Quantum-enhanced Logic-based Blockchain I: Quantum Honest-success Byzantine Agreement and Qulogicoin

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Abstract We proposed a framework of quantum-enhanced logic-based blockchain, which improves the efficiency and power of quantum-secured blockchain. The efficiency is improved by using a new quantum honest-success Byzantine agreement protocol to replace the classical Byzantine agreement protocol, while the power is improved by incorporating quantum protection and quantum certificate into the syntax of transactions. Our quantum-secured logic-based blockchain can already be implemented by the current technology. The cryptocurrency created and transferred in our blockchain is called qulogicoin. Incorporating quantum protection and quantum certificates into blockchain makes it possible to use blockchain to overcome the limitations of some quantum cryptographic protocols. As an illustration, we show that a significant shortcoming of cheat-sensitive quantum bit commitment protocols can be overcome with the help of our blockchain and qulogicoin.

Keywords blockchain · quantum Byzantine agreement · qulogicoin · quantum bit commitment

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1 Introduction

A blockchain is a distributed ledger which enables achieving consensus in a large decentralized network of agents who do not trust each other. It is a ledger in the sense that data stored on a blockchain is transactions like “Alice sends 1 bitcoin to Bob”. It is distributed in the sense that every miner (the agents who are in charge of updating the ledger) has a same copy of the database. One of the most prominent application of blockchains is cryptocurrencies, such as Bitcoin [26]. Another important application of blockchains is the implementation of self-executable smart contracts [32].

This is the first paper of our project on quantum-enhanced logic-based blockchain (QLB). The ultimate goal of our project is to design a framework of blockchain which has the following advantages over the existing classical and quantum blockchains:

1. More efficient.
2. More powerful.
3. More Secure.
4. Cheaper.
5. Smarter.
6. Easier-to-regulate.

In this paper we will use quantum technology to achieve efficiency, powerfulness, security and cheapness. In the future, we will use techniques from logic to achieve smartness and regulatability.

Our starting point in this paper is the quantum-secured blockchain (QB) developed by Kiktenko et al. [19]. Due to the application of quantum technologies, QB is more secure than classical blockchain in the sense that QB is immune from attacks of quantum computers, while classical blockchain is not. QB is probably also more efficient and (will be) cheaper than classical blockchain due to the omission of the costly and time-consuming proof-of-work. The security and cheapness of our QLB is inherited from QB. To achieve higher efficiency, we will develop a new quantum Byzantine agreement (QBA) protocol to replace the classical Byzantine agreement protocol in QB. To make our blockchain more powerful, we will embed quantum protection and quantum certificate into the syntax of transactions in QLB. Those generalized transactions endow more power to QLB than QB and classical blockchain in the sense that QLB is able to handle contracts which involve tests of some quantum properties. As an illustration, we will show that a significant shortcoming of cheat-sensitive quantum bit commitment protocols can be overcome with the help of QLB, while classical blockchain and QB is unhelpful in this case.

The main contribution of this paper is the following:

1. We introduce QLB and demonstrate that it is more efficient and powerful than QB. Just like QB, QLB is also implementable by the current technology.
2. Based on QLB, a new cryptocurrency called qulogicoins is introduced.
3. Our QBA protocol is simpler and easier to be implemented than most QBA
   protocols in the literature.
4. We discover a significant problem of quantum bit commitment and solve
   it. This problem is overlooked for many years.

The structure of this paper is as follows. We present an overview of QLB in
Section 2. Then in Section 3 we introduce a new QBA protocol to improve the
efficiency of QLB. In Section 4 we demonstrate the power of QLB by solving
a problem in quantum bit commitment. We draw conclusions in Section 5.

2 Overview of quantum-enhanced logic-based blockchain

The structure of QLB is similar to the structure of QB [19]. We assume each
pair of nodes (agents), of which at least a half of them are honest, is connected
by an authenticated quantum channel and a not necessary authenticated clas-
sical channel. Each pair of agents can establish a sequence of secret keys by
using quantum key distribution [8]. Those keys will later be used for message
authentication.

New transactions are created by those nodes who wish to transfer their
cryptocurrency to another node. Each new transaction must contain the in-
formation about the Hash value, the receiver and the previous transaction from
which the cryptocurrency is redeemed. Formally, a plain transaction $T_x$ saying
that “$i$ sends the qulogicoins, which $i$ has received from another transaction
$T_y$, to $j$” is of the form

$$T_x = (x, y, j).$$

Here $x$ is the Hash value of this transaction. A Hash function is a one-way
function which maps an arbitrary length string to a fixed-length string. Just
like in QB [19], we use Toeplitz hashing [20,21], of which the core component
Toeplitz matrix is generated by the secret keys distributed via the quantum
channel previously. Formally, $x = T_{S}(y, j) \oplus r$, where $S$ and $r$ are secret keys
and $T_{S}$ is the Toeplitz matrix generated by $S$. $T_{S}()$ maps a string to another
string of which the length is the same as the length of $r$. $\oplus$ is the exclusive-or
operator.

A protected transaction $T_x$ saying that “$i$ sends the qulogicoins, which $i$
has received from another transaction $T_y$, to $j$; The qulogicoins transferred in
this transaction can only be used when both $\alpha$ and $\phi$ is true” is of the form

$$T_x = (x, y, j; \alpha, \phi).$$

Here $\alpha$ is a boolean function about the classical certificate and $\phi$ is a boolean
function about the quantum certificate to be introduced soon. We let $x = T_{S}(y, j; \alpha, \phi) \oplus r$.

A more general form of a transaction is an extension of a protected trans-
action with some classical and quantum certificates.

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1 In the future, we will use logical formulas to express $\alpha$ and $\phi$. 
Here $\beta$ is some classical data and $\psi$ is some quantum data, which are considered as certificates. We let $x = T_S(y; j; \alpha, \phi; \beta) \oplus r$. The functionality of certificates is to satisfy the protection condition of the the transaction $T_y$. An even more general form which involves more than 1 redeemed transaction $y_1, \ldots, y_n$ can be defined as

$$T_x = (x, y_1, \ldots, y_n; j; \alpha, \phi; \beta_1, \ldots, \beta_n, \psi_1, \ldots, \psi_n).$$

where $\beta_i, \psi_i$ are the classical and quantum certificates for $T_{y_i}$ and $x = T_S(y_1, \ldots, y_n, j; \alpha, \phi; \beta_1, \ldots, \beta_n) \oplus r$.

A general transaction, except its quantum certificate, is then sent via classical channels to all miners, while the quantum certificate is sent via quantum channels. Each miner checks the consistency of the new transaction with respect to their local copy of the ledger and forms an opinion regarding the transaction’s admissibility. Here consistency checking for $T_x = (x, y_1, \ldots, y_n, j; \alpha, \phi; \beta_1, \ldots, \beta_n, \psi_1, \ldots, \psi_n)$ means to check the following:

1. Message authentication: check if $x = T_S(y_1, \ldots, y_n, j; \alpha, \phi; \beta_1, \ldots, \beta_n) \oplus r$, where $S$ and $r$ is taken from the secret keys shared between the miner and the sender.
2. check if the sender is the receiver of $T_{y_1}, \ldots, T_{y_n}$.
3. check if $T_{y_i}$ has been redeemed before this transaction, for all $i \in \{1, \ldots, n\}$.
4. check if $\beta_i$ satisfies $\alpha_{y_i}$, where $\alpha_{y_i}$ is the classical protection of $T_{y_i}$.
5. check if $\psi_i$ satisfies $\phi_{y_i}$, where $\phi_{y_i}$ is the quantum protection of $T_{y_i}$.

Then all the miners apply the honest-success quantum Byzantine agreement protocol, which we will introduce in Section 3 to the new transaction, arriving at a consensus regarding the correct version of that transaction and whether the transaction is admissible. The double-spending events (a dishonest agent sending different versions of a particular transaction to different nodes of the network) is excluded in this stage. Finally, the transaction is added to the ledger of every node if at least a half of the miners agree that the transaction to be admissible.

We will explain in the next section that some miners, as well as some special agents called list distributors, are rewarded in the procedure of achieving consensus. This is the only way to generate new cryptocurrency (quilogicoin) in our blockchain.

### 3 Quantum honest-success Byzantine agreement

The Byzantine agreement protocol is the solution to the Byzantine generals problem [29][22].

Three generals of the Byzantine army want to decide upon a common plan of action: either to attack (0) or to retreat (1). They can only communicate in
pairs by sending messages. However, one of the generals might be a traitor, trying to keep the loyal generals from agreeing on a plan. How to find a way in which all loyal generals follow the same plan?

**Definition 1 (Byzantine agreement (BA) protocol [14])** A protocol among $n$ agents such that one distinct agent $S$ (the sender) holds an input value $x_s \in D$ (for some finite domain $D$) and all other agents (the receivers) eventually decide on an output value in $D$ is said to achieve Byzantine agreement if the protocol guarantees that all honest agents decide on the same output value $y \in D$ and that $y = x_s$ whenever the sender is honest.

In QB [19], the authors use classical Byzantine agreement protocol [29] to update the distributed ledger. They noticed that a shortcoming of the classical Byzantine agreement protocol [29] is that it becomes exponentially data-intensive if a large number of cheating nodes are present. Therefore further research on developing an efficient consensus protocol is required.

In the literature of quantum computing, several Byzantine agreement protocols have been studied in the past decade [14,17,15,33]. In the setting of QLB, we need a Byzantine agreement protocol to solve the double-spending problem. It turns out that the following weak notion of Byzantine agreement is already sufficient for our purpose.

**Definition 2 (honest-success Byzantine agreement protocol (HBA))** A protocol among $n$ agents such that one distinct agent $S$ (the sender) holds an input value $x_s \in D$ (for some finite domain $D$) and all other agents (the receivers) eventually decide on an output value in $D$ is said to achieve honest-success Byzantine agreement if the protocol guarantees the following:

1. If the sender is honest, then all honest agents decide on the same output value $y = x_s$.
2. If the sender is dishonest, then either all honest agents abort the protocol, or all honest agents decide on the same output value $y \in D$.

We say that a HBA protocol is $p$-resilient, where $0 < p < 1$, if the protocol still works when less than a fraction of $p$ receivers are dishonest. The quantum honest-success Byzantine agreement (QHBA) protocol that we will present in this section is $\frac{m}{m-2}$-resilient, where $m$ is the number of receivers. Our protocol is much more efficient than classical BA protocol in the presence of a large number of cheating nodes.

There are three phases of our QHBA protocol. The aim of the first phase is to distribute a set of correlated lists among agents. In the second phase, some special correlated lists are generated based on the set of correlated lists. Then in the third phase, agents use the special correlated lists to achieve consensus.

**3.1 List distribution by quantum secure direct communication**

Unlike quantum key distribution, which only allows to distribute non-deterministic message, quantum secure direct communication (QSDC) [13,27,28] allows
messages to be deterministically sent through the quantum channel. We use QSDC to distribute those correlated lists. Our QSDC protocol is based on a quantum version of Shamir’s three-pass protocol \cite{35}. A classical scenario of the three-pass protocol is the following:\footnote{https://en.wikipedia.org/wiki/Three-pass_protocol}

- Alice’s friend Bob lives in a repressive country where the police spy on everything and open all the mails.
- Alice needs to send a valuable object to Bob.
- Alice has a strongbox with a hasp big enough for several locks, but no lock to which Bob also has a key.

How can Alice get the item to Bob securely? Alice and Bob might take the following three pass protocol:

1. Put the item into the box, attach Alice’s lock to the hasp, and mail the box to Bob.
2. Bob adds his own lock and mails the box back to Alice.
3. Alice removes her lock and mails the box back to Bob. Bob now removes his lock and opens the box.

In a previous paper \cite{35}, we have introduced a quantum realization of the three-pass protocol for key distribution. It turns out that this protocol can be straightforwardly used for secure direct communication. Now we recap the quantum three-pass protocol in \cite{35}.

We use qubit $|0\rangle$ and $|1\rangle$ to encode 0 and 1 respectively. Our key space for encryption and decryption contains 4 X-gates \{$X(0), X(\frac{\pi}{2}), X(\pi), X(\frac{3\pi}{2})$\}, where $X(m) = |+\rangle\langle+| + e^{im}\ket{-}\bra{-}$. The encryption of a qubit $|i\rangle$ with key $k$ is defined as $Enc_k(i) = k|i\rangle$, and the decryption of a qubit $|i\rangle$ is $Dec_k(i) = k|i\rangle$, where $k \in \{X(0), X(\frac{\pi}{2}), X(\pi), X(\frac{3\pi}{2})\}$. We let $(X(m), \overline{X}(m) = X(2\pi - m))$ be a pair of encryption/decryption keys.

Figure 1 is our quantum three-pass protocol for a sender (agent 1) to send a sequence of bits to a receiver (agent 2). At the beginning of the protocol, agent 1 encrypts the bit string element-wise and sends the resulting string to agent 2. Then agent 2 encrypts the ciphertext and sends the result back to agent 1. Agent 1 then decrypts the string and sends it to agent 2. Now agent 2 decrypts the string and gets the key.

Now we use our quantum three-pass protocol to distribute correlated lists. Let $\{P_1, P_n, P_{n+1}, \ldots, P_{n+d}\}$ be the set of agents. We let $P_1$ be the sender of the QHBA protocol, $P_2, \ldots, P_n$ be receivers and $P_{n+1}, \ldots, P_{n+d}$ be list distributors who are in charge of distributing lists of correlated numbers. For every agent $P_i \in \{P_{n+1}, \ldots, P_{n+d}\}$, the task of $P_i$ is to use the quantum three-pass protocol to send a list of numbers $L^i_k$ to agent $P_k \in \{P_1, \ldots, P_n\}$ such that the following is satisfied:

1. For all $k \in \{1, \ldots, n\}$, $|L^i_k| = m$ for some integer $m$ which is a multiple of 6.
Protocol for key distribution

Input: a string of binary numbers \((a_1, \ldots, a_n)\).

Agent 1 has a private key \((k_1^1, \ldots, k_n^1)\). Agent 2 has a private key \((k_1^2, \ldots, k_n^2)\).

1. **Agent 1: Encrypt.**
   Produce \((b_1, \ldots, b_n)\), such that \(b_i = \text{Enc}_{k_1^i}(a_i)\).
   Send the list \((b_1, \ldots, b_n)\) to Agent 2.

2. **Agent 2: Encrypt.**
   Let \(c_i = \text{Enc}_{k_2^i}(b_i)\), for all \(i \in \{1, \ldots, n\}\).
   Send the list \((c_1, \ldots, c_n)\) to Agent 1.

3. **Agent 1: Decrypt.**
   Let \(d_i = \text{Dec}_{k_1^i}(c_i)\), for all \(i \in \{1, \ldots, n\}\).
   Send the list \((d_1, \ldots, d_n)\) to Agent 2.

4. **Agent 2: Decrypt.**
   Let \(e_i = \text{Dec}_{k_2^i}(d_i)\). Then \(e_i = a_i\).

Fig. 1: A quantum three-pass protocol for secure direct communication

2. \(L^i_1 \in \{0, 1, 2\}^m\). \(\frac{m}{3}\) numbers on \(L^i_1\) are 0. \(\frac{m}{3}\) numbers on \(L^i_1\) are 1. \(\frac{m}{3}\) numbers on \(L^i_1\) are 2.

3. For all \(k \in \{2, \ldots, n\}\), \(L^i_k \in \{0, 1\}^m\).

4. For all \(j \in \{1, \ldots, m\}\), if \(L^i_1[j] = 0\), then \(L^i_2[j] = \ldots = L^i_n[j] = 0\).

5. For all \(j \in \{1, \ldots, m\}\), if \(L^i_1[j] = 1\), then \(L^i_2[j] = \ldots = L^i_n[j] = 1\).

6. For all \(j \in \{1, \ldots, m\}\), if \(L^i_1[j] = 2\), then for all \(k \in \{2, \ldots, n\}\) the probability of \(L^i_k[j] = 0\) and \(L^i_k[j] = 1\) are equal.

After those lists are selected\(^3\), \(P_1, \ldots, P_n\) are entitled to communicate with \(P_1\) to check whether those lists satisfy the above specification. If for some parameter \(\theta \in [0, \frac{1}{2}]\), more than \(\theta n\) agents report that the lists distributed by \(P_1\) do not satisfy the specification. The \(P_1\) is classified as a corrupted/dishonest distributor. To stimulate \(P_1\) to play honestly, honest distributors will be rewarded by some qulogicoins while those corrupted distributors will not.

### 3.2 List formation by sequential composition

In this phase, \(\{P_1, \ldots, P_n\}\) use a simply sequential composition procedure to form a unique list to be used in the next phase.

Assume there are \(h\) list distributors who are classified to be honest. Without loss of generality, the lists distributed by those distributors \(P_{n+1}, \ldots, P_{n+h}\) can be represented by \(\Sigma^{n+1} = (L_1^{n+1}, \ldots, L_h^{n+1}), \ldots, \Sigma^{n+h} = (L_1^{n+h}, \ldots, L_h^{n+h})\).

The aim of this phase is to form a new sequence of lists \(\Sigma = (L_1, \ldots, L_n)\), which

\(^3\) Some additional decoy qubits may be sent and revealed to detect eavesdroppers.
is to be used in the next phase. We construct $L$ by the sequential composition of $L^{n+1}, \ldots, L^{n+h}$. That is, we let $L_1 = L^{n+1}_1 \ldots L^{n+h}_1, \ldots, L_n = L^{n+1}_n \ldots L^{n+h}_n$.

On average, every honest distributor contributes $\frac{1}{t}$ to the final lists $L$. This property is crucial to counteract the attack of some adversary who tries to bribe the distributor. We will briefly discuss this attack in Section 3.4. This mechanism together with the mechanism of reward will encourage more distributors to behave honestly. On the other hand, the more honest distributors there are, the more reliable is our blockchain.

3.3 Achieving consensus

After the correlated lists $L = (L_1, \ldots, L_n)$ are established, the agents $P_1, \ldots, P_n$, of which we assume at least a half of them are honest, run the following steps to achieve consensus.

1. $P_1$ sends a binary number $b_{1,k}$ to all $P_k$, $k \in \{2, \ldots, n\}$. Together with $b_{1,k}$, $P_1$ sends a list of numbers $ID_{1,k}$, which indicates all positions on $L_1$ where $b_{1,k}$ appears, to $P_k$. The length of $ID_{1,k}$ is required to be $m$, where $m$ is the length of $L_1$. If $P_1$ is honest, then he will send the same message to all agents, i.e. $(b_{1,k}, ID_{1,k}) = (b_{1,j}, ID_{1,j})$ for all $j, k \in \{2, \ldots, n\}$. If $P_1$ is dishonest, then he will send different binary numbers and different lists of numbers to different agents, i.e. $(b_{1,k}, ID_{1,k}) \neq (b_{1,j}, ID_{1,j})$ for some $j, k$.

An honest $P_1$ will also use $b_{1,k}$ as the final value it outputs, while a dishonest $P_1$ will use $b_{1,k}$ or $1 - b_{1,k}$ randomly as its final output value.

2. Agent $P_k$ analyzes the obtained message $(b_{1,k}, ID_{1,k})$ with his own list $L_k$.

If the analysis of $P_k$ shows that $(b_{1,k}, ID_{1,k})$ is consistent with $L_k$, then if $P_k$ is honest, he sends $(b_{1,k}, ID_{1,k})$ to all other agents $P_j \neq 1$. Here $(b_{1,k}, ID_{1,k})$ is consistent with $L_k$ means that for all index $x \in ID_{1,k}, L_k[x] = b_{1,k}$. However, if $(b_{1,k}, ID_{1,k})$ is not consistent with $L_k$, then $P_k$ immediately ascertains that $P_1$ is dishonest and sends $\perp$ to other agents, meaning that “I have received inconsistent message”. A dishonest $P_k$ sends $1 - b_{1,k}$ with whatever indexes he chooses or simply $\perp$. The full information which $P_j$ receives from $P_k$ will be denoted by $(b_{k,j}, ID_{k,j})$.

3. After all messages have been exchanged between $P_2, \ldots, P_n$, every honest agent $P_k$ considers the received data and acts according to the following criterion:

(a) If there is a set of agents $H$ with $|H| \geq 2$ such that

i. for all $j \in H$, $(b_{j,k}, ID_{j,k})$ is consistent with $L_k$, and

ii. for some $i, j \in H$, $b_{i,k} \neq b_{j,k}$,

then $P_k$ sets his output value to be $\perp$.

(b) If there is a set of agents $H$ with $|H| \geq 2$ such that for all $j \in H$, $(b_{j,k}, ID_{j,k})$ is consistent with $L_k$ and all $b_{j,k}$ are the same, and for all $i \notin H$, $(b_{i,k}, ID_{i,k})$ is not consistent with $L_k$, then $H$ is the set of all honest agents and $P_k$ sets his output value $v_k = b_{1,k}$.
(c) If there is a set of agents $H$ with $|H| \geq 2$ such that for all $j \in H$, $(b_{j,k}, ID_{j,k})$ is consistent with $L_k$ and all $b_{j,k}$ are the same, and for all $i \notin H$, the message sent by $P_i$ is $\perp$, then $P_k$ sets $v_k = b_{j,k}$.

(d) In all other cases, $P_k$ sets his value to be $\perp$.

4. We say that consensus is achieved if at least $\frac{n}{2}$ agents output the same bit value $v \in \{0, 1\}$. In this case, those agents whose output is the same as $v$ are rewarded with some quilogicoins.

Now we briefly explain the rationale of these criteria. Suppose $P_j$ is a dishonest receiver, where $j \geq 2$. Now $P_j$ wants to send $(b_{j,k}, ID_{j,k})$ to $P_k$ such that $(b_{j,k}, ID_{j,k})$ is consistent with $L_k$. Note that on $L_1$, there are $\frac{m}{2}$ positions on which $b_{j,k}$ appears. But on $L_1$, there are only $\frac{m}{3}$ positions on which $b_{j,k}$ appears. Therefore, there are $\frac{m}{2} - \frac{m}{3} = \frac{m}{6}$ positions on which there are some discord. But $P_j$ has no knowledge about those discord. We say a position $x$ is a discord position iff $L_1[x] = 2$. If $P_j$ selects a discord position $x$ and put it into $ID_{j,k}$, then with probability $\frac{1}{2}$ it will be that $L_k[x] \neq b_{j,k}$. Therefore, to ensure that $(b_{j,k}, ID_{j,k})$ is consistent with $L_k$, $P_j$ has to avoid all discord positions. The probability of avoiding all discord positions is $\left(\frac{2}{3}\right)^{\frac{m}{6}}$, which is extremely small when $m$ is relatively large. Therefore, if it happens that $(b_{j,k}, ID_{j,k})$ is consistent with $L_k$, then $P_k$ can conclude that $P_j$ is honest. For the same reason $P_k$ can conclude that $P_i$ is honest when $(b_{i,k}, ID_{i,k})$ is consistent with $L_k$. Now, if in addition that $b_{i,k} \neq b_{j,k}$, $P_k$ can safely conclude that $P_1$ is dishonest. This is the rationale of criterion (a).

The rationale of criterion (b) is essentially the same as the rationale of criterion (a). In this case, $P_1 \in H$ and those agents who are not in $H$ are dishonest agents and they failed on cheating.

The rationale of criterion (c) is also essentially the same as the rationale of criterion (a). In this case some agents who are not in $H$ is also honest. They will change their output value from $\perp$ to $b_{j,k}$.

3.4 Some potential attacks

Now we briefly discuss some potential attacks to our blockchain.

3.4.1 Double-spending adversary

Our blockchain is resistant to a double-spending adversary. A double spending adversary can simply be modeled by a dishonest sender $P_1$ who sends 0 to some nodes and 1 to some other nodes. This kind of attack will not work according to criterion (a).

3.4.2 Tampering adversary

Our blockchain is also resistant to a tampering adversary. We model a tampering adversary by an arbitrary set of dishonest receivers, of which the cardinality
is less than $\frac{2}{n}$. A dishonest receiver $P_i$ maliciously sends $1 - b_{1,i}$, together with some indexes, to all other agents. This kind of adversary will not be successful according to criterion (b) and (c), as long as there are still 2 honest receivers.

3.4.3 Bribe the distributor

Every honest list distributor has some knowledge about the list $\mathcal{L} = (L_1, \ldots, L_n)$. Some adversary may bribe list distributors to obtain some valuable knowledge about $\mathcal{L}$. But this attack is costly for the adversary, because he has to bribe many list distributors to obtain sufficient knowledge.

4 Application in quantum bit commitment

Now we apply our QLB to the design of quantum bit commitment protocols. Bit commitment, used in a wide range of cryptographic protocols (e.g. zero-knowledge proof, multiparty secure computation, and oblivious transfer), typically consists of two phases, namely: commitment and opening. In the commitment phase, Alice the sender chooses a bit $a$ ($a = 0$ or $1$) which she wishes to commit to the receiver Bob. Then Alice presents Bob some evidence about the bit. The committed bit cannot be known by Bob prior to the opening phase. Later, in the opening phase, Alice announces some information for reconstructing $a$. Bob then reconstructs a bit $a'$ using Alice’s evidence and announcement. A correct bit commitment protocol will ensure that $a' = a$. A bit commitment protocol is concealing if Bob cannot know the bit Alice committed before the opening phase and it is binding if Alice cannot change the bit she committed after the commitment phase.

The first quantum bit commitment (QBC) protocol is proposed by Bennett and Brassard in 1984 \cite{8}. A QBC protocol is unconditionally secure if any cheating can be detected with a probability arbitrarily close to 1. Here, Alice’s cheating means that Alice changes the committed bit after the commitment phase, while Bob’s cheating means that Bob learns the committed bit before the opening phase. A number of QBC protocols are designed to achieve unconditional security, such as those of \cite{10,11}. However, according to the Mayers-Lo-Chau (MLC) no-go theorem \cite{25,24}, unconditionally secure QBC can never be achieved in principle.

Although unconditional secure QBC is impossible, several QBC protocols satisfy some other notions of security, such as cheat-sensitive quantum bit commitment (CSQBC) protocols \cite{10,12,30,23,34} and relativistic QBC protocols \cite{15,11}. In CSQBC protocols, the probability for detecting cheating is merely required to be non-zero. With this less stringent security requirement, many QBC protocols which are not unconditional secure are regarded as secure in the cheat-sensitive sense.

However, for any CSQBC to work, there has to be a mechanism of enforcing punishment when a cheating behavior is detected. Otherwise both Alice and Bob will always cheat, regardless of whether it will be detected. Therefore the
protocol will either be aborted or end with someone cheats successfully. So far this problem (enforcing punishment in CSQBC) is completely omitted in the literature. In this section, we solve this problem by applying QLB to enforce punishment.

4.1 A cheat-sensitive quantum bit commitment protocol

For the sake of concreteness, we present a CSQBC protocol taken from a recent paper of ours \cite{31} and demonstrate how to enforce punishment for this protocol by using QLB. There are three phases of this protocol, namely: the preparation phase, the commitment phase and the opening phase.

The preparation phase contains the following steps:

1. Bob generates a sequence of \( n \) qubits such that
   (a) \( n \) is a multiple of 4.
   (b) \( \frac{n}{4} \) qubits are \( |0\rangle \), \( \frac{n}{4} \) qubits are \( X(\frac{\pi}{2})|0\rangle = |i\rangle \), and \( \frac{n}{4} \) qubits are \( X(\frac{3\pi}{2})|0\rangle = |1\rangle \).
   (c) for every \( j \in \{1, \ldots, \frac{n}{2}\} \), the \( 2j-1 \)th qubit and the \( 2j \)th qubit are from different ONBs.

   Such a sequence is called a balanced-uniform sequence. Bob generates \( m \) balanced-uniform sequences and sends them to Alice.

2. Alice chooses \( m-1 \) sequences and asks Bob to reveal, qubit by qubit, which state it was prepared. Then, Alice measures those qubits in the appropriate basis to verify whether Bob has prepared those qubits in the required specification: the \{\( |0\rangle, |1\rangle \}\) basis for qubits \( |0\rangle \) and \( |1\rangle \) and the \{\( |i\rangle, |\bar{i}\rangle \}\) basis for qubits \( |i\rangle \) and \( |\bar{i}\rangle \). If Alice detects that Bob has prepared a sequence that is not balanced-uniform, then Alice has detected Bob’s cheating.

The commitment phase contains the following steps:

1. Alice commits 2 bits by applying quantum operations to the only balanced-uniform sequence left. We denote this sequence as \( QS \). If Alice decides to commit \( 00/01/10/11 \), then he/she applies \( X(0) \) to all qubits in \( QS \), respectively. Then, Alice generates a classical string \( CS \) of length \( \frac{n}{2} \). Alice applies the SWAP operator to \( QS[2j-1] \) and \( QS[2j] \) if \( CS[j] = 1 \). Alice sends \( QS \) to Bob.

2. Bob measures each received qubit either in the \{\( |0\rangle, |1\rangle \}\) basis or in the \{\( |i\rangle, |\bar{i}\rangle \}\) basis which is chosen uniformly at random.

The opening phase contains the following steps:

1. Alice reveals \( CS \).

\footnote{While the Bitcoin blockchain has been applied to solve a related problem in classical bit commitment \cite{2}, the solution seems to be inadequate for quantum bit commitment because there is no quantum data in the Bitcoin blockchain.}
2. Based on the information of $CS$, Bob is able to know the original state of each position in $QS$, because it is Bob who prepared $QS$ and now he knows how it was swapped. Now Bob determines whether it was measured in the correct basis for each position in $QS$: for a position that was originally occupied by $|0\rangle$ or $|1\rangle$, the correct basis is the $\{|0\rangle, |1\rangle\}$ basis, for other qubits the correct basis is the other basis. Now, Bob can reconstruct the bits committed by Alice as follows:

(a) If Alice committed to 00, then all the qubits measured in the correct basis must yield a state which is the same as the original one.
(b) If Alice committed to 10, then all the qubits measured in the correct basis must yield a state which can be recovered to the original one by applying a $X(\pi)$ gate afterwards.
(c) If Alice committed to 01, then all the qubits measured in the incorrect basis must yield a state which can be recovered to the original one by applying a $X(\frac{3\pi}{2})$ gate afterwards.
(d) If Alice committed to 11, then all the qubits measured in the incorrect basis must yield a state which can be recovered to the original one by applying a $X(\frac{\pi}{2})$ gate afterwards.

All other cases are classified as Alice’s cheating.

4.2 Enforce punishment by QLB

To enforce punishment for Bob when he cheats, we require Bob to create the following protected transaction on QLB. “Bob sends $n$ qulogicoins, which he has received from another transaction $T_y$, to Bob: The qulogicoins transferred in this transaction can only be used when the following is true:

– Alice discover that all sequence prepared by Bob are balanced-uniform. Or equivalently, Alice does not discover Bob’s cheating in the preparation phase.”

To enforce punishment for Alice when she cheats, we require Alice to create the following protected transaction on QLB. “Alice sends $n$ qulogicoins, which she has received from another transaction $T_y$, to Alice: The qulogicoins transferred in this transaction can only be used when the following is true:

– Bob does not discover Alice’s cheating in the opening phase. Or equivalently, one of the following is true:
  1. All the qubits measured in the correct basis yield a state which is the same as the original one.
  2. All the qubits measured in the correct basis yield a state which can be recovered to the original one by applying a $X(\pi)$ gate.
  3. All the qubits measured in the incorrect basis yield a state which can be recovered to the original one by applying a $X(\frac{3\pi}{2})$ gate.
4. All the qubits measured in the incorrect basis yield a state which can be recovered to the original one by applying a $X(\frac{\pi}{2})$ gate.

5 Conclusion and future work

In this paper we introduced quantum-enhanced logic-based blockchain to improve the efficiency and power of quantum-secured blockchain [19]. The efficiency is improved by using a new quantum honest-success Byzantine agreement protocol to replace the classical Byzantine agreement protocol in quantum-secured blockchain, while the power is improved by incorporating quantum certificate and quantum protection into the syntax of transactions. No multi-particle entanglement is used in our blockchain, which makes it easy to be implemented with the current technology. In fact, all the quantum technology needed for our blockchain is already available in laboratories and even industry. Incorporating quantum certificate and quantum protection into blockchain makes it possible to use our blockchain to overcome a significant shortcoming of cheat-sensitive quantum bit commitment protocols.

In the future, we will further extend QLB to make it smarter and easier-to-regulate. We are also interested in applying QLB in other tasks such as electronic voting, online auction and multiparty lotteries.

Although these quantum protections is expressed informally in this paper, they can be expressed concisely and precisely by some quantum logic, such as the the dynamic logic of quantum programs [19]. We leave this as future work.
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