits that are introduced by Eve's active joint attack and the user's ECC and PAC. To account for such correlation from a joint attack, step (iii) has mostly been achieved by some sort of symmetrization which does not appear to be valid. How does one get symmetry from an asymmetric situation? The usual argument (see, for example, the reduction of a general attack to collective attack in [7]) involving an openly known permutation cannot do any work since Eve knows it and could just rearrange back. A new argument is used in [13] which involves incorrect classical counting on qubits similar to [32] and moreover, does not work for sufficiently small d [15].

The information Eve has on the chosen ECC and PAC are not accounted for in the Shor-Preskill proof. In a direct development of the Shor-Preskill approach, Hayashi has recently incorporated such information for ECC [34] and PAC [35], which are yet to be evaluated for concrete protocols under general attack. In the meantime, the ECC information leak expression

$$leak_{EC} = h(\text{QBER}) \qquad (7)$$

where $h(\cdot)$ is the binary entropy function, is employed by him [36] and in fact universally [9,13,37] to account for such leak. It is pointed out [15] that there is the possibility of information leak from ECC similar to quantum information locking leak [15] that undermines inadequate values of accessible information as a security criterion, and which is neglected in the expression (7). Furthermore, (7) can be justified only for collective attacks asymptotically. Collective attack is extremely restrictive, Eve can launch what is called a joint attack without any entanglement by just attacking a portion of the key bits (which seems to suggest already that collective attacks cannot be optimal for any of Eve's aim, not to mention for this $leak_{EC}$ issue). Indeed, *no* justification for such a crucial treatment of step (iv) by (7) has ever been spelled out because there is *none*. It cannot be true for all attacks if one examines its meaning [15]. This ECC information leakage problem (iv) and also the joint attack problem (iii) appear to be very difficult to resolve in QKD security proofs.

The condition (7) by itself shows that the near-universal step of subtracting it from the generated key bits to get the final K is *invalid*, unless perhaps when the d level of K is so small that (2)-(3) imply the bits are nearly uniform and K functions effectively as U. This is a problem *even* if the users decide that a given large d level is sufficient for security. The security proof itself is supposedly carried out with uniform bits in the amount (7). Note that Even could launch a joint attack just to invalidate (7) regardless of whether collective attack is optimum from the viewpoint of her information gain on K. She may want to minimize the users' key rate which may not turn out positive.

Apart from all these theory problems, the security proof claims are often used by experimentalists to claim security for their systems in an invalid way. For example, the Shor-Preskill asymptotic key rate is often quoted as the system capability, with *no* mention of the criterion and its quantitative level. Equally significantly, Shor-Preskill only claimed to have established such rate for a joint CSS code as ECC and PAC. In [38], for example, the cascade reconciliation protocol is used for error correction which has numerous problems [39] and universal hashing is used for PAC. However, it has *never* been shown that the Shor-Preskill key rate applies to such error correction and privacy amplification procedures.

The asymptotic convergence rate for various criteria yields the actual (asymptotic) key rate for fixed levels of d or p_1 [2,25], and is not given in [24] for its mutual information criterion. In this connection, we would like to bring out a *common misconception* concerning QKD security. Since [30] it is often thought that as long as the key rate is below a certain threshold, security level can be made arbitrarily close to the ideal when the key length l is indefinitely increased. That is, l is taken to be a security parameter, and that is likely why only the secure key rate is quoted in many papers including [38]. Perhaps this is thought to be in analogy with Shannon's Channel Coding Theorem [24], which says that for data rate below capacity, the error rate can be made arbitrarily small for long enough block length. Sometimes it is thought that finite privacy amplification is what renders this untrue. We would like to point out here that the problem is present even asymptotically for any $l \to \infty$, as follows [2].

For key rate below a threshold, let us assume it is indeed proved that Eve's accessible information I_a (or d) goes to 0 as $l \to \infty$, exponentially as $\sim 2^{-\lambda l}$ for some $0 < \lambda < 1$,

$$d \sim 2^{-\lambda l} \text{ or } I_a/l \sim 2^{-\lambda l} \qquad (8)$$

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The situation for finite l is the same. The security level for those l bits is very different depending on what exactly λ is. It is near ideal for $\lambda = 1$ but very far from ideal for $\lambda << 1$. Indeed, Eve's maximum probability p_1 of estimating the whole K sets the limit on the number of uniform bits that can be generated since $p_1 = 2^{-n}$ for n uniformly distributed bits. Thus, it is the *rate* of p_1 or equivalently I_a/l going to zero that determines the rate of uniform key generation, *not* the original key rate threshold [2,15]. It turns out the convergence rate λ in (8) is very small for d in [13], and not evaluated for I_a/l in other proofs except [27] which leads to an even smaller λ [14]. With $d = 10^{-20}$ and $l = 10^6$, $\lambda \sim \frac{2}{3} \times 10^{-4}$ resulting in 66 bits guarantee of (2)-(3) for 10^6 bits, or just 22 bits from (4) after Markov inequality is applied. In [13] the best $d = 10^{-14}$ or $d^{1/3} > 10^{-5}$, and in [14] $I_a/l \sim 10^{-6}$ equivalent to $d^{1/3} \sim 10^{-2}$.

One can relax uniform K to ϵ-secrecy via ϵ-smooth entropy [40]. Intuitively, one cannot expect much would be accomplished when ϵ is only moderately larger than 2^{-l}. In fact, even for very large d for a given l, the results of [13] shows the key rate is still very low.

Thus, the exchange of key rate and security level is a *fundamental* fact in all QKD protocols, asymptotic or finite, and l is not a security parameter. In fact, one needs to prove that a *positive* exponent $\lambda > 0$ would result in (8) which is far from guaranteed. This is especially the case when all system imperfections and message authentication bits are taken into account. Together with the numerical values obtained in [13], this fundamental tradeoff between key rate and security level gives a grim picture of the usefulness of BB84 type protocols.

In QKD security proofs there are numerous problems associated with physical modelling that have been ignored or neglected. We may point out the case of general lossy channel security [16], photon number splitting attacks on multi-photon sources and decoy states [18], and heterodyne-resend attack in CV-QKD [19]. Security is seriously undermined in the last two situations against the prevalent security claims on them. In particular, a grave issue that has been generally overlooked is to what extent the users could accurately determine the various system parameters such as loss, a serious *robustness* issue for security. The well known detector blinding attacks [41] shows detailed detector behavior has to be explicitly represented in a real security proof [17], but so far it has not been done.

V COMMON MISCONCEPTIONS ON QKD SECURITY

The list in the following corrects some major misconceptions on QKD security, most of which have been discussed in this paper as part of our response to [1].

(a) Any single-number security criterion, other than the wrong interpretation of d in [7,8], is not sufficient for security by itself. For operationally meaningful security guarantee, it has to be quantitatively reduced to bounds on Eve's various success probabilities in estimating segments of the key and also her average bit error rate.

(b) One cannot prescribe, as done in [1], that some chosen numerical level of a criterion is always sufficient for security when the level is far from ideal. It is the application user of the cryptosystem who decides what level is adequate for a specific application.

(c) There is a fundamental exchange between key rate and security level. It is not the case that security can be made arbitrarily close to ideal for key rate below a certain threshold. It is the cryptosystem designer's responsibility to evaluate such quantitative tradeoff. The results of [13] give poor security level even at very low key rate.

(d) Contrary to widespread impression, there is no valid QKD general security proof in the literature. For example, the error correction step has never been treated correctly. The burden of proof is on those who claim security, not on other to produce a specific counter-example on the security claim.

(e) As a consequence of (d) and in view of the fundamental difficulties discussed in this paper, QKD is at present no different in security status from other cryptosystems under study or in use. It does not have the advantage of having been proved unconditionally secure in principle.

(f) The problem of complete system representation for security claim is not a "practical security" issue for the application user, but rather a basic one. The incomplete modelling of system component behavior, such as photodetector temporal response to different input signal levels, is not a mere "side channel" issue but a main issue of model completeness, without which there can be no proof of security.

VI CONCLUSION

It is hard to avoid the impression that Eve's standpoint has rarely been taken seriously in the literature and the main concern has been to claim security. A common mistake in general security proofs is to analyze only one type of attacks but claiming unconditional security against all possible attacks. Security is a serious matter. There are an unlimited number of attack scenarios, thus security can only be established theoretically if at all and the burden of proof is on those who claim security. Attacks from the Norway group [41] shows how dangerous a faulty claim may be, with security totally compromised in an unexpected way, a situation actually familiar in conventional cryptography. When addressing security issues it would be good to keep the following question in mind:

How did we come to the present QKD security predicament with endless invalid security proofs?

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