Research Article

An Efficient Electronic English Auction System with a Secure On-Shelf Mechanism and Privacy Preserving

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Received 16 December 2015; Accepted 24 March 2016

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With the rapid development of the Internet, electronic commerce has become more and more popular. As an important element of e-commerce, many Internet companies such as Yahoo! and eBay have launched electronic auction systems. However, like most electronic commerce products, safety is an important issue that should be addressed. Many researchers have proposed secure electronic auction mechanisms, but we found that some of them do not exhibit the property of unlinkability, which leads to the leakage of users’ privacy. Considering the importance of privacy preservation, we have designed a new auction mechanism. Through symmetrical key establishment in the registration phase, all messages transmitted over the Internet would be protected and, meanwhile, achieve the property of unlinkability. The security analysis and performance analysis show that our protocol fulfills more security properties and is more efficient for implementation compared with recent works.

1. Introduction

With the development of network technology, more and more people are searching for information on the Internet. In 2013, the number of Internet users of the whole world reached 2.92 billion [1]. Now, people not only read the news and search for information on the Internet but also do business with others. Not surprisingly, e-commerce has grown rapidly in recent decades. As the founder and CEO of China’s most famous e-commerce company Alibaba, Jack Ma was ranked as the second richest man in China in 2014. Many famous Internet companies launched electronic auction products several years ago such as Yahoo! and eBay. On these websites, users can play the role of not only auctioneer but also bidder after they register their accounts successfully. They can participate in the auction anytime and anywhere when their devices have access to the Internet.

Auctions can be classified into many types [2]. According to numbers of sellers and buyers, auctions can be classified as forward auctions and reverse auctions; according to the determinant of the winner, auctions can be classified as single attribute auctions and multiattribute auctions; and according to whether the bidding price is made open, we can classify auctions as sealed-bid auctions and open auctions. The sealed-bid auctions can be subdivided into sealed-bid first-price auctions and sealed-bid second-price auctions. In the first mode, all bidders submit their sealed bids to the auctioneer of an auction at the same time, and the auctioneer or arbiter of the auction secretly calculates the highest price. After that, the auctioneer or arbiter announces the winner as the owner with the highest price bid. In a sealed-bid second-price auction (also called Vickrey auction), the highest price bidder wins the auction but only needs to pay the second highest price. The designer of the sealed-bid second price auction thinks that everyone will submit their bidding price rationally in this mode; however, this method confronts a lot of problems in practice, such as bidder collusion. Open auctions can be further classified into English auctions and Dutch auctions. In an English auction, the auctioneer changes the current price dynamically, with the bidding price increasing. This means that, if one bidder’s bid price is higher than the current price, then the auctioneer uses this price as the new current price and waits for someone to offer a higher price than the current price. If someone submits a higher price, the current price is changed simultaneously; if no one offers a higher price when the auction is closed, the
owner of the current price bid wins the auction. A Dutch auction is bidding process contrary to the English auction. In a Dutch auction, the auctioneer decreases the current price until one bidder can afford it and is the winner of the auction.

A lot of problems arise when we introduce the auction process in reality on the Internet. An important issue is the information security of the system. As an Internet product is connected with money and goods, users are concerned with the safety of the online auction. Many researchers have proposed their protocols to solve security problems in auction systems. In 1999, based on millionaires’ problem, Cachin [3] proposed a private bidding and auction scheme with an oblivious third party. In 2000, Nguyen and Traoré [4] used a group signature to protect bidders’ anonymity. However, the huge computational cost and the special authority of group managers still cannot be resolved. In 2001, Omote and Miyaji [5] applied a bulletin board to overcome these problems, but their scheme does not publish the winner’s information at the end. In 2003, C.-C. Chang and Y.-F. Chang [6] proposed an anonymous English auction protocol to ensure that bidders can bid arbitrarily. In 2005, Jiang et al. [7] considered that the scheme in [6] cannot protect against man-in-the-middle attacks. In 2006, Y.-F. Chang and C.-C. Chang [8] proposed another anonymous auction scheme to resolve the problem in [6]. In 2005, Suzuki and Yokoo proposed safety problem in the multiattribute auction systems [9]. In 2007, Shih et al. proposed a privacy preserving multi-item auction mechanism with a shared key chain [10]. In 2008, Parkes et al. used a homomorphic cryptograph to achieve bid privacy in multi-item auction [11]. In 2009, Xiong et al. [12] proposed an anonymous auction scheme based on the ring signature. However, like the group signature-based protocol in [4], huge computational cost is an essential problem that should be resolved. In 2012, Xiong et al. [13] proposed another protocol based on revocable ring signature to solve the problem of high computational cost in [12] and added a dispute section.

In 2013, Chang et al. [14] pointed out that [13] is vulnerable to denial of service attacks and designed an ECC-based protocol which provides a secure on-shelf phase. Unfortunately, we found that Chang et al.’s proposal [14] does not provide unlinkability. In [14], users’ privacy can be leaked by monitoring the communication of system and linking the captured information. Although some important data such as public key and certificate are encrypted before transmission, unencrypted messages such as on-shelf information can link different packets together. For example, in the on-shelf phase, although attackers cannot calculate the true public key of the auctioneer using an encrypted message transmitted from the auctioneer and the published anonymous public key on website, attackers still can link transmitted packets and website information together through on-shelf information. This is because the on-shelf information is transmitted in plaintext. On the other hand, bidders’ privacy is in more serious danger during the bidding phase. At the end of the bidding phase, the agent center (AC) publishes the information with the bidder’s true public key on its website. Attackers can link this public key with a certain IP address and know what the user bids on.

Then, attackers can trace this public key owner’s transaction history.

Until now, many researchers have stressed the importance of privacy preservation in online auctions [15–17]. Hence, in order to overcome the privacy problem in [14], in this paper, we provide a new English auction system with privacy preservation. The overview of the auction system architecture is shown in Figure 1. Using the same system mode with Chang et al.’s proposal [14], our system has 5 phases: the registration phase, on-shelf phase, bidding phase, product-claim phase, and dispute phase. We utilize a trusted third party as the AC of our system, a well-meaning role that will not initiate attacks. However, the safety of the AC’s database cannot be completely guaranteed. We do not consider the case of hackers controlling the AC, but hackers may get access to read data in the AC. The only data we consider to be completely safe is the private key of AC. Besides this, any leaked data cannot do serious harm to the safety of the whole system. In addition, we built our protocol on Elliptic Curve Cryptosystem. According to the analysis in Section 8, our proposal has an efficiency advantage over the original proposal. In our scheme, messages transmitted between any two entities are encrypted with a symmetrical encryption algorithm such as AES. By utilizing this method, monitors cannot link different messages together. Security analysis shows that our proposal provides more security properties than the original one.

The rest of this paper is organized as follows. In Section 2, we introduce the Elliptic Curve Cryptosystem and ECDLP (elliptic curve discrete logarithm problem). Subsequently, we briefly review Chang et al.’s auction protocol [14] in Section 3. In Section 4, we talk about network model, adversary model, and properties that an auction mechanism needed. We describe our proposal in detail and use BAN logic to analyze authentication accuracy of on-shelf phase and bidding phase in Sections 5 and 6, respectively. In Sections 7 and 8, we compare the security and efficiency of our protocol with related schemes.
2. Preliminaries

In this part, we introduce some basic ideas of Elliptic Curve Cryptosystem including the definition of elliptic curve, basic operations on the Elliptic Curve, and ECDLP on ECC that can be used to construct cryptographic algorithms.

2.1. Elliptic Curve Cryptosystem. Elliptic Curve Cryptosystem (ECC) is an asymmetrical cryptosystem. It was independently proposed by Miller [19] and Koblitz [20] in 1985 and 1987. Compared to RSA, ECC can achieve the same security requirement with a shorter key-length [21]. Hence, it has been widely used in many cryptographic schemes recently.

An elliptic curve [22, 23] is defined over a finite field \( F_p \) by equation \( E_p(a,b) : y^2 = x^3 + ax + b \), where \( p \) is a large prime and \( 4a^3 + 27b^2 \neq 0 \mod p \). The points on this elliptic curve form a cyclic group. Addition in this group is defined as if \( P, Q, R \in E_p(a,b) \) on one line, and then \( P + Q + R = O \) (\( O \) is infinite point). Given an integer \( s \in F_p^* \) and a point \( P \in E_p(a,b) \), the multiplication operation \( s \cdot P \) over \( E_p(a,b) \) is defined as \( P + P + \cdots + P \) in \( s \) times. If \( P \) is symmetrical with \( P^* \) on the \( x \)-axis, then \( P + P^* = O \). Furthermore, point \( P \) is a base point with an order \( n \) if and only if \( n \cdot P = O \).

2.2. ECDLP. Every cryptosystem has its own difficult problem, such as the integer factorization used in RSA. The most important difficult problem in ECC is the elliptic curve discrete logarithm problem (ECDLP) [24]. Based on ECDLP, we can develop many other difficult problems, such as the computational Diffie-Hellman problem (CDLP) and the elliptic curve factorization problem (ECFP). In our scheme, we will use ECDLP.

Definition 1 (elliptic curve discrete logarithm problem (ECDLP)). Given two points \( P \) and \( Q \) over \( E_p(a,b) \), it is very hard to find an integer \( s \in F_p^* \) such that \( Q = sP \).

3. Related Work

In this part, we describe Chang et al.’s proposal [14] briefly and analyze the security and privacy preserving in it.

Chang et al’s protocol includes five phases: registration phase, off-shelf phase, bidding phase, product claiming phase, and dispute phase. A new user should register to an agent center (AC) and AC will issue a certificate for him/her such that he/she can play the role of both auctioneer and bidder. If a registered user wants to initiate an auction, he/she should send some basic information about auction (i.e., product identity, basic price of the auction, and deadline) to AC via the off-shelf phase. Upon checking the legality of user’s identity and the information of the new auction, AC publishes an advertisement on its website (BB\(_{AC}\)) such that anyone can read it after the auction has started. If someone wants to bid for the product of this auction via the bidding phase, he/she can send bidding information to AC. After AC checked the legality of bidder’s identity and the bidding price is higher than current price, AC should change the value of current price to the bidding price and publish the bidder’s public key and bidding price on BB\(_{AC}\); else, AC ignores this bid and waits for new bid. After the auction deadline, AC selects the bidder with highest price as the winner, sends a receipt to the winner, and publishes final result on BB\(_{AC}\) such that anyone can read and verify it. After getting the receipt, the winner can claim the product from the auctioneer by showing the receipt via the product claiming phase. Then, the auctioneer can verify the correctness of this receipt and send the product to the user. With regard to the dispute phase, if a user takes action illegally, the user trading with him/her can submit dispute information to AC and wait for the arbitration of AC. If illegal action existed, AC can trace the identity of malicious user and punish him/her.

The notations used in Chang et al’s protocol are as follows and the details of their protocol are described in the following except of the dispute phase:

- AC: a trusted agent center.
- \( B_p \): a Bidder Z.
- \( A_Z \): an auctioneer Z.
- \( ID_Z \): the identity of Z.
- \( SK_{AC} \): AC’s private key.
- \( PK_Z \): Z’s public key.
- \( PW_Z \): Z’s password.
- \( CERT_Z \): the certificate of PK\(_Z\) signed by AC.
- \( BB_{AC} \): the Bulletin board of AC.
- \( P \): the base point of ECC group over a finite field \( F_p \) with order \( p \), where \( p \) is a large prime.
- \( (\cdot)_x \): an operation using \( x \)-coordinate in ECC.
- \( (\cdot)_y \): an operation using \( y \)-coordinate in ECC.
- \( E_k[\cdot] / D_k[\cdot] \): AES-based encryption/decryption with key \( k \).
- \( f(\cdot) \): a secure one-way hash function.

3.1. Registration Phase. If a user wants to play the role of an auctioneer or a bidder in the auction, he/she should register an account at AC by the following steps.

1. User chooses \( ID_u \), \( PW_u \in Z_p^* \) and a random number \( r_u \in Z_p^* \), and computes his/her public key \( PK_u = PW_u \cdot P \mod p \). Then, the user calculates \( R_0 = r_u \cdot P \mod p \), \( R_1 = 1D_u + (r_u \cdot PK_{AC}) \cdot x \mod p \), and \( R_2 = PK_u + r_u \cdot PK_{AC} \cdot mod p \) and sends \((R_0, R_1, R_2)\) to AC.
2. AC retrieves user’s identity \( ID_u = R_1 - (SK_{AC} \cdot R_0) \mod p \) and public key \( PK_u = R_2 - SK_{AC} \cdot R_0 \mod p \). Subsequently, AC chooses a random number \( r_{AC} \in Z_p^* \) calculates \( R_0' = r_{AC} \cdot P \mod p \) and \( CERT_u = r_{AC} + (PK_u \cdot x) \cdot SK_{AC} \cdot ID_u \mod p \), and sends them to the user. User checks the correctness of equation \( CERT_u \cdot P - R_0' \equiv (PK_u \cdot x) \cdot ID_u \cdot PK_{AC} \mod p \) to verify the validation of this certificate. If valid, then user stores it with \( R_0' \).
3.2. On-Shelf Phase. If a registered user wants to host an auction, then he/she becomes an auctioneer \( A_j \) and performs the following.

(1) \( A_j \) chooses a random number \( r_1 \in Z_p^* \) and a nonce \( n_1 \in Z_p^* \) and calculates \( O_0 = r_1 \cdot P \mod p, O_1 = (PK_{A_j} + r_1 \cdot PK_{AC}) \mod p, K_{na} = (PW_{A_j} \cdot PK_{AC} \cdot n_1)_x \mod p, \) and \( O_2 = E_{K_{na}}(R_{01}^j || CERT_{A_j}). \) \( A_j \) generates auction information \( AI = (pid,j || BasicPrice || Deadline), \) that is, the identity of a product, basic price of this auction, and the deadline of this auction. Finally, \( A_j \) computes \( Sig = (r_1 + AI \cdot PW_{A_j} \cdot n_1) \mod p \) and sends \((ID_{A_j}, n_1, O_0, O_1, O_2, AI, Sig)\) to \( AC. \)

(2) \( AC \) retrieves \( A_j \)'s public key \( PK_{A_j} = O_1 - SK_{AC} \cdot O_0. \) Then, \( AC \) computes the symmetrical key shared with \( A_j : K_{na} = (SK_{AC} \cdot PK_{A_j} \cdot n_1)_x \mod p. \) \( AC \) can decrypt \( O_2 \) with \( K_{na} \) to extract \( A_j \)'s certificate. \( AC \) should check the correctness of the certificate by verifying if equation \( CERT_{A_j} \cdot P - R_{01}^j \equiv (PK_{A_j})_x \cdot ID_{A_j} \cdot PK_{AC}(mod \ p) \) holds and the integrity of \( AI \) by verifying if equation \( Sig \cdot P - O_0 \equiv PK_{A_j}^x \cdot AI(mod \ p) \) holds where \( PK_{A_j}^x = n_1 \cdot PK_{AC} \mod p. \) If both are valid, \( AC \) generates a unique \( gid \) for \( A_j \)'s product. \( AC \) then computes a verifier \( V = h(gid \parallel K_{na}) \) and sends \((V, gid)\) to \( A_j. \)

(3) After \( A_j \) received message from \( AC, \) he/she computes and checks if \( V = h(gid \parallel K_{na}). \) If the equation holds, \( A_j \) responds \( Approval \) message to \( AC. \) Upon receiving \( Approval \) from \( A_j, \) \( AC \) publishes \((gid, ID_{A_j}, AI, O_0, PK_{A_j}^x, Sig, N_1)\) on \( BB_{AC} \) and anyone can verify this message by checking equation \( Sig \cdot P - O_0 \equiv PK_{A_j}^x \cdot AI(mod \ p) \).

3.3. Bidding Phase. If someone is interested in this auction, he/she could play the role of a bidder \( B_i \) and send bidding message to \( AC \) by the following.

(1) \( B_i \) chooses a random number \( r_2 \in Z_p^* \) and computes \( D_0 = r_2 \cdot P \mod p, D_1 = (PK_{B_i} + r_2 \cdot PK_{AC}) \mod p, K_{ba} = (PW_{B_i} \cdot PK_{AC} \cdot (D_0)_y \mod p, \) and \( D_2 = E_{K_{ba}}(R_{02}^i \parallel CERT_{B_i} \parallel ID_{B_i})). \) \( B_i \) generates bidding message \( BM = (gid \parallel price) \) and signs it as \( BSig_{B_i} = (r_2 + BM \cdot PW_{B_i}) \mod p. \) \( B_i \) sends \((D_0, D_1, D_2, BM, BSig_{B_i})\) to \( AC. \)

(2) Upon receiving these messages, \( AC \) retrieves \( B_i \)'s public key \( PK_{B_i} = D_1 - D_0 \cdot SK_{AC} \mod p \) and computes \( K_{ba} = (SK_{AC} \cdot PK_{B_i} \cdot (D_0)_y \mod p, \) then, \( AC \) decrypts \( D_2 \) using \( K_{ba} \) to extract \( AC \)'s certificate. \( AC \) can verify the correctness of \( CERT_{B_i} \) by checking equation \( CERT_{B_i} \cdot P - R_{02}^j \equiv (PK_{B_i})_x \cdot ID_{B_i} \cdot PK_{AC}(mod \ p). \) If it is valid, \( AC \) checks the correctness of \( BM \) by checking equation \( BSig_{B_i} \equiv PK_{B_i} \cdot BM(mod \ p). \) If it is valid too, \( AC \) further checks \( Deadline \) and \( BasicPrice \) of the auction by using \( gid \) to search the corresponding information on its website. If the auction has closed or the \( price \) is not larger than \( BasicPrice, \) \( AC \) rejects this bid; otherwise, \( AC \) generates a unique transaction identity \( tid \) for \( B_i \) and chooses a random number \( r_3 \in Z_p, \) \( AC \) then computes \( D_3 = r_3 \cdot P \mod p, BM' = (tid \parallel BM), \) \( Rec = r_3 + (BM' \cdot SK_{AC}) \mod p, \) and \( D_4 = E_{K_{ba}}(tid \parallel D_4 \parallel Rec). \) Finally, \( AC \) updates \( BasicPrice = price, \) publishes \((tid, price, date, D_0, BM, BSig_{B_i}, PK_{B_i}, D_2)\) in database, and sends \( D_4 \) to bidder.

(3) After \( B_i \) received the message from \( AC, \) \( B_i \) can extract the transaction information \((tid \parallel D_3 \parallel Rec)\) from \( D_4. \) Then, \( B_i \) checks the validation of receipt \( Rec \) by verifying \( Rec \cdot P - D_3? \equiv (tid \parallel BM) \cdot PK_{AC} \mod p. \) If the equation holds, \( B_i \) stores \((Rec, D_3). \)

(4) After deadline, \( AC \) sets the winner as the bidder with the highest price. \( AC \) then publishes the winner's information on \( BB_{AC} \) including several items \((tid, price, date, D_0, bid, BSig_{B_i}, PK_{B_i}, D_2)\) such that anyone can verify its validity by checking \( BSig_{B_i} \equiv PK_{B_i} \cdot BM(mod \ p). \)

3.4. Product Claiming Phase. After the auction deadline, the winner can claim the product from the auctioneer by showing his/her receipt and performing the following steps. After the auctioneer checked the correctness of receipt, the auctioneer should send the product to the winner.

(1) \( B_i \) selects a random number \( r_c \) and a nonce \( n_2 \) from \( Z_p^*, \) computes \( C_0 = r_c \cdot P \mod p, C_1 = (Rec + r_c \cdot n_2 \cdot PK_{A_j}^x) \mod p, \) and \( C_2 = (D_3 + r_c \cdot n_2 \cdot PK_{A_j}^x) \mod p, \) and sends \((bid, C_1, C_2, C_0, n_2)\) to \( A_j. \)

(2) Once receiving \( B_i \)'s claiming request, \( A_j \) retrieves \( Rec = (C_1 - (C_0 \cdot n_2 \cdot PW_{A_j})_x \mod p \) and \( D_3 = (C_2 - C_0 \cdot n_2 \cdot PW_{A_j})_x \mod p. \) Then, \( A_j \) verifies \( Rec \cdot P - D_3? \equiv (tid \parallel bid \parallel price) \cdot PK_{AC} \mod p. \) If the verification holds, \( A_j \) is convinced that \( B_i \) is the actual winner and sends the product to \( B_i. \)

3.5. Security Defect of Chang et al.'s Protocol. According to our analysis, we found that Chang et al.'s protocol meets most of the security requirements of an auction protocol except for unlinkability. In Chang et al.'s protocol, although some important data such as users' public keys and certificates are encrypted before being transferred, unencrypted messages such as the on-shelf information still can be linked together with different packets. Figures 2 and 3 show the linkage between transferred messages and published messages on \( AC \)'s website. The solid border represents the message transferred on the Internet, and the dotted border represents the message published on \( AC \)'s website.

From Figures 2 and 3, we can see that these messages can be linked together through certain parameters. For example, in the on-shelf phase (Figure 2), although attackers cannot calculate the public key or certificate of an auctioneer \( A_j \) from
the encrypted message (solid border) based on the definition of EC-\text{DLP} and the security assumption of underlying AES algorithms, attackers can still find the relevance of transferred messages (solid message) and published messages (dotted message) to analyze the specific user’s privacy. As shown in Figure 2, we find that ID_{A_i}, n_1, A_i, O_0, and Sig are linkable. Obviously, an adversary can link the captured message on the Internet with the published message if they have the same parameters ID_{A_i}, n_1, A_i, O_0, and Sig. Furthermore, the adversary can decide that if these messages come from the specific IP address. If so, the adversary obtained this IP address owner’s identity ID_{A_i}.

On the other hand, as mentioned previously, bidders’ privacy is in more serious danger in the bidding phase. At the end of the bidding phase, the AC publishes the information with the winner’s true public key on AC’s website. As shown in Figure 3, similar to Figure 2, attackers have the ability to determine the IP addresses of captured messages on the Internet and to link the specific transferred encrypted bidding information with the published message (the winner’s information). Consequently, attackers would find the relevance of the winner’s public key and the specific IP address. If this user continues to anticipate other auctions, his/her transaction history will be traced. For example, an adversary used Sniffer (a network tool to capture the packets transferred in local network) to capture packets transferred in the local network of his/her office environment and found that some packets are transferred to the auction server (AC). After analyzing the important parts of these packets and comparing them with the messages published on AC’s website, the adversary can know what the specific IP address owner had hidden for or sold out. Obviously, the adversary can easily know who uses the IP address in this office if he/she wishes.

According to the aforementioned analyses, we can see that the main problem that results in privacy disclosure is that some published data is transferred in plaintext before such that an adversary can easily link them together. Hence, in our proposal, we establish a shared symmetrical key between each user and the AC to encrypt the message transferred on the Internet to avoid linkability. By using symmetrical encryptions and fewer ECC operations, our proposal can not only improve the security but also reduce the system cost. In the registration phase, we connect a user’s identity and the corresponding symmetrical key so that the AC can compute the shared symmetrical key easily with the user’s identity. Besides, each user’s identity is encrypted with the AC’s public key so it cannot be revealed without the knowledge of AC’s private key. In our proposal, we fulfill the verifiability of all messages published on the AC’s website; however, Chang et al.’s proposal only partially achieved this feature.

4. System and Adversary Model

In this section, we describe the definitions of our network model, adversary model, and requirements as follows before introducing our proposed scheme.

4.1. Network Model. We consider a network composed of an agent center (AC) and users. The AC is a trusted third party that undertakes most tasks of system running, such as user registration, generation of users’ certificates, and product on-shelf. With regard to the application of the trusted third party, it is widespread in e-commerce systems [25–28]. The AC is also an arbiter of an auction and has the right to determine who the winner is or punish the illegal user’s identity. Hence, we think that the AC has large capability of computation and storage. The AC should maintain a database on its machine to store users’ data. Herein, we do not consider this database to be completely secure. Hackers may have methods to access it, but such actions will not destroy the security of the whole system. Furthermore, the AC’s private key should be kept in a trusted place such as a bank security box.

On the other hand, users use their devices such as computers or mobile devices to communicate with the AC through the Internet. When a user wants to connect with the AC, he/she should type in a password or insert a smart card with a password into the machine. The client in the user’s machine erases the password after the user goes offline.

4.2. Adversary Model. In this paper, we assume that an adversary can launch a passive attack to monitor the communication channel of the system. The adversary has knowledge of the format of a packet, so he/she can analyze what content is included in the packet. We also think that the adversary has the ability to access the database stored in the AC and can read the AC’s website as the other users. In addition, some registered users may attack the system jointly.

4.3. Security Requirements. In order to provide a secure auction scheme, the following security properties are critical [29].

Anonymity. User’s identification should be kept secret as the system is running. No one can obtain the user’s identification from messages transmitted or published.
Easy Revocation. A user’s right should be easily and correctly revoked in the auction system by the AC.

Fairness. All bidders should have the ability to verify whether their bids have indeed been included in the auction.

Nonrepudiation. Users including bidders and auctioneers cannot deny the actions that have been taken before. For example, if an auctioneer puts a product on-shelf, he/she cannot deny that he/she did it and off-shelf this product arbitrarily.

Onetime Registration. Any registered user can host or participate in any auction without reregistration at the AC.

Traceability. If some illegal actions are taken such as a non-paying bid (NPB), the AC should have the ability to identify and publish the dishonest user’s true identity anytime.

Unforgeability. No one can forge a valid message or impersonate any legal users to do illegal things.

Unlinkability. No one can link different messages together to trace a specific user’s transaction history even if he/she does not know the true identification of the user.

Verifiability. All winning bids and product information published on a bulletin board should be publicly verifiable without revealing the bidders’ identities.

5. Proposed Scheme

In this section, we propose a secure English auction system with privacy preservation. Our proposal consists of six phases: the system setup phase, registration phase, on-shelf phase, bidding phase, product claiming phase, and dispute phase. There are two kinds of participants in this system: the AC and the users. In the system setup phase, the AC inputs a security parameter and generates a set of system parameters. The AC then requests a certificate from an acknowledged certificate authority and publishes these data on its website. Anyone can get these data from the AC’s website. If a new user wants to register an account, he/she can connect with the AC during the registration phase. After registration, the user can either host or participate in an auction. If he/she wants to host an auction, he/she can on-shelf his/her products in the on-shelf phase; if he/she wants to bid for some on-shelved products, he/she can send the bidding information to the AC during the bidding phase. The AC should publish every bidder’s bidding information except for the bidder’s identity on its website such that anyone can read it. If a bidder wins the auction, he/she will receive a receipt and a session key shared with the auctioneer from the AC. Then, the winning bidder can obtain his/her product from the auctioneer during the product claiming phase. In our proposal, the AC has the capability of tracing the whole transaction and identifying the participants in an auction if necessary. If a dispute has occurred, anyone participating in an auction can submit the dispute request to the AC in the dispute phase. The notations used in our proposal are as follows and the details of our proposal are described in the following subsections:

\[ B_i \text{; a bidder } i. \]
\[ A_j \text{; an auctioneer } j. \]
\[ AC \text{; a trusted agent center.} \]
\[ \kappa \text{; the system security parameter chosen by } AC. \]
\[ F_q \text{; finite filed of order } q. \]
\[ E/F_q \text{; an elliptic curve based on } q \text{ order finite field.} \]
\[ G_q \text{; a cyclic group of the elliptic curve.} \]
\[ P \text{; the base point of ECC group.} \]
\[ (\cdot)_x \text{; an operation using } x \text{-coordinate in ECC.} \]
\[ SK_{AC} \text{; AC’s private key.} \]
\[ PK_{AC} \text{; AC’s public key.} \]
\[ Cert_{AC} \text{; the certificate of } PK_{AC} \text{ signed by the certificate authority.} \]
\[ id_U \text{; the identity of a user } U. \]
\[ pw_U \text{; } U \text{’s password.} \]
\[ N_i \text{; a nonce.} \]
\[ P_i \text{; } U \text{’s partial key used for computing symmetrical key shared with } AC. \]
\[ K_{AU} \text{; the symmetrical key of } AC \text{ and a user.} \]
\[ K_{AR} \text{; the symmetrical key of } AC \text{ and a bidder.} \]
\[ K_{AA} \text{; the symmetrical key of } AC \text{ and an auctioneer.} \]
\[ E_K(\cdot) \text{; an AES-based encryption with key } K. \]
\[ D_K(\cdot) \text{; an AES-based decryption with key } K. \]
\[ H(\cdot) \text{; a secure one-way hash function.} \]
\[ BB_{AC} \text{; the bulletin board of } AC. \]

5.1. System Setup Phase. Before the system is running, the AC chooses \( SK_{AC} \in Z_q^* \) as the private key. The AC then inputs a security parameter \( \kappa \in Z_q^* \) and generates a set of system parameters \( \Omega = \{ F_q, E/F_q, G_q, P, PK_{AC}, Cert_{AC}, H(\cdot) \} \) through the steps below:

1. Choose a \( \kappa \)-bit prime \( q \).
2. Determine the tuple \( \{ F_q, E/F_q, G_q, P \} \); \( F_q \) is a finite filed modular \( q \); \( E/F_q \) is an elliptic curve defined over \( F_q \); \( G_q \) is a cyclic group defined over \( F_q \) and \( P \) is the generator of \( G_q \).
3. Compute the AC’s public key \( PK_{AC} = SK_{AC} \cdot P \text{ mod } q. \)
4. Choose a cryptographic hash function \( H(\cdot) \).
5. Request a certificate \( Cert_{AC} \) of \( PK_{AC} \) from the certificate authority.

Then, the AC publishes \( \Omega \) on its online \( BB_{AC} \) and keeps \( SK_{AC} \) secret.
5.2. Registration Phase. If a user wants to host or participate in an auction, he/she must perform the following steps to register an account at the AC.

1. The user obtains system parameters on $BB_{AC}$ and checks the validation of the AC’s public key by $Cert_{AC}$. If $PK_{AC}$ is invalid, he/she terminates the subsequent operations; otherwise, he/she chooses his/her password $pw_{Uj} \in Z_q^*$ and identity $id_{Uj} \in Z_q^*$ and generates a random number $r_0$ and a nonce $N_1$. Afterwards, he/she computes $R_0 = r_0 \cdot P \mod q$, $P_{Uj} = pw_{Uj} \cdot P \mod q$, $C = (r_0 \cdot PK_{AC} + P_{Uj}) \mod q$, and $C_0 = ((r_0 \cdot PK_{AC}) + M) \mod q$ and sends $(C, C_0, R_0)$ to AC, where $M = (id_{Uj}, N_1)$.

2. Upon the receipt of the message sent from the user, the AC can extract $P_{Uj}$ and $M$ by computing $P_{Uj} = C - SK_{AC} \cdot R_0 \mod q$ and $M = (id_{Uj}, N_1) = C_0 - (SK_{AC} \cdot R_0)_x \mod q$. The AC then checks the freshness of $N_1$. If $N_1$ is valid, the AC chooses a nonce $N_2$ and computes $RESPONSE = ((success, N_2) + (SK_{AC} \cdot P_{Uj})_x) \mod q$. The AC then sends $RESPONSE$ to the user and stores $(id_{Uj}, N_2)$ in its database, where $v_{Uj} = P_{Uj} = H(SK_{AC})$.

3. After receiving $RESPONSE$, the user retrieves $success, N_2) = (RESPONSE - (PK_{AC} \cdot pw_{Uj})_x \mod q$ and checks if $success$ is contained in it. If so, the user checks the freshness of $N_2$. If both are valid, the user ascertains that he/she has registered successfully and then can either host or participate in an auction.

Note that each registered user has a partial key $P_{Uj}$ and can share a key $K_{AU} \equiv (pw_{Uj} \cdot PK_{AC})_x \equiv (SK_{AC} \cdot P_{Uj})_x (\mod q)$ with the AC. For convenience, in the following, we use $K_{AU}$ to imply the key shared between the AC and a user who plays as an auctioneer $A_j$, and $A_j$’s partial key is $P_{A_j}$. In contrast, the keys of a user who plays as a bidder $B_j$ are $K_{AB}$ and $P_{B_j}$.

5.3. On-Shelf Phase. If a registered user wants to host an auction to sell some products, he/she becomes an auctioneer $A_j$ and performs the following steps.

1. $A_j$ generates on-shelf information $y = (ID_{product} || Basic\_price || Deadline)$ firstly, where $ID_{product}$ refers to the identity of a product. $Basic\_price$ indicates the basic price of this auction (every bidder’s bidding price should not be less than this value), and $Deadline$ represents the deadline of this auction. Then, $A_j$ computes $K_{AA} = (pw_{A_j} \cdot PK_{AC})_x \mod q$. After that, $A_j$ randomly chooses a nonce $N_3$ and calculates $e_1 = E_{K_{AA}}(y, N_3, id_{A_j})$, $h_1 = H(e_1, K_{AA})$, $C_1 = (h_1 \cdot PK_{AC})_x + id_{A_j} \mod q$, and $R_1 = h_1 \cdot P \mod q$. Then, $A_j$ sends $(C_1, R_1, e_1)$ to the AC.

2. The AC retrieves $id_{A_j}$ from $C_1$ by computing $id_{A_j} = C_1 - (R_1 \cdot SK_{AC})_x \mod q$. Then, the AC searches its database to extract the corresponding $P_{A_j}$, $(P_{A_j} = H(SK_{AC}) \oplus v_{A_j})$ of $id_{A_j}$, and calculates $K_{AA} = (SK_{AC} \cdot P_{A_j})_x \mod q$. The AC extracts $(y, N_3, id_{A_j})$ by decrypting operation $D_{K_{AA}}(e_1)$. The AC checks whether the identity $id_{A_j}$ in $e_1$ is equal to that retrieved from $C_1$. If they are not equal, the AC may confront a replay attack, and the AC should terminate sequent operations immediately; otherwise, the AC checks the freshness of $N_3$. If both are valid, the AC generates a unique on-shelf identity $ID_{on\_shelf}$ for $A_j$ and sends $E_{K_{AA}}(ID_{on\_shelf}, id_{A_j}, N_4)$ to $A_j$ where $N_4$ is a nonce.

3. After receiving the message from the AC, $A_j$ retrieves $(ID_{on\_shelf}, id_{A_j}, N_4)$ by decryption with key $K_{AA}$. $A_j$ checks the integrity of the message by checking if a correct $id_{A_j}$ is in it and checks the freshness of this message by checking $N_4$. If both are valid, the auctioneer then sends $APPROVAL$ to AC.

4. Upon receiving $APPROVAL$ from $A_j$, the AC chooses a random number $r_1 \in \mathbb{Z}_q^*$ and computes $R_2 = r_1 \cdot P \mod q$ and $S_1 = r_1^{1/x}(M_1 - SK_{AC} \cdot (R_2)_x) \mod q$, where $M_1 = (y, ID_{on\_shelf}, id_{A_j})$. Waiting $r$ minutes $(r \in [0, t])$, the AC publishes $(M_1, R_2, S_1)$ on $BB_{AC}$. Once the AC publishes the on-shelf information, the auction has been held, and anyone can verify the validation of the auction information by checking the correctness of equation $S_1 \cdot R_2 + (R_2)_x \cdot PK_{AC} \equiv M_1 \cdot P \mod q$.

5.4. Bidding Phase. If a bidder $B_j$ wants to bid for an on-shelf product, he/she should send the bidding information to the AC, including the corresponding identity $ID_{on\_shelf}$ of the product and a bidding price $price$. We denote $(ID_{on\_shelf} || price)$ as $eta$ here.

1. $B_j$ computes $K_{AB} = pw_{B_j} \cdot PK_{AC} \mod q$ firstly. Then, $B_j$ computes $e_2 = E_{K_{AB}}(eta, N_3, id_{B_j})$, $h_2 = H(e_2, K_{AB})$, $C_2 = ((h_2 \cdot PK_{AC})_x + id_{B_j}) \mod q$, and $R_2 = h_2 \cdot P \mod q$, where $N_3$ is a nonce. Then, $B_j$ sends $(C_2, R_2, e_2)$ to the AC.

2. After receiving the bid sent from $B_j$, the AC can retrieve $id_{B_j}$ from $C_2$ by computing $id_{B_j} = C_2 - (R_2 \cdot SK_{AC})_x \mod q$. Then, the AC searches the $id_{B_j}$ in the database. If the $id_{B_j}$ does not exist, the AC terminates the sequent operation; otherwise, the AC retrieves the corresponding $P_{B_j}$ by computing $P_{B_j} = H(SK_{AC}) \oplus v_{B_j}$ and computes the symmetrical key shared with $B_j$ as $K_{AB} = SK_{AC} \cdot P_{B_j} \mod q$. The AC decrypts $e_2$ with $K_{AB}$ to extract $(eta, N_3, id_{B_j})$. The AC can check the integrity of this bid by seeing if $id_{B_j}$ is equal to the one retrieved from $C_2$. If they are not equal, the AC may confront a replay attack, and the AC should terminate the sequent operations; otherwise, the AC checks the freshness of $N_3$. If both are valid, the AC uses $ID_{on\_shelf}$ in $eta$ to search the corresponding auction information in $BB_{AC}$.

3. After finding the corresponding auction, the AC compares $price$ in $eta$ with $Basic\_price$ of the auction. If $price$ is not larger than $Basic\_price$, the AC ignores
5.6. Dispute Phase. In our proposal, the AC has the capability of tracing the whole transaction and identifying the participants in an auction if necessary. If a dispute has occurred, anyone who participates in an auction can submit a dispute request to the AC in this phase. In the following, we consider two situations to explain the dispute phase.

**Situation 1** (auctioneer appeals to AC). If a nonpaying auction happened, which means that the winner \( B_i \) did not contact the auctioneer \( A_j \) after he/she won the auction, \( A_j \) can appeal to the AC and the AC will trace the transaction to deal with this dispute.

\( A_j \) browses \( BB_{AC} \) and finds the winner’s \( ID_{trans} \) firstly. Then, \( A_j \) selects a nonce \( N_6 \) and computes \( K_{AA} = pw_{A_j} \cdot PK_{AC} \), \( e_4 = E_{K_{AA}}(ID_{trans} \parallel id_{A_j} \parallel N_6) \), \( h_3 = H(e_4, K_{AA}) \), \( C_3 = (h_3 \cdot PK_{AC}) \cdot id_{A_j} \mod q \), and \( R_q = h_3 \cdot P \mod q \). Subsequently, \( A_j \) sends \((C_3, R_q, e_3)\) to AC. Once receiving the dispute request from \( A_j \), the AC retrieves \( id_{A_j} = C_3 \cdot (R_q \cdot SK_{AC}) \mod q \) and checks the validation of \( id_{A_j} \) in the database. If it is valid, then the AC computes \( K_{AA} = (H(SK_{AC} \parallel v_A) \cdot SK_{AC}) \mod q \) and decrpts \( e_3 \) to extract \( ID_{trans}, id_{A_j}, \) and \( N_6 \). The AC checks the freshness of \( N_6 \). If the nonce is fresh, the AC checks if \( id_{A_j} \) in \( C_3 \) equals \( id_{A_j} \) in \( e_3 \). If they are not equal, the AC terminates operation immediately; otherwise, the AC searches the \( ID_{trans} \) on \( BB_{AC} \) and traces the transaction history to determine whether the problem really exists. If the AC ascertains that the problem claimed by \( A_j \) is true, the AC then finds out the corresponding \( dis \) and \( N_6 \) among the winner’s information from \( BB_{AC} \). Afterwards, the AC computes \( k_{dis} = H(SK_{AC} \parallel N_6) \) and extracts \((C_2, R_q)\) from \( dis \). Finally, the AC can receive the dishonest winner’s identity as \( id_{B_j} = C_2 - (R_q \cdot SK_{AC}) \mod q \) and publish it.

**Situation 2** (bidder appeals to AC). If the auctioneer \( A_j \) of an auction refuses to send the product to the winner \( B_i \), \( B_j \) also can appeal to the AC.

Firstly, \( B_i \) computes \( K_{AB} = pw_{B_i} \cdot PK_{AC} \mod q \), \( e_4 = E_{K_{AB}}(RECEIPT \parallel ID_{trans} \parallel N_{10} \parallel id_{A_j}) \), \( h_4 = H(e_4, K_{AB}) \), \( C_4 = (h_4 \cdot PK_{AC}) \cdot id_{A_j} \mod q \), and \( R_q = h_4 \cdot P \mod q \), where \( N_{10} \) is a nonce. \( B_j \) then sends \((C_4, R_q, e_4)\) to the AC. Upon receiving the dispute request from \( B_j \), the AC retrieves \( id_{B_j} = C_4 - (R_q \cdot SK_{AC}) \mod q \) and checks if \( id_{B_j} \) exists in the database. If it exists, the AC then computes \( K_{AB} = (H(SK_{AC} \parallel v_B) \cdot SK_{AC}) \mod q \) and decrypts \( e_4 \) to extract \( RECEIPT, ID_{trans} \parallel N_{10} \parallel id_{B_j} \). The AC checks the freshness of \( N_{10} \). If the nonce is fresh, the AC checks if \( id_{B_j} \) in \( C_4 \) equals \( id_{B_j} \) in \( e_4 \). If they are not equal, the AC terminates the operation immediately; otherwise, the AC then finds the corresponding \( N_6 \) and \( id_{A_j} \) of \( ID_{trans} \) on \( BB_{AC} \) and the corresponding \( v_A \), of \( id_{A_j} \) in the database. Then, the AC calculates \( P_{A_j} = H(SK_{AC}) \parallel v_A \) and \( K_{AA} = P_{A_j} \cdot SK_{AC} \mod q \). The AC checks the validation of RECEIPT by verifying \( RECEIPT \parallel id_{A_j} = (K_{AA}) \cdot H(SK_{AC} \parallel N_6) \cdot M_2 \). Note that \( M_2 \) and \( N_6 \) can be found in the winner’s information on \( BB_{AC} \). If RECEIPT is valid, the AC traces the transaction history to determine whether the problem really exists. If the AC

this bid and returns to the waiting state; otherwise, the AC updates Basic_price = price and generates a unique identity ID_{trans} for this transaction. Then, the AC generates a nonce \( N_6 \) and computes \( k_{dis} = H(SK_{AC} \parallel N_6) \) and \( dis = E_{k_{dis}}(C_2, R_3) \). Let \((ID_{trans}, price, dis, N_6) \) be \( M_2 \); the AC then generates \( r_3 \cdot x 

\text{and computes } R_3 = r_3 \cdot P \mod q \) and \( S_3 = r_3^{-1} \cdot (M_3 - SK_{AC} \cdot (R_3)_x) \mod q \). Waiting \( t \) minutes, \( t \in [0, t) \), the AC publishes \((M_3, R_3, S_3)\) on \( BB_{AC} \) such that anyone can verify it by checking if equation \( S_3 = r_3^{-1} \cdot (M_3 - SK_{AC} \cdot (R_3)_x) \mod q \) holds.

The AC then finds out the corresponding \( P_{A_j} \) of the auctioneer’s id_{A_j} of this auction in the database.

The AC computes the symmetrical key shared with \( A_j \) as \( K_{AA} = SK_{AC} \cdot P_{A_j} \mod q \). Then, the AC generates a session key shared between \( B_i \) and \( A_j \) as \( K_{session} = H(ID_{trans}, price, date, (K_{AA})) \). The AC generates a receipt for \( B_i \) as \( RECEIPT = (K_{AA})_x \cdot H(SK_{AC} \parallel N_6) \cdot M_2 \) and sends \( E_{K_{session}}(RECEIPT, K_{session}, id_{B_i}, N_6, ID_{trans}) \) to \( B_i \), where \( N_6 \) is a nonce.

Upon receiving the message from the AC, \( B_i \) decrypts it with \( K_{AB} \) and checks the id_{B_i} and \( N_6 \) in it. If id_{B_i} is correct and the nonce is fresh, \( B_i \) stores \( RECEIPT, K_{session}, ID_{trans} \).

After the Deadline arrives, the AC closes the auction and determines the bidder with the highest price as the winner. The AC determines from the corresponding winning bid information on \( BB_{AC} \) whose price of the bid is equal to Basic_price. Let \( M_3 = (ID_{trans}, price, date, H(SK_{AC} \parallel N_6) \cdot P, dis, N_6) \); the AC chooses \( r_3 \cdot x \cdot Z_2^\ast \) and computes \( R_3 = r_3 \cdot P \mod q \) and \( S_3 = r_3^{-1} \cdot (M_3 - SK_{AC} \cdot (R_3)_x) \mod q \). Then, the AC publishes the winning information \((M_3, R_3, S_3)\) on \( BB_{AC} \). Anyone can verify the winner’s information by checking \( S_3 = r_3^{-1} \cdot (M_3 - SK_{AC} \cdot (R_3)_x) \mod q \).
ascerts that the problem claimed by $B_i$ is true, the AC publishes the identity of the dishonest auctioneer $A_j$.

6. BAN Logic Analysis

In this part, we will use BAN logic to analyze the authentication accuracy. Burrows-Abadi-Needham logic (also known as the BAN logic) is a set of rules for defining and analyzing information exchange protocols. Specifically, BAN logic helps its users to determine whether exchanged information is trustworthy, secured against eavesdropping, or both [30]. The notations of BAN logic are as follows:

\[ P | X: P \text{ believes } X. \]
\[ P < X: P \text{ sees } X. \]
\[ P \vdash X: P \text{ once said } X. \]
\[ P \vdash PK: P \text{ has } PK \text{ as a public key.} \]
\[ #(X): \text{the formula } X \text{ is fresh.} \]
\[ P \Rightarrow X: \text{has jurisdiction over } X. \]
\[ P \iff Q: P \text{ and } Q \text{ have a shared key } K \text{ for communication.} \]
\[ (X)_K: \text{the formula } X \text{ encrypted under key } K. \]

We mainly focus on the proof of on-shelf phase and bidding phase.

6.1. On-Shelf Phase. We idealized the on-shelf phase as below:

(I1) $A_j \to AC: \{id_{A_j}\}_{PK_{AC}}, \{y, N_j, id_{A_j}\}_{K_{AA}}$.

(I2) $AC \to A_j: \{ID_{on-shelf} N_j, id_{A_j}\}_{K_{AA}}$.

In this phase, we want to ensure that AC believes in the on-shelf information $y$ and $A_j$ believes in the $ID_{on-shelf}$ transferred from AC, so we can conclude the two goals below:

(G1) $AC |\equiv y$.

(G2) $A_j |\equiv ID_{on-shelf}$.

We assume that AC believes the nonce $N_j$ is fresh and $A_j$ believes the nonce $N_j$ is fresh; AC believes that $A_j$ does not send fake $y$ and $id_{A_j}$, so if $A_j$, believes $y$ and $id_{A_j}$ are true then AC will believe them too; $K_{AA}$ is computed by AC self, so $A_j$ believes that $K_{AA}$ is shared between him/her and AC; and $A_j$ believes that AC does not send fake $ID_{on-shelf}$, so if AC believes $ID_{on-shelf}$ is true then $A_j$ will believe them too. All 6 assumptions are listed as below:

(A1) $AC |\equiv \#(N_j)$.

(A2) $AC |\equiv A_j |\equiv y$.

(A3) $AC |\equiv A_j |\equiv id_{A_j}$.

(A4) $A_j |\equiv (AC \iff A_j)$.

(A5) $A_j |\equiv \#(N_j)$.

(A6) $A_j |\equiv AC \iff ID_{on-shelf}$.

Proof. For goal (G1), our deduction is shown as the following formulas:

(F1) $AC \leftarrow \{id_{A_j}\}_{PK_{AC}}$.

(F2) $AC \leftarrow id_{A_j}$ (message decryption rule).

(F3) $AC |\equiv \#id_{A_j}$ (our hypothesis, we will prove that it is true later).

(F4) $AC |\equiv (AC \iff A_j)$ (F3), the computing property of believing in operator.

(F5) $AC \leftarrow \{y, N_j, id_{A_j}\}_{K_{AA}}$.

(F6) $AC |\equiv A_j |\equiv \#(y, N_j, id_{A_j})$ (F4), (F5), message meaning rule).

(F7) $AC |\equiv \gamma (F11), (A3), jurisdiction rule, our hypothesis in (F3) is proved).

(F8) $AC |\equiv A_j |\equiv \gamma (F8), believing rule).

(F9) $AC |\equiv A_j |\equiv id_{A_j}$ (F8), believing rule).

(F10) $AC |\equiv id_{A_j}$ (F9), (A3), jurisdiction rule, our hypothesis in (F3) is proved).

(F11) $AC |\equiv A_j |\equiv \gamma (F11), (A3), jurisdiction rule).

According to formula (F12), the proof of (G1) is completed.

For goal (G2), our deduction is shown as following formulas:

(F13) $A_j \leftarrow \{ID_{on-shelf}, N_j, id_{A_j}\}_{K_{AA}}$.

(F14) $A_j |\equiv AC |\equiv \#id_{A_j}$ (message meaning rule).

(F15) $A_j |\equiv \#(ID_{on-shelf} N_j, id_{A_j})$ (A5), freshness propagation rule).

(F16) $A_j |\equiv AC |\equiv \#ID_{on-shelf}$ (F14), (F15), nonce verification rule).

(F17) $A_j |\equiv AC |\equiv ID_{on-shelf}$ (F16), (A6), jurisdiction rule).

According to formula (F18), the proof of (G2) is completed.

6.2. Bidding Phase. Our bidding phase can be idealized as below:

(B1) $B_i \rightarrow AC: \{id_{B_i}\}_{PK_{AC}}, \{\eta, N_j, id_{B_i}\}_{K_{AB}}$.

(B2) $AC \rightarrow B_i: \{RECEIPT, K_{session}, N_j, id_{B_i}\}_{K_{AB}}$.

In bidding phase, we want to ensure that AC can be convinced that bidding information $\eta$ transferred from $B_i$ is true; additionally, $B_i$ should be convinced that $RECEIPT$ and $K_{session}$ transferred from AC are true. So the three goals below can be concluded:

(G3) $AC |\equiv \eta$. 
(G4) $B_i \models RECEIPT$.
(G5) $B_i \models K_{session}$.

We need to assume that $AC$ believes $N_A$ is fresh and $B_i$ believes $N_A$ is fresh; if $B_i$ believes $\eta$ and $id_B$ are true, $AC$ believes in them too because they are generated by $B_i$; similarly, if $AC$ believes in $RECEIPT$ and $K_{session}$ then $B_i$ believes in them too; because $K_{AB}$ is generated by $B_i$, $B_i$ believes that he/she shared $K_{AB}$ with $AC$. All assumptions are listed as below:

(A7) $AC \models \#(N_A)$.
(A8) $AC \models B_i \models \eta$.
(A9) $AC \models B_i \models id_B$.
(A10) $B_i \models (AC \rightarrow B_i)\cdot K_{AB}\cdot SK_{AC\cdot PB}$.
(A11) $B_i \models \#(N_A)$.
(A12) $B_i \models AC \models RECEIPT$.
(A13) $B_i \models AC \models K_{session}$.

Proof. For goal (G3), our deduction is shown as the following formulas:

(F19) $AC \models \{id_B\}_{PK_{AC}}$.
(F20) $AC \models id_B$ (message decryption rule).
(F21) $AC \models id_B$ (our hypothesis, we will prove that it is true later).
(F22) $AC \models (AC \rightarrow B_i)\cdot K_{AB}\cdot SK_{AC\cdot PB}$.
(F23) $AC \models \{\eta, N_A, id_B\}_{K_{AB}}$.
(F24) $AC \models B_i \models \{\eta, N_A, id_B\}$ ((F22), (F23), message
meaning rule).
(F25) $AC \models \#(\{\eta, N_A, id_B\})$ ((A7), freshness propagation
rule).
(F26) $AC \models B_i \models \{\eta, N_A, id_B\}$ ((F24), (F25), nonce
verification rule).
(F27) $AC \models B_i \models id_B$ ((F26), believing rule).
(F28) $AC \models id_B$ ((F27), (A9), jurisdiction rule, our
hypothesis in (F21) is proved).
(F29) $AC \models B_i \models \eta$ ((F26), believing rule).
(F30) $AC \models \eta$ ((F29), (A8), jurisdiction rule).

According to formula (F30), the proof of (G3) is completed.

For goal (G4), our deduction is shown as the following formulas.

(F31) $B_i \models \{RECEIPT, K_{session}, N_A, id_B\}_{K_{AB}}$.
(F32) $B_i \models AC \models \{RECEIPT, K_{session}, N_A, id_B\}$ ((F31),
(A10), message meaning rule).
(F33) $B_i \models \#(RECEIPT, K_{session}, N_A, id_B)$ ((A11), freshness
propagation rule).
(F34) $B_i \models AC \models \{RECEIPT, K_{session}, N_A, id_B\}$ ((F32),
(F33), nonce verification rule).
(F35) $B_i \models AC \models RECEIPT$ ((F34), believing rule).
(F36) $B_i \models RECEIPT$ ((F34), (A12), jurisdiction rule).

According to formula (F36), the proof of (G4) is completed. Finally, the goal of (G5) is deduced by the following formulas:

(F37) $B_i \models AC \models K_{session}$ ((F34), believing rule).
(F38) $B_i \models RECEIPT$ ((F37), (A13), jurisdiction rule).

The proof of (G5) is completed.

According to our proofs, we can see that our protocol completes the mutual authentication between users and $AC$. In on-shelf phase, $AC$ can be sure that on-shelf information is sent from legal user and auctioneer can be sure that ID$_{on-shelf}$ is transmitted from $AC$; in bidding phase, $AC$ can be sure that bidding information is sent from legal user and bidder can be sure that receipt and session key are generated and sent by $AC$. As the results, our protocol achieves authentication accuracy.

7. Security Analysis

In this part, we analyze the security of our proposal. We assume that an adversary can eavesdrop on public communications on the Internet and read the information on $BB_{AC}$; however, he/she cannot read ciphertexts without getting the encrypting keys. Of course, the adversary cannot calculate the keys from ciphertexts. All roles in the system except for the $AC$ can conspire to do something illegally for their benefit. In the following, we provide different scenarios to explain our security defense.

(1) Impersonation Attack. It is impossible for an adversary to impersonate a user. When a user wants to communicate with the $AC$, he/she should send his/her identity ciphertext ($C_{n}, R_{n}, e_{n}$) to the $AC$. The $AC$ retrieves and checks the user’s identity from this message. We can see that the adversary cannot generate a legal ($C_{n}, R_{n}, e_{n}$) to pass this verification without the knowledge of the $AC$’s private key $SK_{AC}$ and the key $K_{AB}$ shared between the $AC$ and the user. Even if the adversary eavesdrops on the other users’ communications and stores their ($C_{n}, R_{n}, e_{n}$), he/she still cannot use these to do anything because the $AC$ will check if the identity included in $C_{n}$ equals that in $e_{n}$. The only method for the adversary is to replay the whole ($C_{n}, R_{n}, e_{n}$); however, this will not work because the $AC$ can check the freshness of the nonce in $e_{n}$.

(2) Collusion Attack. In some cases, bidders and auctioneers may conspire to break the secret of the $AC$. For example, a bidder may send RECEIPT instead of RECEIPT $\cdot$ $P$ to an auctioneer. However, with this knowledge, they can only compute $H(SK_{AC} \parallel N_A) = (RECEIPT \oplus (K_{AA})) / M_2$, where $K_{AA}$ can be computed by the auctioneer and $M_2$ can be found in $BB_{AC}$ Even obtaining $H(SK_{AC} \parallel N_A)$, they cannot compute $SK_{AC}$ because $H(\cdot)$ is a one-way hash function.

(3) Forging Receipt. Firstly, we consider the case that a malicious bidder wants to forge a receipt to impersonate the winner of an auction by himself/herself. Because $RECEIPT =$
(K_{AA}x + H(SK_{AC} || N_6) \cdot M_2), the malicious bidder obviously cannot forge a valid receipt without knowing the AC’s private key SK_{AC} and the key K_{AA} shared between the AC and the auctioneer. Secondly, it is also impossible for the winner and auctioneer to conspire and create the receipt of another auction. As mentioned in the Collusion Attack, they only can compute $H(SK_{AC} || N_6)$. However, for different bidders, $N_6$'s are different, so $H(SK_{AC} || N_6)$ are different in different auctions. Obviously, they cannot create a useful receipt of the other auction with $H(SK_{AC} || N_6)$ by collusion. Besides, it is meaningless for the winner and auctioneer of an auction to forge a receipt of the auction.

(4) Denial of Service Attack. If an adversary wants to mount a deny of service attack on a bidder (B_i) such that he/she cannot claim the product in the product claiming phase when he/she wins an auction, the adversary should generate a fake receipt and send it to the bidder during the bidding phase. However, the receipt transmitted to B_i needs to be encrypted with B_i's identity by the symmetrical key shared between B_i and the AC as $E_{K_{bi}}(RECEIPT, K_{session}, id_{B_i}, N_6, ID_{trans})$. After receiving the ciphertext, the bidder should decrypt it and check if his identity id_{B_i} is correct. So it is impossible for an adversary to deceive a bidder to accept a fake receipt.

(5) Publishing Fake Information. In our proposal, all published information, including new auction information in the on-shelf phase and bidding information and winner information in the bidding phase are signed by the private key of AC, so anyone can verify the published information with AC's public key. Let us consider a situation: if a bidder wants to win an auction, he/she may try to publish a fake bidding message with a very high bidding price on BB_{AC} so that no one else wants to compete with him/her. However, he/she cannot be successful without knowing the private key of the AC, because every user can check the signature of the AC on this message.

(6) Privacy Preserving. In our scheme, an adversary cannot link any information together to analyze a user’s privacy. Only auctioneers’ identities need to be published in BB_{AC} for enhancing users’ willingness to bid. All packets transmitted in the public channel are encrypted, so the adversary cannot know whether these packets can be linked to certain information published on BB_{AC} even if they captured these packets. It is noteworthy that, in our schemes, we use a delay operation in bidding and on-shelf phases for increasing difficulty of linkage of different messages. For example, if the adversary detects that Alice sends an on-shelf message to the AC and the AC publishes an auction advertisement on the website including the auctioneer’s identity immediately, the adversary would ascertain that Alice is the auctioneer and obtain Alice’s identity. If we delay publishing the auction message several minutes later (i.e., the AC publishes it with another auction information together), then the adversary cannot distinguish a specific user from them. The larger the τ we use, the stronger the privacy preserving function is. However, we should balance the privacy preserving and user experience. Moreover, in the bidding phase, a bidder's identity can be retrieved by $id_{B_i} = C_2 - (R_3 \cdot SK_{AC})x \mod q$, where $C_2$ and $R_3$ are involved in the information published on BB_{AC}. These parameters are protected by AC’s private key as $dis = E_{K_{ac}}(C_2, R_3)$ before being published on BB_{AC}, where $k_{dis} = H(SK_{AC} || N_6)$, such that no one can extract $id_{B_i}$ except for the AC. In the product claiming phase, an auctioneer cannot know the winner’s identity from RECEIPT \cdot P but can only know the validity of the receipt. As indicated in the results, our scheme indeed achieves privacy preserving.

(7) Accessing to the Database of the AC. In the definition of a network model (Section 4), we have mentioned that we do not consider the database of the AC to be completely secure in our proposal. An adversary may access the messages stored in it by certain methods. However, accessing the database would not destroy the security of the whole system. Furthermore, the AC’s private key should be kept in a trusted place, such as a bank. There are mainly four data sets maintained in the AC: the first is $(id_{U_i}, v_{U_i})$ generated in the registration phase, the second is $(ID_{product}, Basic_price, Deadline, ID_{on-shelf}, id_{A_i}, R_3, S_1)$ generated in the on-shelf phase, and the final are $(ID_{trans}, date, price, dis, N_6, R_3, S_2)$ and $(ID_{trans}, price, date, H(SK_{AC} || N_6) \cdot P, dis, N_6)$ generated in the bidding phase. Only the first data set is unpublished, so we only consider the safety of the first data set here. If a hacker reads the content of the first data set, he/she only can obtain all users’ identities and their partial keys (P_i) which have been protected by AC’s private key as the form $v_{U_i} = P_{U_i} \oplus H(SK_{AC})$. Without only protected partial keys, the hacker cannot compute the symmetrical key $K_{AU}$ ($K_{AU} = pw_{u_i} \cdot PK_{AC} \mod q = SK_{AC} \cdot P_{U_i} \mod q$) shared between users and the AC, because the private key of the AC is kept secret. Furthermore, he/she cannot retrieve a user’s password from the partial key based on ECDLP. So we can see that accessing the database does not destroy the safety of the whole system.

(8) Password Guessing Attack. In our scheme, users’ passwords are needed to protect system security. However, because the user’s password is not very long and there is a certain routine mode, attackers may try to mount the password guessing attack to the password-based communication schemes. To prevent this attack, in our scheme, users’ passwords will not be transmitted or stored in plaintext. As mentioned in the registration phase (Section 5.2), the password related information $P_{U_i}$ is transformed to ciphertext $C = (r_q \cdot PK_{AC} + P_{U_i}) \mod q$ before transferring and is stored as the format of $v_{U_i} = P_{U_i} \oplus H(SK_{AC})$ in AC’s database. Obviously, even an attacker collects ciphertext or $v_{U_i}$ by eavesdropping the whole communication channel or intruding AC’s database, he/she can not obtain any user’s password by password guessing attack without the knowledge of AC’s secret key SK_{AC}.

Table 1 (“O” means fully achieved, “Δ” means partially achieved, and “×” means not achieved) shows the security comparison among our proposal and three other schemes: Chang et al.’s [14], Xiong et al.’s [13], and Chung et al.’s [18]. As shown in Table 1, our scheme fulfills the most secure properties of an electronic auction system. In the analysis of “privacy preserving,” our scheme can achieve the
Table 1: Comparison in security properties of the three schemes.

<table>
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<tr>
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<tbody>
<tr>
<td>Anonymity</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Easy revocation</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Fairness</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Nonrepudiation</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Onetime registration</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Traceability</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Unforgeability</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Unlinkability</td>
<td>O</td>
<td>×</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Verifiability</td>
<td>O</td>
<td>Δ</td>
<td>×</td>
<td>O</td>
</tr>
<tr>
<td>On-shelf mechanism</td>
<td>O</td>
<td>O</td>
<td>×</td>
<td>O</td>
</tr>
<tr>
<td>Without secure channel</td>
<td>O</td>
<td>O</td>
<td>×</td>
<td>O</td>
</tr>
<tr>
<td>Password guessing attack defending</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Table 2: Comparison in computational cost of the three schemes.

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<tbody>
<tr>
<td>Registration phase</td>
<td>8PM + H</td>
<td>9PM</td>
<td>4PM + 2H</td>
<td>5PM + 3H</td>
</tr>
<tr>
<td>On-shelf phase</td>
<td>7PM + 2E + 2D + 2H</td>
<td>10PM + 2E + 2D + 2H</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Bidding phase</td>
<td>(10n + 2)PM + 3nE + 2nD + 5nH</td>
<td>12nPM + 2nE + 2nD</td>
<td>(4n + 1)PM + 3BM + 2H</td>
<td>(8n + 2)PM + (3n + 1)H</td>
</tr>
<tr>
<td>Product claiming phase</td>
<td>2PM + E + D + 1H</td>
<td>6PM</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Dispute phase (bidder/auctioneer)</td>
<td>6PM + E + 1D + 3H/6PM + E + 2D + 3H</td>
<td>3PM + 2H/3PM + E + D</td>
<td>0.5nBM/×</td>
<td>×</td>
</tr>
</tbody>
</table>

Properties of anonymity and unlinkability; in the analysis of “Publishing Fake Information,” our scheme can achieve the properties of fairness and verifiability; and in the analyses of “Impersonation Attack, Forging Receipt, and Denial of Service Attack,” our scheme can achieve the property of unforgeability. Similar to [13, 14, 18], the bidding information should be published on an open website, so the bidder can check if his/her bid appeared on it to ensure fairness. Based on the digital signature, bidders cannot deny their bids so nonrepudiation is achieved in four proposals. By providing the dispute mechanism, our scheme achieves the properties of easy revocation, nonrepudiation, and traceability. Furthermore, our scheme overcomes the security problem (leakage of unlinkability) and meanwhile inherits the advantage of without a secure channel in Chang et al.‘s scheme [14]. It is noteworthy that, compared to [14], our protocol needs to store a little of the verification table in the server side. However, as we analyzed before, leakage of these verification tables will not influence system security, so we say that our protocol achieves partial property of no verification table.

With regard to verifiability, in the bidding phase of Chang et al.‘s proposal [14], only the winner’s bidding information will be signed by the AC and can be publicly verified, which may lead attackers to modify any new bidding information with a higher price such that no one else wants to bid for it further. So verifiability is not fully achieved in [14]. As [14] analyzed, the designed revocation function in [13, 18] only partially achieved easy revocation. Our protocol and [14] have a secure on-shelf phase compared to [13, 18]. Our protocol does not need a secure channel to achieve verification in any phase similar to [14]. However, in [13, 18], a secure channel is needed to assist in the completion of the whole protocol.

8. Performance Analysis

In this section, we compare the cost of our scheme with the other three schemes [13, 14, 18] with regard to computational cost, traffic, and communication rounds.

Table 2 shows the comparison of computational cost, where “PM” means a point multiplication operation of ECC, “BM” means a bilinear mapping which can be implemented on ECC such as Weil pairing, “E” means a symmetrical encryption, “D” means a symmetrical decryption, “H” means a hash function, and “n” means the number of bidders in an auction.

As we know, a bilinear map is an expensive operation; the more it is used, the more computation cost is needed. Compared with point multiplication, the hash function only consumes negligible computation cost. Symmetrical cryptographic operation is also cheaper than point multiplication. From the comparison in Table 2, we can see that our proposal needs less computation cost compared with Chang et al.‘s proposal [14] in each phase, except for the dispute phase.
Table 3: Comparison in traffic of the three schemes (B: bytes).

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<tbody>
<tr>
<td>Registration phase</td>
<td>82 B</td>
<td>192 B</td>
<td>108 B</td>
<td>128 B</td>
</tr>
<tr>
<td>On-shelf phase</td>
<td>144 B</td>
<td>266 B</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Bidding phase</td>
<td>176n B</td>
<td>290n B</td>
<td>(96n + 120) B</td>
<td>(119n + 248) B</td>
</tr>
<tr>
<td>Product claiming phase</td>
<td>48 B</td>
<td>149 B</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Dispute phase (auctioneer/bidder)</td>
<td>112 B/128 B</td>
<td>37 B/85 B</td>
<td>48 B/×</td>
<td>×</td>
</tr>
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</table>

Table 4: Comparison in communication rounds of the three schemes.

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</thead>
<tbody>
<tr>
<td>Registration phase</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>On-shelf phase</td>
<td>3</td>
<td>3</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Bidding phase</td>
<td>2n</td>
<td>2n</td>
<td>1</td>
<td>n + 2</td>
</tr>
<tr>
<td>Product claiming phase</td>
<td>1</td>
<td>1</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Dispute phase (auctioneer/bidder)</td>
<td>1/1</td>
<td>1/1</td>
<td>1</td>
<td>×</td>
</tr>
</tbody>
</table>

However, in reality, the first four phases are more frequently executed.

To make the traffic comparison, we determine the elliptic curve operation as NistP 192 [24], hash function as SHA-256 [31], and symmetrical encryption/decryption as AES-256 [32]. The length of the user's identity is 4 bytes, product identity is 5 bytes, transaction identify is 5 bytes, GID in [14] is 5 bytes, price is 5 bytes, and Deadline is 4 bytes. Note that we ignore the length of nonce transmitted in communications. As shown in Table 3, we can see that our protocol has a traffic advantage compared with related works [13, 14, 18], except for dispute phase of Chang et al.'s scheme [14]. The main reason for this is that our scheme finished the key establishment in the registration phase for saving the traffic cost of public keys and certificates. Comparing with Chang et al.'s proposal, though our dispute phase needs more traffic, this phase is not often used compared with the other four phases. As a result, we believe that our proposal has traffic advantages still. Finally, we compare the communication rounds of our scheme and the related schemes in Table 4. As shown in this table, our protocol needs the same communication rounds as those in Chang et al.'s protocol [14].

9. Conclusions

In this paper, we pointed out that Chang et al.'s protocol does not fulfill the unlinkability such that users' privacy will be leaked by linking different messages together. Considering the importance of privacy preservation, we proposed a novel electronic English auction system. By using symmetrical encryptions and fewer ECC operations, our protocol can not only improve the security but also reduce the system cost. In the registration phase, we connect a user's identity and the corresponding symmetrical key so that the AC can compute the shared symmetrical key easily with the user's identity. Furthermore, each user's identity is encrypted with the AC's public key so it cannot be revealed without the knowledge of the AC's private key. In the bidding phase, we improve the efficiency of generating bidding receipts. In our proposal, we fulfill the verifiability of all messages published on the AC's website; however, Chang et al.'s proposal only achieved this feature partially. We used BAN logic to prove that our protocol indeed realizes mutual authentication. The security analysis and performance analysis show that our protocol fulfills more security properties and is more efficient for implementation compared with recent works.

Competing Interests

The authors declare that they have no competing interests.

References


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