Quantum Tagging for Tags Containing Secret Classical Data

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(Dated: August 2010; revised July 2011 (extended discussion; scheme unaltered))

Various authors have considered schemes for quantum tagging, that is, authenticating the classical location of a classical tagging device by sending and receiving quantum signals from suitably located distant sites, in an environment controlled by an adversary whose quantum information processing and transmitting power is potentially unbounded. All of the schemes proposed elsewhere in the literature assume that the adversary is able to inspect the interior of the tagging device. All of these schemes have been shown to be breakable if the adversary has unbounded predistributed entanglement. We consider here the case in which the tagging device contains a finite key string shared with distant sites but kept secret from the adversary, and show this allows the location of the tagging device to be authenticated securely and indefinitely. Our protocol relies on quantum key distribution between the tagging device and at least one distant site, and demonstrates a new practical application of quantum key distribution. It also illustrates that the attainable security in position-based cryptography can depend crucially on apparently subtle details in the security scenario considered.

INTRODUCTION

There is now a great deal of theoretical and practical interest in the possibility of basing unconditionally secure cryptographic tasks on some form of no signalling principle as well as, or even instead of, the laws of non-relativistic quantum theory. The earliest examples of which we are aware are bit commitment protocols based on no signalling [1, 2], which are provably secure against all classical attacks and against Mayers-Lo-Chau quantum attacks. Another significant development was the first secure quantum key distribution protocol based on no signalling [3], which was followed by other schemes and stronger security results [4–9]. Other interesting examples include a protocol for variable bias coin tossing [10], and recent results based on the no-summoning theorem [11], including a protocol for location-oblivious data transfer [12] and a simple practical and provably unconditionally secure quantum relativistic protocol for bit commitment [13].

The idea of quantum tagging – authenticating the location of a tagging device (or tag) by exchanging classical and quantum information with a number of suitably located sites – has recently been independently considered by several authors[14–17]. A scheme which offers security against current technology, but is not unconditionally secure, was patented in 2006 [14]. Other schemes initially presented as unconditionally secure[15, 16] were recently proposed, but subsequently shown to be breakable by teleportation-based attacks [17]. These attacks were significantly extended [18] and shown to apply to a large class of tagging schemes, including some discussed in Ref. [17], where their security was left as an open question, and others conjectured to be secure in Ref. [19]. However, it appears that all the schemes proposed in Refs. [14–17, 19] may be secure against eavesdroppers who are unable to predistribute and store entanglement; this is proven [16, 18] for the schemes of Ref. [16]. All of these schemes implicitly or explicitly assume a security model in which an adversary can send signals through the tag, and can observe its interior workings, but cannot manipulate information within it.

Quantum tagging, and other tasks in position-based quantum cryptography [16, 18], raise new questions about cryptographic security assumptions. It seems reasonable to think of the remote sites which exchange signals with the tag as secure laboratories, to which the standard cryptographic assumptions for sending and receiving stations apply. In particular, it seems reasonable to assume that classical and quantum data can be generated, processed and stored securely within these sites, in a way that prevents an adversary from reading classical data, measuring quantum data, or interfering with any processing.

On the other hand, there is more than one sensible and practically relevant security scenario for the tag. One can imagine scenarios in which the sending and receiving stations are large and cryptographically hardened, while the tag is designed to be small, is operating in a more hostile environment, and therefore cannot utilize the same resources or guarantee the same level of security. It may make sense in such a scenario to assume that an adversary can send signals through a tag, and inspect its interior at will, even if the tag is protected well enough that direct physical sabotage is not possible (at least within a short enough time interval to allow the tagging protocol to be spoofed). Equally, though, one can imagine scenarios in which the tagging device and sending and receiving stations are all
functionally equivalent – for instance, are all satellites – and should all be covered by the same security model. In this case, the standard cryptographic assumptions imply that both the tag and the distant sites can keep data secret from the adversary.

Practical considerations aside, quantum tagging raises interesting theoretical questions when considered as a more abstract problem about the possible query-response tasks that an agent can carry out given control of only a subset $R$ of Minkowski space. In this context too it is interesting to consider different types of tasks, in which, for example, the agent may or may not be allowed to send signals through the complement $\bar{R}$ of $R$ and infer information about localized physical states in $\bar{R}$.

All of these points suggest it is worth thinking carefully about the various possible security models for quantum tagging. An even stronger motivation comes from recent results of [18] showing that a large class of quantum tagging schemes are not unconditionally secure, and their conjecture that these results extend to all quantum tagging schemes within the security model considered to date. It would clearly be advantageous to have unconditionally secure tagging schemes if they are available within a reasonable security model. It would also be very interesting, for both theoretical and practical reasons, to understand what are the minimal security resources required to ensure unconditionally secure tagging.

In this paper we show that unconditionally secure quantum tagging is indeed possible and can be sustained indefinitely within a sensible security scenario, in which the tag, like the sending and receiving stations, is able to keep classical data secret from the adversary. We give a simple secure tagging protocol in this scenario, which uses quantum key distribution (more precisely, quantum key expansion) between one (or more) site(s) and the tag, and then uses the generated secret key as a resource for secure authentication of the tag’s position. The protocol defines a new, simple and practical application of quantum key distribution. Our protocol appears reasonably efficient, but we do not know whether it is close to optimally efficient, or whether perhaps significantly greater efficiency can be achieved by other means, for example by protocols that do not use quantum key distribution as an explicit sub-protocol. This is an interesting and potentially practically significant open question.

**PREVIOUSLY CONSIDERED SCENARIOS**

We work within Minkowski space-time, $M^{(n,1)}$, with $n$ space dimensions. The most practically relevant case is $n = 3$ [20]. However, we will initially consider the case of one space dimension, which simplifies the discussion while illustrating all the key points. Tagging schemes rely on using signalling constraints to give a lower bound on the distance between the tag and remote sites. In our scheme, once one sees this can be done securely for a tag between two remote sites in one dimension, it is easy to see that the same applies for a tag within the convex hull of $n + 1$ remote sites in $n$ dimensions, using multilateration.

The following two security scenarios for quantum tagging were defined in Ref. [17], from which (to avoid any possible confusion by altering language) we quote verbatim. We take these as the standard definitions for the task as analysed to date: earlier discussions in the academic literature [15, 16] were less than fully explicit about their possible confusion by altering language) we quote verbatim. We take these as the standard definitions for the task as analysed to date: earlier discussions in the academic literature [15, 16] were less than fully explicit about their security scenario, and subsequent work [18, 19] to date has followed these definitions, implicitly or explicitly.

**Security scenario I**

Alice operates cryptoographically secure sending and receiving stations $A_0$ and $A_1$, located in small regions (whose size we will assume here is negligible, to simplify the discussion) around distinct points $a_0$ and $a_1$ on the real line. The locations of these stations are known to and trusted by Alice, and the stations contain synchronized clocks trusted by Alice. Her tagging device $T$ occupies a finite region $[t_0, t_1]$ of the line in between these stations, so that $a_0 < t_0 < t_1 < a_1$. The tagging device contains trusted classical and/or quantum receivers, computers and transmitters, which are located in a small region (which again, to simplify the discussion, we assume is of negligible size compared with $\langle t_1 - t_0 \rangle$ and other parameters) around the fixed point $t_+ = \frac{1}{2}(t_0 + t_1)$. The device is designed to follow a protocol in which classical and/or quantum outputs are generated via the computer from inputs defined by the received signals. The outputs are sent in one or both directions, left and/or right (i.e. towards $a_0$ and/or $a_1$), this choice again in general depending on the inputs. The tagging device may also contain a trusted clock, in which case the clock time is another allowed input.

We assume that signals can be sent from $A_i$ to $T$, and within $T$, at light speed, and that the time for information processing within $T$ (or elsewhere) is negligible. $T$ is assumed *immobile* and *physically secure*, in the sense that an adversary Eve can neither move it nor alter its interior structure. However, $T$ is not assumed *impenetrable* by Eve:
Eve may be able to send signals through it at light speed. Nor (for now – we will reconsider this below) is it assumed cryptographically secure: Eve may also be able to inspect its interior. In particular, T contains no classical or quantum data which Alice can safely assume secret, and she must thus assume that its protocol for generating outputs from inputs is potentially public knowledge.

T can be switched on or off. When switched off, it remains immobile and physically secure, and simply allows any signals sent towards it to propagate unmodified through it: in particular, signals travelling at light speed outside T also travel through T at light speed.

Eve may control any region of space outside A_i and T, may send classical or quantum signals at light speed through A_i and T without A (or T) detecting them, may be able to jam any signals sent by A_i or T, and may carry out arbitrary classical and quantum operations, with negligible computing time, anywhere in the regions she controls. Eve cannot cause any information processing to take place within T, other than the (computationally trivial) operation of transmitting arbitrary signals through T, except for the operations that T is designed to carry out on appropriate input signals. Her task is to find a strategy which spoofs the actions of T, that is, makes it appear to A that T is switched on when it is in fact switched off. Conversely, A’s task is to design T, together with a tagging protocol with security parameter N, so that the chance, p(N), of E successfully spoofing T throughout a given time interval ∆t obeys p(N) → 0 as N → ∞.

Security scenario II

In scenario II, the tag is physically secure, but not immobile. Eve can move it, without disturbing its inner workings, at any speed up to some bound v, known to Alice. Clearly v = c, the speed of light, gives an absolute upper bound. To avoid considering relativistic effects, we assume v ≪ c in this scenario.

NEW SECURITY SCENARIO: A CRYPTOGRAPHICALLY SECURE TAG

While the above scenarios may be the most reasonable in some important contexts, they are not the only interesting ones. As we have already noted above, in quantum key distribution schemes, and other cryptographic schemes based on physics, one normally assumes that Alice’s laboratories are cryptographically secure. That is, Eve cannot to gain any information about the physics taking place within these laboratories or affect it in any way: she cannot read any classical or quantum data generated within the laboratories, nor alter any of the devices within the laboratories that generate or process data.

To be sure, whether or not this is justified in any given context is a significant empirical question. However, cryptography is useless if one cannot generate or process information securely anywhere. And if it is reasonable to suppose that the remote sites A_i can be made cryptographically secure, it is also reasonable (in appropriate scenarios) to suppose that T can too. So, we now consider variants of the above security models, in which both the A_i and T are cryptographically secure. Specifically, and crucially, we suppose that T can contain a finite secret classical bit string, preshared with and hence known to A, which is E unable to read by any means.

Note that we do not suppose that T is impenetrable to Eve: we suppose that she may be able to send signals at light speed through T (and indeed, though it is less relevant, through the A_i). There are at least two good reasons for this. First, impenetrability would be a logically stronger assumption, which (it turns out) we do not need to make, and we are interested in identifying the minimal necessary assumptions here. Second, the distinction is sensible in practice: one can easily imagine regions secure enough that Eve cannot, practically speaking, get a useful detailed image of their interior, but which are nonetheless semi-transparent to signals on some frequency or of some type. In fact, every putatively secure cryptographic site has the latter feature (as a reductio, consider the possibility of Eve signalling with gamma ray bursts, neutrino beams, or high energy shock waves).

A secure tagging protocol using a cryptographically secure tag

We need one further assumption: that A and T were at one point able to share a finite secret random bit string while maintaining its secrecy. This seems reasonable for many, perhaps most, applications of tagging: if Alice has T within one of her laboratories at some point prior to the tagging protocol, she can include the shared random key at this point. Given this, and given that the A_i and T are cryptographically secure, A and T can carry out a secure quantum key distribution – or, more precisely, quantum key expansion – protocol, using the initial shared random
Quantum key expansion between $A_0$ and $T$ generates shared secret key $k$.
Each $A_i$ sends queries to $T$, which returns the requested key bits.

**FIG. 1:** One implementation of secure tagging in two dimensions. Here the key is generated by quantum key expansion between $A_0$ and $T$. $A_0$ shares the key with $A_1$ and $A_2$ either via secure communication based on quantum key expansion, or by transmitting relevant key bits after they have been queried.

Consider the following tagging scheme (recall that for now we are working in one space dimension).

1. $A$ sends a series of independently randomly chosen bits, $a_i$, from $A_0$, and another series of independently randomly chosen bits, $b_i$, from $A_1$. These signals are sent at light speed, timed so as to arrive pairwise simultaneously at $t_i$: that is, $a_1$ and $b_1$ arrive together, then $a_2$ and $b_2$, and so on.
2. On receiving $a_i$ and $b_i$, $T$ immediately retrieves the key bit $k_{4i+2a_i+b_i}$ from memory storage, and sends this bit at light speed to both $A_0$ and $A_1$.
3. $A$ tests that the outputs are correct and arrived at the appropriate times. If this test is passed for $N$ successive bit pairs, sent within the interval $\Delta t$, she accepts the location of $T$ as authenticated.

This scheme is evidently secure under both scenarios. In scenario I, if $T$ is switched off, then $T$ will not release the relevant key bits (even if $T$ was able to generate them before being switched off). $E$ thus has no information about which key bit value to broadcast, and will send the wrong value with probability $1/2$ per query.

In scenario II, the relevant key bit is known only to $A$ and $T$ until $T$ receives instructions to broadcast it. $T$ will only ever release and broadcast one out of the four bits $k_{4i}$, $k_{4i+1}$, $k_{4i+2}$, $k_{4i+3}$. $E$ cannot identify which of these bits should be broadcast until she knows both $a_i$ and $b_i$; if she generates and supplies her own input on one side (or both) to a relocated $T$ before the correct bit arrives from $A$, she risks obtaining an incorrect key bit from the string as output, in which case $T$ will never release the correct key bit. Any relocation of $T$ thus either introduces a detectable delay in the responses to $A_0$ or $A_1$, or (with probability $1/2$ per query) causes incorrect key bit values to be sent, or both.

**COMMENTS**

It might at first sight seem puzzling that secure tagging requires a protocol involving anything more than secure communication channels, since one might think that the tag can identify its own position using something like GPS technology and then securely broadcast this information to Alice over shared secure channels. Note, however, that in
all our scenarios, we make the cryptographically standard assumption that everything except $T$ and $A$’s laboratories is potentially under the control of Eve, and hence cannot be trusted. In particular, $T$ cannot trust any remote GPS system to give accurate readings. More generally, we cannot (without giving $T$ more internal resources) assume that $T$ initially knows its own position.

We have seen that tagging can nonetheless be securely implemented using a quantum protocol – essentially bootstrapping on the security of quantum key expansion – under the assumption of a cryptographically secure tag. This scheme has the advantage that it does not require $T$ to contain even a trusted clock. It can easily be extended to higher dimensions, using suitably located sending and receiving stations to authenticate each of the tag’s coordinates. An efficient way to do this is by authenticated multilateration within the convex region spanned by Alice’s laboratories.

For example, in three dimensions, Alice could proceed as follows. She sets up four laboratories $A_i$ which do not lie in a common plane. Using quantum key expansion, she generates a shared secret key with the tag, which is split into four separate keys $k_i$, which themselves are split into length two blocks.

This does not necessarily require QKE to be implemented between all four $A_i$ and the tag: a QKE link from $A_0$ to $T$ suffices. $A_0$ can share the keys $k_i$ with the other $A_i$ using QKE links from $A_0$ to $A_i$. Alternatively, bits from these keys can be shared over an authenticated, but not necessarily secret, link, after $A_i$ has (allegedly) received the relevant bits from $T$. This adds to the delay in authenticating position, but does not compromise its security.

Each $A_i$ sends at light speed requests to $T$ for randomly chosen bits from successive blocks of the key $k_i$, and $T$ immediately returns the requested bits. This allows each $A_i$ to obtain an authenticated bound on its distance from $T$. Comparing these bounds allows the $A_i$ to authenticate the location of $T$, provided that $T$ lies within the tetrahedron that they span.

Clearly, the scheme could be modified in many ways. One interesting option is to use the shared key generated by quantum key expansion to authenticate the tagging messages sent between $A$ and $T$. While this is not necessary for the security of the scheme, it does make security even more transparent, since authenticating all transmissions effectively eliminates the possibility of successful spoofing. It also has the advantage of making it much harder for Eve (or random noise) to interfere with the tagging protocol by sending fake inputs to the tag – although, of course, if Eve has sufficiently advanced technology, resources and determination she can jam any quantum cryptography scheme, and in particular any tagging scheme. It might too have some efficiency advantages in some scenarios.

Our protocol is intrinsically quantum, in the sense that it requires quantum information to be sent in at least one direction between at least one of the $A_i$ and $T$, in order to use the power of quantum key expansion to generate an arbitrarily long shared secret bit string from the initial finite shared secret bit string. This allows the tagging scheme to continue indefinitely. Without the use of quantum key expansion, the duration of the tagging scheme is limited by the size of the secure memory that the tag can contain. Of course, a finite duration classical tagging scheme may well be useful in some scenarios, just as a finite classical one-time pad can be useful for sending secret messages of limited length. In both cases, the power of using quantum information is that it allows secure transmissions to be continued indefinitely, even though the physically secure resources initially (and indeed at any later time) are necessarily finite.

ACKNOWLEDGEMENTS

This work was partially supported by an FQXi mini-grant and by Perimeter Institute for Theoretical Physics. Research at Perimeter Institute is supported by the Government of Canada through Industry Canada and by the Province of Ontario through the Ministry of Research and Innovation. I thank William Munro, Jonathan Oppenheim, Timothy Spiller and Damian Pitalua-Garcia for helpful conversations.

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