

Flexible quantum tokens in spacetimeAdrian Kent^{1,2,*} and Damián Pitalúa-García^{1,†}¹*Centre for Quantum Information and Foundations, DAMTP, Centre for Mathematical Sciences, University of Cambridge, Cambridge CB3 0WA, United Kingdom*²*Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada N2L 2Y5*

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S-money [A. Kent, *Proc. R. Soc. A* **475**, 20190170 (2019)] schemes define virtual tokens designed for networks with relativistic or other trusted signaling constraints. The tokens allow near-instant verification and guarantee unforgeability without requiring quantum state storage. We present refined two stage S-money schemes. The first stage, which may involve quantum information exchange, generates private user token data. In the second stage, which need only involve classical communications, users determine the valid presentation point, without revealing it to the issuer. This refinement allows the user to determine the presentation point anywhere in the causal past of all valid presentation points. It also allows flexible transfer of tokens among users without compromising user privacy.

DOI: [10.1103/PhysRevA.101.022309](https://doi.org/10.1103/PhysRevA.101.022309)**I. INTRODUCTION**

Money and other type of tokens allow a user to access a resource, while guaranteeing to the issuer that the tokens cannot be forged. Quantum money and quantum token schemes [1–4] can theoretically guarantee unforgeability with unconditional security. However, standard quantum money and quantum token schemes are impractical with current technology because they require long-term quantum state storage. Quantum memories cannot currently store quantum states reliably for more than a fraction of a second. Although longer term quantum memories will presumably be developed in future, it is unclear whether (or when) quantum memory technology will ever be competitive in price and practicality with classical alternatives.

S-money [5] schemes [6–9] offer alternatives to quantum money that do not require quantum memory and can respond more flexibly to generalized summoning tasks [6]. However, many other theoretical and practical questions about the relative advantages, implementability and resource costs of S-money and quantum money token schemes remain to be addressed. In our view, both technologies are potentially promising and merit further refinement and development.

In this paper we describe refinements of S-money schemes that improve their flexibility and transferability. We focus on a single round implementation of a simple quantum S-money token scheme in order to illustrate the essential ideas; it is straightforward to extend these to multiple rounds, to other types of S-money token, to schemes involving subtokens, and to more complex scenarios. We also simplify the discussion by focusing on an S-money scheme that guarantees unforgeability and future privacy for the user, without the extra cryptographic layer required to ensure past privacy; again, the extension is straightforward.

II. FLEXIBLE S-MONEY

We follow the standard scenario for S-money [6]. The issuer (Bob the bank) consists of a network of local agents based at secure sites, with authenticated and secure communication links, working in collaboration and with mutual trust. Similarly, the user (Alice the acquirer) consists of a network of local agents based at secure sites, with authenticated and secure communication links, working in collaboration and with mutual trust. The user and issuer agree to implement the scheme but do not trust one another to behave honestly. The user's secure sites do not overlap with the issuer's. The user and issuer agree on a reference frame, where spacetime coordinates are defined. The user and issuer agree in advance on a set of presentation points Q_i , where the user can present an S-money token to the issuer in order to access a resource. The scheme begins at some start point P with $P \prec Q_i$ (that is, P is in the causal past of Q_i) for all i . To be precise, both P and the Q_i actually represent localized spacetime regions containing separate secure sites for the user and issuer, with a time window allowing prescribed communications between these sites. Because the spatial and/or temporal separations between these regions are large (in the relevant rest frame) compared to those of the regions, we can think of them as effectively points on a spacetime network. The token scheme is initiated by classical and/or quantum information communications between user and issuer agents at P . To consider transferability of tokens we refer to two or more users (Alice₁, Alice₂, . . .). In this case each user has his or her own separate secure site at each relevant network point.

A. Bit-string coordination and S-money schemes

These schemes are based on bit-string coordination [6] protocols between the user and issuer. Bit-string coordination is an intrinsically relativistic task in which the user inputs, or *commits*, a string b at some point in spacetime and later *unveils* by giving classical data to the issuer to show that her input

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was b . A secure implementation of bit-string coordination satisfies two security properties: binding and hiding. We say a protocol is *binding* if it guarantees to the issuer that if the user successfully proves having input b , then she cannot also prove (either at the same spacetime point or elsewhere) having input a different string b' . We say a protocol is *hiding* if it guarantees to the user that the issuer cannot know b until it is unveiled by the user. Bit-string coordination is similar to but weaker than bit-string commitment, which also needs to guarantee to the issuer that the user committed to her input at some specified start point. In this paper we apply the language of bit-string commitment to bit-string coordination, as specified above.

In the S-money schemes [6,7] we consider here, the user defines her bit string by choices of measurements on quantum states sent by the issuer. The schemes and our refinements are secure regardless of the user's technological limitations. However, to simplify the discussion, we will assume the user is technologically limited and has no quantum state storage, which effectively forces her to carry out these measurements on receipt. Given this limitation, the bit-string coordination protocol effectively becomes a bit-string commitment protocol, with the commitment being made when the states are measured. Specifically, the commitment phase for each bit in the string is that of the BB84 bit commitment protocol of Ref. [10], whose security was analyzed in Refs. [10–13]. This protocol was implemented experimentally [13] with a modification involving precommitment to a random string in order to allow practical implementation without requiring long distance quantum communication. This technique was used also used in practical protocols for spacetime-constrained oblivious transfer [14,15]. We use variations on this idea here.

1. Example of a bit coordination scheme

We present a simple bit coordination scheme given in Ref. [7], which is based on the bit commitment protocol of Ref. [10], to illustrate why bit-string coordination and bit-string commitment are different tasks.

Let $\{|0\rangle, |1\rangle, |+\rangle, |-\rangle\}$ be the set of Bennett-Brassard 1984 (BB84) states, where $|\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$ and where the states $|0\rangle$ and $|1\rangle$ are orthonormal. We define the following qubit states:

$$|\phi_0^0\rangle = |0\rangle, \quad |\phi_1^0\rangle = |1\rangle, \quad |\phi_0^1\rangle = |+\rangle, \quad |\phi_1^1\rangle = |-\rangle. \quad (1)$$

Let $n \in \mathbb{N}$ be a security parameter. For strings $\mathbf{r}, \mathbf{s} \in \{0, 1\}^n$, let their respective bit entries be denoted by $r_l, s_l \in \{0, 1\}$, for $l \in [n]$, where we define $[n] = \{1, 2, \dots, n\}$. We define the state

$$|\Psi_{\mathbf{r}, \mathbf{s}}\rangle = \bigotimes_{l \in [n]} |\phi_{r_l}^{s_l}\rangle, \quad (2)$$

for $\mathbf{r}, \mathbf{s} \in \{0, 1\}^n$.

The issuer generates a state $|\Psi\rangle = |\Psi_{\mathbf{r}, \mathbf{s}}\rangle$ of n qubits, with \mathbf{r} and \mathbf{s} chosen randomly from $\{0, 1\}^n$, and sends $|\Psi\rangle$ to the user at a spacetime point P . The issuer sends the labels l of the transmitted qubits, for $l \in [n]$. The user commits to the bit $b = 0$ by measuring all received qubits in the computational basis ($\{|0\rangle, |1\rangle\}$) or to the bit $b = 1$ by measuring all received qubits in the Hadamard basis ($\{|+\rangle, |-\rangle\}$). Let y_l be the bit

measurement outcome corresponding to the qubit labeled by l , for $l \in [n]$, and let $\mathbf{y} = (y_1, \dots, y_n)$. The user unveils at some point $Q > P$ by giving the bit b and the string of outcomes \mathbf{y} to the issuer. In the ideal case that errors are not tolerated, the issuer accepts b as valid if $y_l = r_l$ for all $l \in [n]$ satisfying $s_l = b$. This means, for example, that if the user unveils $b = 0$, and he is being honest, he measured all qubits in the computational basis; hence, the user obtains the correct outcomes for all qubits prepared by the issuer in the computational basis. In a realistic case, the issuer accepts b as valid if it holds that $y_l \neq r_l$ for no more than $\gamma|\Omega_b|$ qubits with labels $l \in \Omega_b$, where $\Omega_b = \{l \in [n] | s_l = b\}$, for a predetermined small-enough $\gamma \in (0, \frac{1}{2})$.

This bit coordination protocol is hiding because the user does not give any information to the issuer about her chosen bit b before she unveils. It is binding because the user cannot, at any two points Q, Q' , give the issuer two n -bit strings $\mathbf{y} = (y_1, \dots, y_n)$ and $\mathbf{z} = (z_1, \dots, z_n)$, corresponding, respectively, to unveiling $b = 0$ and $b = 1$, that satisfy both conditions (1) $y_l \neq r_l$ for no more than $\gamma|\Omega_0|$ qubits with labels $l \in \Omega_0$ and (2) $z_l \neq r_l$ for no more than $\gamma|\Omega_1|$ qubits with labels $l \in \Omega_1$ for a predetermined small-enough $\gamma \in (0, \frac{1}{2})$. This property follows from the security analyses given in Refs. [10–13,16].

However, this does not define an unconditionally secure bit commitment protocol, since the issuer receives no useful guarantee on the spacetime region where the user chose b . For example, a technologically unlimited user could store all received states in a perfect quantum memory, send them to Q , and measure them there in the relevant basis just before unveiling b . The issuer is guaranteed that the bit was chosen at some point $Q' \leq Q$ but not that it was chosen at P or any other specified point $Q' < Q$.

B. Limitations of previous S-money schemes

1. Initiation time

The bit coordination protocol just discussed can be repeated N times, giving an N -bit-string coordination protocol [6]. This defines a simple S-money token protocol [6,7], in which the bit string labels the point Q_i (for $i \in \{0, 1\}^N$) at which the token may validly be presented. The S-money scheme is initiated by the issuer sending a string of quantum states to the user at the start point. In the ideal version, these states are pure qubits drawn randomly from the four BB84 states, sent along a lossless channel, and the user carries out perfect BB84 basis measurements on each state. In practical embodiments with photonic systems, this quantum communication step involves generating a sequence of weak photon pulses, with some errors in the polarizations chosen, some losses, and some measurement errors. Depending on the experimental parameters, a reasonable level of security may require the transmission and measurement of a large number of photon pulses. With current technology, this could take at least a few seconds. In an S-money scheme, this would require the user to choose her presentation point Q_b at least a few seconds in the past of Q_b .

This is a significant and undesirable limitation, since S-money schemes are intended for application in relativistic scenarios where time is critical and where decisions about when and where to present the S-money are ideally made as

flexibly as possible (and in particular as late as possible) on the basis of incoming information received at various spacetime points.

Quantum technology is developing rapidly, and it may be possible to generate, send, and measure enough quantum states to initiate secure tokens within very short time intervals in the future. Nonetheless, we think it likely that the alternatives we discuss below, which require only classical communications at the critical decision point(s), will continue to be faster and cheaper. Our discussion and illustrations rely only on this assumption, rather than on specific quantitative estimates.

2. Transferability and transfer time

A related limitation of the S-money schemes [6,7], as presented, is that the process of transferring tokens either lacks flexibility or requires a delay to initiate a new token.

Suppose that B issues a token to A_1 , by sending a string of quantum states within a (suitably extended) spacetime region P . We assume that A_1 has no long-term quantum memory, since this is the underlying motivation for the schemes. Generating a token thus requires A_1 to measure the BB84 states sent by B as soon as she receives them, in bases that label her chosen presentation point Q_b .

Suppose now that A_1 later wishes to transfer the token to A_2 at some point Q , where $P < Q < Q_b$. Two options are considered in Ref. [6] as follows:

(1) A_1 may give A_2 the rights to a token which is valid only at her already-determined presentation point, Q_b . She can do this by giving A_2 at Q her measurement outcomes and the number b , along with a digitally signed classical message stating that A_1 relinquishes her token rights and A_2 is now the owner. A_2 can send this signed message to a local agent of B at or near Q , who informs all agents of B in his causal future. These agents will then no longer accept the token from any agent of A_1 but will accept it from A_2 .

(2) A_1 may give A_2 the rights to the token at Q in a way that allows A_2 to choose a new valid presentation point, $Q_{b'} > Q$. She can do this by giving A_2 a digitally signed message stating that she relinquishes her token rights and that the token is no longer valid. A_2 sends this to a local agent of B , as above. In this case, the local agents of B and A_2 need to initiate a replacement token. This requires B 's local agent to send a string of quantum states to A_2 's local agent, who measures them, following the protocol above.

The first option has the advantage that transfers require only classical communications and so can be completed relatively quickly. However, it is inflexible; A_2 is restricted to presenting the token at the point Q_b previously chosen by A_1 .

The second has the advantage of flexibility; A_2 may choose a new presentation point, which may be any valid presentation point within the causal future of the transfer point Q . However, it requires a new round of quantum communications, with the associated delay.

C. Flexible S-money schemes

In this paper, we propose an implementation of S-money that has none of the above disadvantages. The scenario we envisage requires that users may realize they may potentially want to acquire and use S-money well in advance of actually

doing so. This seems generally realistic. For example, traders who plan high-value high-speed trades on the global financial network expect to be registered, authenticated, and licensed, to set up infrastructure, and so on, before they begin trading: They do not expect to be able to show up on the network unannounced and uncredentialed and instantly trade.

We thus propose that such users go through information exchanges with the bank, in which the bank sends strings of quantum states which the user measures, in some starting region S , well before they might acquire or use S-money. These exchanges define bit-string coordination protocols which, if the user is unable to store quantum states, effectively commit the user to long random bit strings x . To simplify the discussion, we will assume the users have this technological limitation. However, this is not required for the security of the schemes, which (like the original schemes discussed above) require only secure bit-string coordination, not bit-string commitment. The bank's data received from each user's protocol are shared with all the bank's local agents but kept private from other users.

To acquire an S-money token, a user A then needs only to communicate classically with the bank at some later point P_A . They first agree a set of valid presentation points $\{Q_i : i \in S\}$. Here S satisfies $2^{M-1} < |S| \leq 2^M$, each $Q_i \geq P_A$, and they agree a standard convention for the labeling of the Q_i by bit strings i . They also agree which previously unused length M segment x of the user's committed bit string will be associated with this token, by labeling the relevant bits. (The user keeps the value of x secret here.) They may also at this point agree the price to be paid (e.g., in some standard currency) for the S-money token and perhaps process the payment. The bank's local agent sends all the information received to the bank's agents at each Q_i .

The user may then later decide where the token will be valid and commit to this decision by choosing $b \in S$ at any network point P_D such that $P_A \leq P_D \leq Q_i$ for all $i \in S$. The user's local agent at P_D commits this to the bank's local agent by sending him the string $m = x \oplus b$, and the bank's local agent sends this to the bank's agents at each Q_i , where " \oplus " denotes sum modulo two.

Finally, at Q_b , the user's local agent unveils the commitment to x by sending her commitment data to the bank's local agent. The bank's local agent verifies the commitment and that $m \oplus x = b$; if these tests are passed, then the S-money token is validated at Q_b , and the user is given whatever resources were agreed there.

1. Example

In the token scheme presented in Ref. [7] the issuer transmits a quantum state $|\Psi\rangle$ to the user, chosen from a predetermined set. At reception of $|\Psi\rangle$, the user chooses the number b labeling the presentation point Q_b by applying on $|\Psi\rangle$ a quantum measurement M_b that belongs to a predetermined set, obtaining a classical measurement outcome \mathbf{y} [17]. The user presents the token at Q_b by presenting the classical measurement outcome \mathbf{y} at Q_b . The issuer validates the token at Q_b if he verifies that the data \mathbf{y} received from the user at Q_b corresponds to a valid measurement outcome of the quantum measurement M_b applied on $|\Psi\rangle$.

The following example to implement the previous token scheme is given in Ref. [7]. Let the presentation points Q_i be labeled by strings $i = (i_1, \dots, i_M) \in \{0, 1\}^M$ for an integer M predetermined by the user and issuer. Let $b = (b_1, \dots, b_M) \in \{0, 1\}^M$ be the string that labels the user's chosen presentation point Q_b . The user and issuer engage in M parallel protocols of the bit coordination scheme presented in Sec. II A 1. The k th bit coordination protocol defines the bit entry b_k of the user's string b , for $k \in [M]$. Thus, more precisely, the issuer generates a state $|\Psi\rangle = |\Psi_{\mathbf{r},\mathbf{s}}\rangle$ of nM qubits given by

$$|\Psi_{\mathbf{r},\mathbf{s}}\rangle = \bigotimes_{(k,l) \in [M] \times [n]} |\phi_{r_l^k}^{s_l^k}\rangle, \quad (3)$$

where \mathbf{r} and \mathbf{s} are chosen randomly from $\{0, 1\}^{Mn}$ by the issuer and where r_l^k and s_l^k denote the respective bit entries with labels (k, l) of the strings \mathbf{r} and \mathbf{s} , for $k \in [M]$ and $l \in [n]$. The issuer sends to the user the state $|\Psi\rangle$ and the labels (k, l) of the transmitted qubits for $k \in [M]$ and $l \in [n]$. The user's measurement M_b consists in measuring the received qubit with label (k, l) in the computational basis ($\{|0\rangle, |1\rangle\}$) if $b_k = 0$ or in the Hadamard basis ($\{|+\rangle, |-\rangle\}$) if $b_k = 1$, respectively, for $l \in [n]$ and for $k \in [M]$.

In our flexible S-money scheme, at reception of the token from the issuer, the user applies the quantum measurement M_x on the quantum state $|\Psi\rangle$ received from the issuer, where x is a random M -bit string chosen by the user. The user obtains a classical measurement outcome \mathbf{y} . Then the user chooses the M -bit string b labeling her presentation point Q_b and sends $m = x \oplus b$ to the issuer at a point in the causal future of the point where she completed the measurement M_x and within the intersection of the causal pasts of all the presentation points. The user gives the token \mathbf{y} to the issuer at Q_b . The issuer validates the token if he verifies that \mathbf{y} is a statistically plausible measurement outcome of the quantum measurement $M_{m \oplus b}$ applied to $|\Psi\rangle$. This is illustrated in Fig. 1.

D. Security of flexible S-money schemes

1. Unforgeability

A refined S-money scheme based on a bit-string coordination protocol that is binding satisfies the property of unforgeability, according to which the user cannot have two or more tokens validated at two or more presentation points, as we discuss. In a cheating strategy by the user trying to present tokens at two different presentation points Q_{i_1} and Q_{i_2} , the user must be able to present unveiling data that correspond to a valid commitment to a number x_1 , satisfying $m \oplus x_1 = i_1$, and also to a number x_2 , satisfying $m \oplus x_2 = i_2$. Since $i_1 \neq i_2$, we have that $x_1 \neq x_2$. However, if the bit-string coordination protocol is binding, then, by definition, if the user presents unveiling data that corresponds to a valid commitment to a number x_1 , then the user cannot also present unveiling data that correspond to a valid commitment to a number $x_2 \neq x_1$. Thus, the property of unforgeability follows.

2. Future privacy for the user

A refined S-money scheme based on a bit-string coordination protocol that is hiding and where x is chosen randomly and securely by the user satisfies the property of future privacy

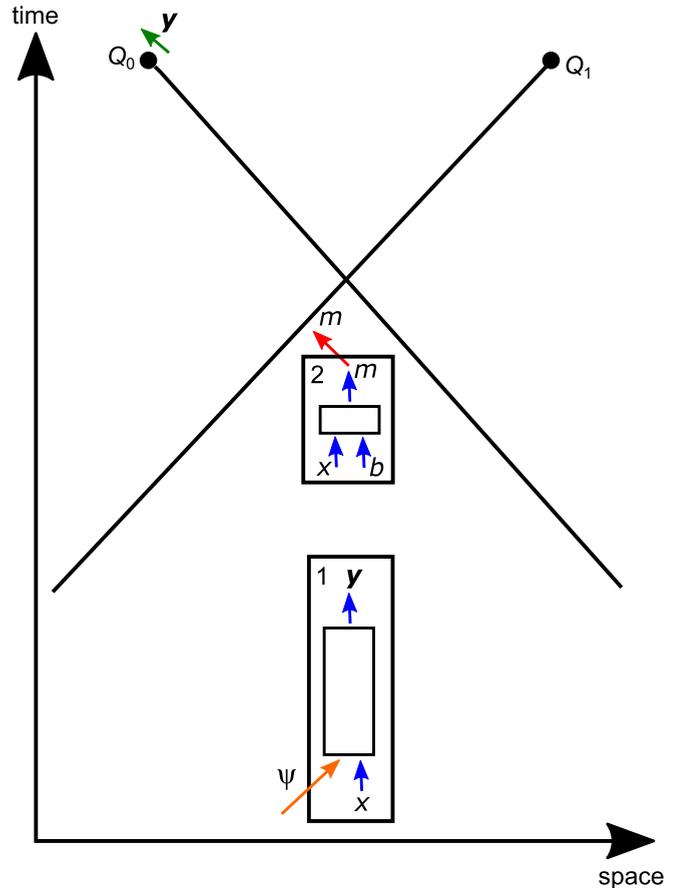


FIG. 1. Our flexible S-money scheme described in the main text is illustrated in 1 + 1-dimensional Minkowski spacetime for the case of two presentation points Q_0 and Q_1 (black dots). We use units in which the speed of light is unity. The black lines denote light rays. Bob's transmission of the quantum state $|\Psi\rangle$ to Alice is illustrated with the large orange diagonal arrow. The measurement on $|\Psi\rangle$ by Alice is represented by the rectangle labeled "1." The generation of the classical message $m = x \oplus b$ by Alice is represented by the square labeled "2." Alice's transmission of m to Bob is illustrated with the red diagonal arrow. The transmission of the token consists in Alice giving her measurement outcome \mathbf{y} to Bob at Q_b (green diagonal arrow). The case $b = 0$ is illustrated. The box labeled "1" illustrates Alice's generation of the random string x and the application of the measurement M_x on the received quantum state $|\Psi\rangle$, which outputs a classical measurement outcome \mathbf{y} . The box labeled "2" illustrates Alice's computation of the message $m = x \oplus b$, where b labels her chosen presentation point Q_b . Alice's inputs, x and b , and outputs, m and \mathbf{y} , are represented by the blue vertical arrows.

for the user, according to which the issuer cannot obtain any information about the presentation point Q_b chosen by the user before the token is presented by the user, as we discuss. In a cheating strategy by the issuer trying to obtain some information about the number b labeling the presentation point Q_b chosen by the user, the issuer may try to learn some information about the number x to which the user commits at the reception of the token in the bit-string coordination protocol and use this obtained information together with the message $m = x \oplus b$ received from the user to obtain some information about b . However, if we assume that the bit-string

coordination protocol is hiding, then, by definition, the issuer cannot know the value of x before it is unveiled by the user. Therefore, assuming that x is chosen randomly and securely by the user, the issuer cannot obtain any information about b from the message $m = x \oplus b$ before x is unveiled by the user. Thus, future privacy for the user follows.

III. TRANSFERRING S-MONEY TOKENS

Our refinement allows S-money tokens to be traded and transferred between users quite simply and flexibly. Suppose the first user A_1 has acquired a token at point P , associated with her committed bit string x_1 , and now wishes to transfer it to a second user A_2 at point P_T , where $P \leq P_T \leq Q_i$ for all i . In the simplest version, A_1 's local agent at P_T simply gives A_2 's local agent all the data defining the labels of the presentation points in S and an authenticated digitally signed message transferring her rights in the token. A_2 verifies this message and registers the transfer with the bank's local agent, agreeing to associate to the token a labeled segment x_2 of A_2 's precommitted random string. The local agents of A_1 and A_2 may also at this point agree the price to be paid (e.g., in some standard currency) for the S-money token transfer and perhaps process the payment. The bank's local agent notifies all agents at points Q_i of the transfer and of the labeled string segment.

Now A_2 may decide the valid presentation point Q_b at any point P_D such that $P_T \leq P_D \leq Q_i$ for all i and commit to this by sending the string $m_2 = x_2 \oplus b$ to Bob. She may present the token at Q_b by sending all the commitment data for x_2 (which comes from her own commitments) to Bob's local agent there. Bob's local agent validates both commitments and accepts the token if the commitments are validly unveiled and $m_2 \oplus x_2 = b$.

Alternatively, instead of deciding a presentation point, A_2 may transfer the token to A_3 at some transfer point $P_{T'} \geq P_T$ by sending all the relevant data and her own authenticated digitally signed transfer message, and so on.

Each user A_i is guaranteed future privacy regarding their token presentation point, since when they commit to the valid presentation point Q_b at some point P_D they send a string $m_i = x_i \oplus b$, where x_i is a committed private random string.

The key advantage is summarized schematically in Fig. 2.

IV. DELAYING THE CHOICE OF PRESENTATION POINT

This technique extends to allow the user to make a sequence of decisions and commitments at separate points in spacetime that collectively decide the presentation point, while still guaranteeing to the issuer that there can be no more than one valid presentation point.

Let P_{D_i} for $i = 1, \dots, N$ be a set of decision points, with at least one of them, P_{D_1} , in the causal past of all valid presentation points. Let $\{Q_i : i \in S\}$ be the set of presentation points. The user may decide and commit at P_{D_1} to restrict the valid presentation point to lie in a subset $\{Q_i : i \in S_1\}$, sending the issuer a description of the subset S_1 committed using data from their precommitted random string x . Let P_{D_2} lie in the causal past of all Q_i with $i \in S_1$. The user may decide and commit at P_{D_2} to restrict the valid presentation point to lie in a subset $\{Q_i : i \in S_2\}$, sending the issuer a

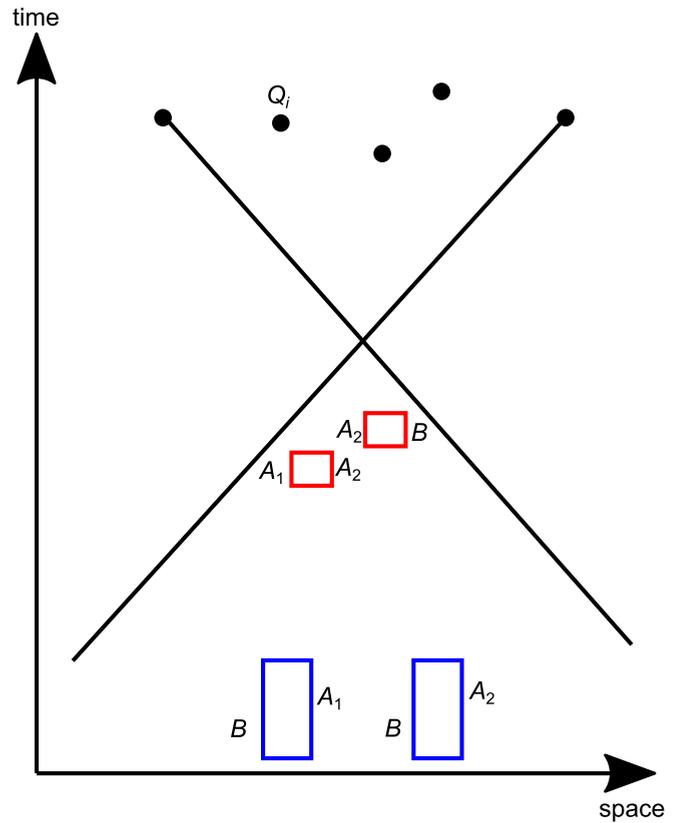


FIG. 2. Schematic illustration in 1 + 1-dimensional Minkowski spacetime of transfer of an S-money token in our flexible scheme. We use units in which the speed of light is unity. The black lines denote light rays. The bank sends quantum states to potential users A_1, A_2, \dots to initiate bit-string coordination protocols, which effectively commit these users to random classical bit strings x_1, x_2, \dots . These protocols (represented by the large blue boxes) may be relatively lengthy but can be carried out well before tokens are generated or transferred. If A_1 initiates a token protocol (not illustrated), then she may later wish to transfer the token to another user A_2 . This requires only classical communications (represented by the small red boxes) between local agents of A_1 and A_2 and between local agents of A_2 and B . Such communications can be completed relatively quickly, leaving A_2 in control of the token and free to make her own choice of a presentation point.

description of the subset $S_2 \subset S_1$ committed using further data from their precommitted random string, and so on, with the valid presentation point finally decided and committed to at (or before) the final point P_{D_m} .

These commitments may be coded efficiently if the configuration of the decision points and the sizes and relations of the relevant subsets are suitable and known in advance. For example, if it is known in advance that a binary choice will be made at each successive decision point, selecting one of two equally sized known subsets, then the user may simply commit using successive bits of the string x that would have been used to commit directly to b in the unrefined protocol.

A. Example

In Fig. 3, we illustrate a simple example with eight presentation points Q_i , with $i \in S = \{0, 1\}^3$, and two decision points,

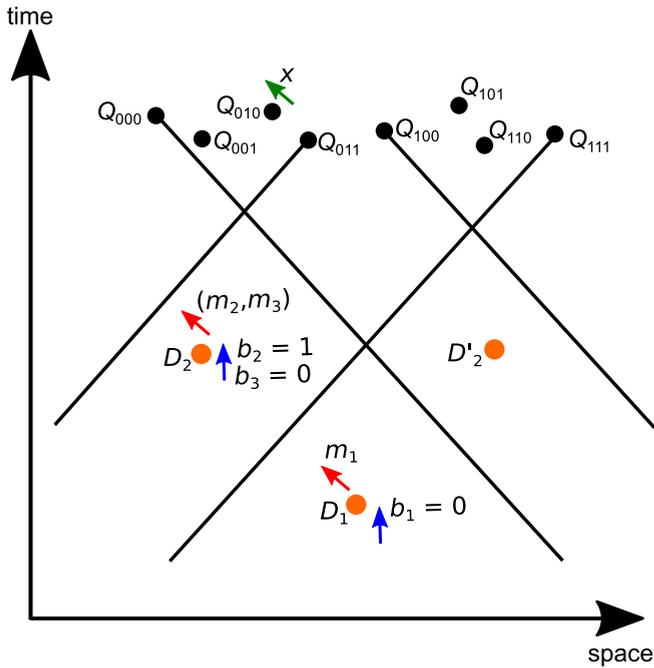


FIG. 3. The refinement allowing Alice to delay her chosen presentation point described in the main text is illustrated in $1 + 1$ -dimensional Minkowski spacetime. We use units in which the speed of light is unity. In this example, there are eight presentation points (black dots). The black lines denote light rays. Alice has spacetime decision points D_1 and D_2 (orange dots). D_1 is in the causal past of all the presentation points. D_2 is in the causal past of $Q_{0i_2i_3}$ for all $i_2, i_3 \in \{0, 1\}$. Alice's choices for the bit entries of the label $b = (b_1, b_2, b_3) = (0, 1, 0)$ of her chosen presentation point Q_b are illustrated with the blue vertical arrows. The bit $m_1 = x_1 \oplus b_1$ and the two-bit string $(m_2, m_3) = (x_2, x_3) \oplus (b_2, b_3)$ that Alice sends Bob at D_1 and D_2 , respectively, are indicated by the red diagonal arrows. Presentation of the token by Alice to Bob at Q_b consists in Alice unveiling her three bit string x to Bob at the presentation point Q_b , as illustrated with the green diagonal arrow. An alternative decision point, D'_2 , is also shown. Alice may use this if she chooses $b_1 = 1$ at D_1 .

$N = 2$. Let $x, b \in \{0, 1\}^3$ and let i_k be the k th bit entry of i for $k \in \{1, 2, 3\}$ and for $i \in \{x, b\}$. $D_1 \equiv P_{D_1}$ is a spacetime point within the intersection of the causal pasts of all the presentation points, where Alice decides that her presentation point Q_b will belong to the set $\{Q_{b_1,00}, Q_{b_1,01}, Q_{b_1,10}, Q_{b_1,11}\}$, i.e., with $S_1 = \{(b_1, i_2, i_3) : i_2, i_3 \in \{0, 1\}\}$. In this example, we suppose she chooses $b_1 = 0$. At D_1 , Alice indicates to Bob that she has chosen her presentation point to have the bit b_1 fixed, without telling him the chosen value for b_1 , and sends him the bit $m_1 = x_1 \oplus b_1$, where x_1 is the first bit of the previously committed string $x = (x_1, x_2, x_3)$. At the decision point $D_2 \equiv P_{D_2}$, which is in the causal past of all Q_i with $i \in S_1$, Alice chooses the bits b_2 and b_3 of her presentation point Q_b , with values $b_2 = 1$ and $b_3 = 0$ in this example, she indicates to Bob that she has chosen her presentation point and sends the two-bit string $(m_2, m_3) = (x_2, x_3) \oplus (b_2, b_3)$ to Bob. Alice presents her token at Q_b by unveiling to Bob's agent at Q_b her commitment to the string x . Bob's agent at Q_b validates Alice's token at Q_b , with $b = (b_1, b_2, b_3)$, if he

validates Alice's commitment to x and if $m_i \oplus x_i = b_i$ for $i = 1, 2, 3$.

B. Comparison with previous S-money schemes

Previous S-money schemes can also allow users to delay the choice of presentation point. For example, Ref. [7] considers a scheme in which the user may present the token at a presentation point Q_b by giving an issuer's agent there her string y of measurement outcomes, or she may delay the presentation of her token by stating this to the issuer's agent at Q_b . In the latter case, the issuer's agent gives further quantum states to the user at Q_b , and the user measures the received quantum states at Q_b in a basis labeling her chosen presentation point $Q_{b'} > Q_b$, obtaining a string of measurement outcomes y' . At $Q_{b'}$, the issuer may present the token by giving the issuer's agent there the string (y, y') , or she may choose to further delay the presentation point, and so on.

This method has the disadvantage that it requires various quantum communication exchanges between user's and issuer's agents at various spacetime points. This is technologically very demanding because the issuer and user's agents must have quantum devices to transfer and measure quantum states at all presentation points where the token presentation can be delayed. On the other hand, our scheme only requires the quantum communication between user and issuer to take place once, between a single pair of adjacent laboratories at a spacetime region P , so that delays of the presentation point are needed only to allow time for classical communications between user and issuer's agents at spacetime points in the causal future of P .

V. DISCUSSION

In this paper we have presented refinements of S-money schemes introduced in Refs. [6–9]. These refinements make the schemes considerably more flexible and practical. They allow the initial commitment phase, which involves quantum communications and measurements and potentially may be relatively lengthy, to take place long in advance. This allows the user to choose her presentation point at potentially any point in the intersection of the causal pasts of all the presentation points, limited only by the need to complete the commitment by relatively short classical communications. It also allows the user to make a series of decisions, which may be independent, that collectively determine the presentation point. This flexibility is valuable in applications where speed is critical. Further, it allows S-money tokens to be simply and efficiently transferred between users. The refinements retain the properties of unforgeability and future user privacy, both for the original user and for users to whom the token is transferred.

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- [1] S. Wiesner, *ACM Sigact News* **15**, 78 (1983).
- [2] D. Gavinsky, in *Proceedings of the 2012 IEEE 27th Annual Conference on Computational Complexity (CCC'12)* (IEEE, Los Alamitos, CA, 2012), pp. 42–52.
- [3] F. Pastawski, N. Y. Yao, L. Jiang, M. D. Lukin, and J. I. Cirac, *Proc. Natl. Acad. Sci. USA* **109**, 16079 (2012).
- [4] M. Georgiou and I. Kerenidis, in *Leibniz International Proceedings in Informatics*, LIPIcs, Vol. 44 (Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, Dagstuhl, Germany, 2015).
- [5] Depending on context, “S” may denote “summonable” or “super.”
- [6] A. Kent, *Proc. R. Soc. A* **475**, 20190170 (2019).
- [7] A. Kent, Quantum tokens, International Patent Application No. WO2017001850A1 (2017).
- [8] A. Kent, Future position commitment, International Patent Application No. WO2017001850A1 (2018).
- [9] A. Kent, Cryptographic method and system, UK Patent Application No. GB1719870.6 (2017).
- [10] A. Kent, *Phys. Rev. Lett.* **109**, 130501 (2012).
- [11] S. Croke and A. Kent, *Phys. Rev. A* **86**, 052309 (2012).
- [12] J. Kaniewski, M. Tomamichel, E. Hänggi, and S. Wehner, *IEEE Trans. Inf. Theory* **59**, 4687 (2013).
- [13] T. Lunghi, J. Kaniewski, F. Bussières, R. Houlmann, M. Tomamichel, A. Kent, N. Gisin, S. Wehner, and H. Zbinden, *Phys. Rev. Lett.* **111**, 180504 (2013).
- [14] D. Pitalúa-García and I. Kerenidis, *Phys. Rev. A* **98**, 032327 (2018).
- [15] D. Pitalúa-García, *Phys. Rev. A* **100**, 012302 (2019).
- [16] A. Kent, D. Lowndes, D. Pitalúa-García, and J. Rarity, Practical quantum tokens without quantum memories: towards a proof-of-principle experimental demonstration (unpublished).
- [17] In practical implementations with current technology, the transmitted state will be a sequence of (approximate) qubits, and the measurement a sequence of individual measurements on these. We represent these as a single state and single collective measurement to simplify the notation.