Research Article

Provable Secure and Efficient Digital Rights Management Authentication Scheme Using Smart Card Based on Elliptic Curve Cryptography

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Since the concept of ubiquitous computing is firstly proposed by Mark Weiser, its connotation has been extending and expanding by many scholars. In pervasive computing application environment, many kinds of small devices containing smart card are used to communicate with others. In 2013, Yang et al. proposed an enhanced authentication scheme using smart card for digital rights management. They demonstrated that their scheme is secure enough. However, Mishra et al. pointed out that Yang et al.'s scheme suffers from the password guessing attack and the denial of service attack. Moreover, they also demonstrated that Yang et al.'s scheme is not efficient enough when the user inputs an incorrect password. In this paper, we analyze Yang et al.'s scheme again, and find that their scheme is vulnerable to the session key attack. And, there are some mistakes in their scheme. To surmount the weakness of Yang et al.'s scheme, we propose a more efficient and provable secure digital rights management authentication scheme using smart card based on elliptic curve cryptography.

1. Introduction

In 1991, ubiquitous computing was firstly proposed by Mark Weiser, who thought that ubiquitous computing technology could provide users service with a variety of equipment in environment which would be disappeared from the user's consciousness [1]. Later, IBM Corporation scientists also raised the idea in 1999, and they forecasted that pervasive computing can be a way to compute everywhere, anytime, and anywhere [2, 3]. Since the computer and internet technology development, multimedia contents (image, document, music, movie, video, etc.) have been greatly enriched all the time, and all of them can be easily redistributed, copied, and downloaded on the internet without authorization. This drawback results in rampant piracy and causes huge revenue to lose to the electronic commerce [4]. As a result, in pervasive computing application environment, the protection of digital publication copyright becomes more and more

important. Digital rights management (DRM) technology is developed to overcome the problem [5]. Normally, DRM is only software which usually restricts the usage of the content to protect copy and distributed contents [6–9]. The DRM system manages the procedure of the digital contents including protection, distribution, and authorization. Using DRM technology, intellectual property is respected and protected by data encryption, so it can only be accessed by authorised users without limitless distribution [10, 11].

In 2009, the first three-role based DRM implementation scenario authentication scheme using smart card was proposed by Zhang et al. [12]. Then, Yang et al. showed that Zhang et al.'s scheme was vulnerable to the insider attack and the stolen smart card attack [10]. Due to surmounting the weaknesses of Zhang et al.'s scheme, Yang et al. proposed an enhanced digital rights management authentication scheme based on smart card. They demonstrated that their scheme could preclude all the weaknesses existing in Zhang et al.'s

scheme. Recently, Mishra and Mukhopadhyay cryptanalyzed Yang et al.'s scheme and found that their scheme cannot resist the password guessing attack and the denial of service attack. Moreover, they also pointed out that Yang et al.'s scheme is not efficient enough when the user inputs an incorrect password, and this drawback may cause a denial of service attack [13]. Except for the attacks mentioned by Mishra et al., we find out that Yang et al.'s scheme does not resist the session key attack. In addition to this, we also discover that there are some mistakes in their scheme.

We proposed a new efficient and provable secure digital rights management authentication scheme using smart card based on elliptic curve cryptography [14–16]. To demonstrate the scheme is provable secure, we introduce a security model AFP05 [17, 18] and analyze our scheme in this model. In the following, we will give the proof that our proposed scheme is secure in the AFP05 model. As known to all, one-way hash function is more efficient than the operation of scalar multiplication and pairings [19–21]. Moreover, the pairing operation costs much more than the scalar multiplication operation. The effort of evaluating one pairing operation is approximately three times the effort of evaluating one scalar multiplication operation. So, we cut down some pairings operation of point on elliptic curve and use hash function instead to increase the scheme's efficiency.

The structure of this paper is arranged as follows. In Section 2, we introduce the notations and definitions used in this paper. Section 3 reviews Yang et al.'s scheme, and Section 4 discusses its weakness analysis. We show the scheme details we propose in Section 5. Section 6 shows a formal security proof of the scheme, while Section 7 demonstrates the security analysis of our proposed scheme. In Section 8, we compare our proposed scheme with Yang et al.'s and Zhang et al.'s scheme. Section 9 concludes the paper.

2. Notations and Definitions

Let G_1 be an additive group with an elliptic curve by the generator P and G_2 a multiplicative cyclic group by the generator g . And both of them have the prime order q . Let e denote a computable bilinear map $e : G_1 \times G_1 \mapsto G_2$ satisfying the following three properties [10, 12]:

- (i) *Computability*. Given $R, Q \in G_1$, there is an efficient algorithm to compute $e(R, Q)$.
- (ii) *Bilinear*. $e(aR, bQ) = e(R, Q)^{ab}$, where $R, Q \in G_1$ and $a, b \in \mathbb{Z}_q^*$.
- (iii) *Nondegenerate*. Let P be the generator of G_1 , $e(P, P) \neq 1_{G_2}$.

Several commonly used notations and their descriptions are described after the Conclusions Section to facilitate the following references.

3. Review of Yang et al.'s Scheme

There are three phases in their scheme; they are, respectively, registration phase, mutual authentication and key agreement phase, and password update phase.

3.1. Registration Phase

3.1.1. User's Registration Section. In this part, a user U requests to be a legal user and the server S conducts the next operations.

$U1$ ($U \rightarrow S: \{ID_U, PWD_U\}$). The user U generates his/her own identity ID_U and password PW_U freely. Then, U chooses a nonce N_U randomly and computes

$$PWD_U = H_2(PW_U \oplus N_U). \quad (1)$$

After that, U sends $\{ID_U, PWD_U\}$ to the server securely.

$U2$ ($S \rightarrow U: \{S_U, H_2(\cdot)\}$). After obtaining the message sent by U , the server S begins to compute

$$\begin{aligned} K_U &= H_2(sH_1(ID_U)), \\ S_U &= K_U \oplus PWD_U, \\ T_U &= PWD_U \oplus K_U. \end{aligned} \quad (2)$$

Then, S stores $\{T_U\}$ in the verification table. Afterward, the server issues a smart card containing $\{S_U, H_2(\cdot)\}$ and transmits it to U through a secure channel.

$U3$. The N_U is input into the smart card by the U , which contains $\{S_U, N_U, H_2(\cdot)\}$, finally.

3.1.2. Device's Registration Section. In this section, the device V requests to be authorized by the S , and the following steps should be performed together with the server.

$D1$ ($V \rightarrow S: \{ID_V\}$). The device V transmits its identity $\{ID_V\}$ to the server S through a secure channel.

$D2$ ($S \rightarrow V: \{S_V\}$). After obtaining the message sent by V , the S begins to compute

$$S_V = sH_1(ID_V). \quad (3)$$

And it is sent to V via a secure channel. Afterward, the device's public key and secret key are $P_V = H_1(ID_V)$ and S_V .

3.2. Mutual Authentication and Key Agreement Phase

$M1$ ($U \rightarrow V: \{M_U\}$). After the U inserts his/her smart card into a smart card reader and inputs his/her identity ID_U and password PW_U , the smart card randomly chooses a secret number r_U and a nonce N'_U . And it computes

$$\begin{aligned} PWD'_U &= H_2(PW_U \oplus N'_U), \\ M_{L1} &= PWD'_U \oplus S_U, \\ M_{L2} &= H_2(S_U \oplus PWD'_U), \end{aligned}$$

$$\begin{aligned} \text{PWD}_U &= H_2(\text{PW}_U \oplus N_U), \\ K_U &= S_U \oplus \text{PWD}_U. \end{aligned} \quad (4)$$

Next U transmits the message $M_U = \{E_{K_U}(r_U), M_{L1}, M_{L2}\}$ to V .

$M2$ ($V \rightarrow S: \{\text{ID}_V, \text{ID}_U, X, Y, M_U\}$). Upon obtaining the message sent by U , the V chooses a number r_V randomly and computes

$$\begin{aligned} X &= r_V P, \\ H_V &= H_3(\text{ID}_V \| \text{ID}_U \| X \| M_U), \\ Y &= r_V P_V + H_V S_V. \end{aligned} \quad (5)$$

Then, V transmits the message $\{\text{ID}_V, \text{ID}_U, X, Y, M_U\}$ to S .

$M3$ ($S \rightarrow V: \{\text{ID}_S, \text{ID}_V, \text{ID}_U, M_{S1}, M_{S2}, M_{S3}, M_{S4}, M_{S5}, M_{S6}\}$). When the server receives the message, it computes

$$\begin{aligned} K_U &= H_2(sH_1(\text{ID}_U)), \\ \text{PWD}_U &= T_U \oplus K_U, \\ \text{PWD}'_U &= M_{L1} \oplus K_U \oplus \text{PWD}_U \end{aligned} \quad (6)$$

and checks whether M_{L2} is equal to $H_2(K_U \oplus \text{PWD}_U \oplus \text{PWD}'_U)$. If this holds, the S will authenticate U and update T_U with $T'_U = \text{PWD}'_U \oplus K_U$. Otherwise, this authentication request is rejected. Then, S computes

$$\begin{aligned} r'_U &= D_{K_U}(E_{K_U}(r_U)), \\ H'_V &= H_3(\text{ID}_V \| \text{ID}_U \| X \| M_U) \end{aligned} \quad (7)$$

and checks whether

$$e(P, Y) = e(P_V, X + H'_V P_S). \quad (8)$$

If this holds, the device V is authenticated by S . Otherwise, this authentication request is rejected. After that, the server generates two random strings r_{S1} , r_{S3} , and a random number r_{S2} . S computes

$$\begin{aligned} M_{S1} &= E_{K_U}(r_{S1}), \\ M_{S2} &= E_{r_{S1}}(H_2(\text{ID}_S \| \text{ID}_V \| r_{S1}) \oplus r'_U), \\ M_{S3} &= r_{S2} P, \\ k_{SV} &= H_2(r_V r_{S2} P), \\ k_{SU} &= H_2(r'_U \| r_{S1}), \\ M_{S5} &= E_{k_{SV}}(r_{S3}), \\ M_{S6} &= E_{k_{SU}}(r_{S3}), \\ h_S &= H_3(\text{ID}_S \| \text{ID}_V \| \text{ID}_U \| M_{S1} \| M_{S2} \| M_{S3} \| M_{S5} \| M_{S6}), \\ M_{S4} &= r_{S2}(P_S + P_U) + sh_S P. \end{aligned} \quad (9)$$

At last, the S replies with the message $\{\text{ID}_S, \text{ID}_V, \text{ID}_U, M_{S1}, M_{S2}, M_{S3}, M_{S4}, M_{S5}, M_{S6}\}$ to V .

The correctness of (8) is shown as follows:

$$\begin{aligned} e(P, Y) &= e(P, r_V \cdot P_V + H_V \cdot S_V) \\ &= e(P, r_V \cdot P_V) e(P, H_V \cdot S_V) \\ &= e(r_V \cdot P, P_V) e(sP, H_V \cdot P_V) \\ &= e(P_V, X) e(P_V, H_V \cdot P_S) \\ &= e(P_V, X + H_V \cdot P_S) \\ &= e(P_V, X + H'_V \cdot P_S). \end{aligned} \quad (10)$$

$M4$ ($V \rightarrow U: \{\text{ID}_S, \text{ID}_V, M_{S1}, M_{S2}, M_{S6}, E_{r'_{S3}}(r_{V1})\}$). After receiving the message from U , V computes

$$h'_S = H_3(\text{ID}_S \| \text{ID}_V \| \text{ID}_U \| M_{S1} \| M_{S2} \| M_{S3} \| M_{S5} \| M_{S6}) \quad (11)$$

and checks whether

$$e(P, M_{S4}) = e(P_S + P_U, M_{S3}) e(h'_S P, P_S). \quad (12)$$

If this holds, the server S is authenticated by the device V . Otherwise, this authentication procedure fails. Then, V generates a random string r_{V1} and computes

$$\begin{aligned} k_{SV} &= H_2(r_V M_{S3}), \\ r'_{S3} &= D_{k_{SV}}(M_{S5}), \\ E_{r'_{S3}}(r_{V1}). \end{aligned} \quad (13)$$

Finally, V sends the message $\{\text{ID}_S, \text{ID}_V, M_{S1}, M_{S2}, M_{S6}, E_{r'_{S3}}(r_{V1})\}$ to the user U .

The correctness of (12) is shown as follows:

$$\begin{aligned} e(P, M_{S4}) &= e(P, r_{S2}(P_S + P_U) + sh_S \cdot P) \\ &= e(P, r_{S2}(P_S + P_U)) e(P, sh_S \cdot P) \\ &= e(r_{S2} \cdot P, P_S + P_U) e(sP, h_S \cdot P) \\ &= e(P_S + P_U, M_{S3}) e(h_S \cdot P, P_S) \\ &= e(P_S + P_U, M_{S3}) e(h'_S \cdot P, P_S). \end{aligned} \quad (14)$$

$M5$ ($U \rightarrow V: \{E_{r'_{S3}}(r_{U1})\}$). The user U computes

$$\begin{aligned} r'_{S1} &= D_{K_U}(M_{S1}) \\ S'_U &= S_U \oplus \text{PWD}_U \oplus \text{PWD}'_U \end{aligned} \quad (15)$$

and checks whether $D_{r'_{S1}}(M_{S2}) \oplus r_U$ is equal to $H_2(\text{ID}_S \| \text{ID}_V \| r'_{S1})$. If it holds, the S is authenticated by the U . Otherwise, this authentication procedure fails. Then, U updates N_U and S_U with N'_U and S'_U , which are saved in

the smart card. After that, U generates a random string r_{U1} and computes

$$\begin{aligned} k_{SU} &= H_2(r_U \| r_{S1}), \\ r_{S3} &= D_{k_{SU}}(M_{S6}), \\ r_{V1} &= D_{r_{S3}}(E_{r'_{S3}}(r_{V1})), \\ &E_{r_{S3}}(r_{U1}). \end{aligned} \quad (16)$$

Finally, U generates the session key shared with V by computing $k_{UV} = H_2(r_{U1} \| r_{V1})$ and sends the message $\{E_{r_{S3}}(r_{U1})\}$ back to the device V .

M6. After obtaining the message sent by U , the device V computes

$$\begin{aligned} r_{U1} &= D_{r_{S3}}(E_{r'_{S3}}(r_{U1})), \\ k_{UV} &= H_2(r_{U1} \| r_{V1}). \end{aligned} \quad (17)$$

The k_{UV} is the session key between U and device V .

3.3. *Password Update Phase.* When the user requests to change the password PW_U to a new one (PW_{new}), he/she should perform the next procedures.

P1 ($U \rightarrow S: \{M_C\}$). After the U inserts the smart card into a smart card reader and inputs his/her identity ID_U , old password PW_U and new password PW_{new} . Then the smart card chooses a secret nonce N'_U randomly to compute the following results:

$$\begin{aligned} PWD'_U &= H_2(PW_U \oplus N'_U), \\ M_{C1} &= PWD'_U \oplus S_U, \\ PWD_{\text{new}} &= H_2(PW_{\text{new}} \oplus N'_U), \\ M_{C2} &= H_2(S_U \oplus PWD'_U \oplus PWD_{\text{new}}), \\ M_{C3} &= PWD_{\text{new}} \oplus S_U. \end{aligned} \quad (18)$$

Then, U transmits $M_C = \{M_{C1}, M_{C2}, M_{C3}\}$ to S .

P2 ($S \rightarrow U: \{M_{C4}\}$). Once obtaining the message sent by U , the S computes

$$\begin{aligned} K_U &= H_2(sH_1(ID_U)), \\ PWD_U &= T_U \oplus K_U, \\ PWD'_U &= M_{C1} \oplus K_U \oplus PWD_U, \\ PWD_{\text{new}} &= M_{C3} \oplus K_U \oplus PWD_U, \\ M_{C4} &= H_2(PWD_{\text{new}} \oplus K_U \oplus PWD_U) \end{aligned} \quad (19)$$

and checks whether M_{C2} is equal to $H_2(K_U \oplus PWD_U \oplus PWD'_U \oplus PWD_{\text{new}})$. If it holds, the S will accept the user's

request and update the verifier $T'_U = PWD_{\text{new}} \oplus K_U$. Otherwise, this request procedure is rejected. Then, the server S transmits the message $\{M_{C4}\}$ back to the user U .

P3. Once the user obtains the message sent by the server, he/she checks whether M_{C4} is equal to $H_2(PWD_{\text{new}} \oplus S_U)$. If this holds, the user replaces N_U and S_U with N'_U and S'_U , where $S'_U = S_U \oplus PWD_U \oplus PWD_{\text{new}}$.

4. Cryptanalysis of Yang et al.'s Scheme

Recently, Mishra and Mukhopadhyay demonstrated Yang et al.'s scheme is vulnerable to the password guessing attack and the denial of service attack. Moreover, they also pointed that Yang et al.'s scheme does not present efficient login and password change phases such that smart card executes the session in case of incorrect input [13]. Based on the attacks and problems mentioned in Mishra et al.'s article, we analyze Yang et al.'s scheme and find out that the scheme does not resist the session key attack. In addition to this, we also discover that there are some mistakes in their scheme. We will introduce our new discoveries in the following.

4.1. *Session Key Attack.* If an attacker intercepted the message $\{ID_S, ID_V, ID_U, M_{S1}, M_{S2}, M_{S3}, M_{S4}, M_{S5}, M_{S6}\}$ which was sent from the server to the device and modified some data in it, the user and the device may establish different session key. So the attacker A can realize the session key attack as the following steps.

(1) The attacker A can intercept and capture the message $\{ID_S, ID_V, ID_U, M_{S1}, M_{S2}, M_{S3}, M_{S4}, M_{S5}, M_{S6}\}$ sent to device by the server. Next, A generates a number r_0 randomly and computes

$$\begin{aligned} M_{S3_0} &= r_0 P, \\ h_{S_0} &= H_3(ID_S \| ID_V \| ID_U \| M_{S1} \| M_{S2} \| M_{S3_0} \| M_{S5} \| M_{S6}), \\ M_{S4_0} &= r_0 (P_S + P_U) + h_{S_0} P_S. \end{aligned} \quad (20)$$

Then, the message $\{ID_S, ID_V, ID_U, M_{S1}, M_{S2}, M_{S3_0}, M_{S4_0}, M_{S5}, M_{S6}\}$ is sent to the device V by the attacker A .

(2) After receiving the message, V computes

$$h'_{S_0} = H_3(ID_S \| ID_V \| ID_U \| M_{S1} \| M_{S2} \| M_{S3_0} \| M_{S5} \| M_{S6}) \quad (21)$$

and checks the equation

$$e(P, M_{S4_0}) = e(P_S + P_U, M_{S3_0}) e(h'_{S_0} P, P_S). \quad (22)$$

Obviously, they are equal. Then, V generates a random string r_{V1} and computes

$$\begin{aligned} k_{SV_0} &= H_2(r_V M_{S3_0}), \\ r_{S3_0} &= D_{k_{SV_0}}(M_{S5}), \\ &E_{r_{S3_0}}(r_{V1}). \end{aligned} \quad (23)$$

Finally, V sends the message $\{ID_S, ID_V, M_{S1}, M_{S2}, M_{S6}, E_{r_{S3_0}}(r_{V1})\}$ to the user U . In this step, the string r_{S3_0} is not equal to the random string r_{S3} generated by the server.

The correctness of (22) is shown as follows:

$$\begin{aligned} e(P, M_{S4_0}) &= e(P, r_0(P_S + P_U) + h_{S_0} \cdot P_S) \\ &= e(P, r_0(P_S + P_U)) e(P, h_{S_0} \cdot P_S) \\ &= e(r_0 \cdot P, P_S + P_U) e(h_{S_0} \cdot P, P_S) \\ &= e(P_S + P_U, M_{S3_0}) e(h'_{S_0} \cdot P, P_S). \end{aligned} \quad (24)$$

(3) Because A did not modify the message $\{ID_S, ID_V, M_{S1}, M_{S2}, \dots, D_{r'_{S1}}(M_{S2}) \oplus r_U\}$ is equal to $H_2(ID_S \| ID_V \| r'_{S1})$. Then, U updates N_U and S_U . After that, U generates a random string r_{U1} and computes

$$\begin{aligned} k_{SU} &= H_2(r_U \| r_{S1}), \\ r'_{S3} &= D_{k_{SU}}(M_{S6}), \\ r_{V1_0} &= D_{r'_{S3}}(E_{r_{S3_0}}(r_{V1})), \\ E_{r'_{S3}}(r_{U1}). \end{aligned} \quad (25)$$

Finally, U generates the session key $k_{UV} = H_2(r_{U1} \| r_{V1_0})$ shared with the device and sends the message $\{E_{r'_{S3}}(r_{U1})\}$ back to the device V . In this step, the string r'_{S3} is equal to the random string r_{S3} generated by the server and not equal to the string r_{S3_0} computed by the device.

(4) Once obtaining the message sent by the user, the device computes

$$\begin{aligned} r_{U1_0} &= D_{r_{S3_0}}(E_{r'_{S3}}(r_{U1})), \\ k_{UV_0} &= H_2(r_{U1_0} \| r_{V1}), \end{aligned} \quad (26)$$

k_{UV_0} is the session key shared between the user U and the device V . Obviously, the session key k_{UV} computed by the user is different from the session key k_{UV_0} computed by the device. So Yang et al.'s scheme suffers from the session key attack.

4.2. Some Mistakes. In mutual authentication and key agreement phase, the identity ID_U has not been sent to the device V . But, when the device computes $H_V = H_3(ID_V \| ID_U \| X \| M_U)$, it already knows the user's identity. According to the common sense, if the user has not sent identity to the device, the device cannot obtain the user's identity. So there is a mistake in this phase. What is more, this mistake also exists in the password update phase of Yang et al.'s scheme.

5. Our Proposed Scheme

Based on Yang et al.'s scheme, our protocol also contains four phases: the registration phase, the login phase, the key agreement phase, and the password update phase. Algorithm 1

describes our scheme's registration phase. The login phase and the key agreement phase will be shown in Algorithm 2. At last, we show the password update phase in Algorithm 3. The detail is shown as the following.

5.1. Registration Phase. In our proposed scheme, the registration phase also can be divided into two parts: the user's registration phase and the device's registration phase. Our device's registration phase is the same as the device's registration phase in Yang et al.'s scheme. We will describe our user's registration phase as follows.

R1 ($U \rightarrow S: \{ID_U, PWD_U, IDD_U\}$). An identity ID_U and password PW_U are chosen by user U freely. Then, U generates a nonce r_U randomly and computes

$$\begin{aligned} PWD_U &= H_2(PW_U \oplus r_U), \\ IDD_U &= H_2(ID_U \oplus r_U). \end{aligned} \quad (27)$$

After that, U sends $\{ID_U, PWD_U, IDD_U\}$ to the server S via a secure channel.

R2 ($S \rightarrow U: \{S_U, P_U, M_U, P, H_2(\cdot), E_K(\cdot)/D_K(\cdot)\}$). After obtaining the message sent by U , S computes

$$\begin{aligned} K_U &= H_2(sH_1(IDD_U)), \\ Q_U &= H_2(sH_1(PWD_U)), \\ S_U &= K_U \oplus PWD_U \oplus H_2(ID_U), \\ M_U &= Q_U \oplus ID_U, \\ P_U &= H_2(K_U \oplus Q_U). \end{aligned} \quad (28)$$

Then, the server U issues a smart card containing $\{S_U, P_U, M_U, P, H_2(\cdot), E_K(\cdot)/D_K(\cdot)\}$ and passes it to U securely.

R3. U enters r_U into the smart card, so it contains $\{r_U, S_U, P_U, M_U, P, H_2(\cdot), E_K(\cdot)/D_K(\cdot)\}$.

5.2. Login Phase. U inserts his/her smart card into a smart card reader and inputs his/her identity ID_U and password PW_U . Then the smart card begins to compute

$$\begin{aligned} PWD_U &= H_2(PW_U \oplus r_U), \\ K'_U &= S_U \oplus PWD_U \oplus H_2(ID_U), \\ Q'_U &= M_U \oplus ID_U \end{aligned} \quad (29)$$

and checks whether P_U is equal to $H_2(K'_U \oplus Q'_U)$. If this holds, it will authenticate the identity and password of the user. Otherwise, this user's request procedure is rejected.

ALGORITHM 1: The registration phase.

5.3. *Key Agreement Phase.* There are six steps and five messages during each run of the proposed protocol. The details are as follows.

A1 ($U \rightarrow V: \{M_{U2V_1}\}$). Then, the smart card generates a secret string r_{U1} randomly and computes

$$\begin{aligned} M_{U1} &= H_2(K'_U \oplus Q'_U \oplus r_{U1}), \\ IDD_U &= H_2(ID_U \oplus r_U). \end{aligned} \quad (30)$$

Next U transmits the message $M_{U2V_1} = \{IDD_U, E_{K'_U}(r_{U1}), E_{r_{U1}}(PWD_U), M_{U1}\}$ to V .

A2 ($V \rightarrow S: \{M_{V2S}\}$). Upon obtaining the message sent by U , the V generates a number r_{V1} randomly and computes

$$\begin{aligned} X &= r_{V1} \cdot P, \\ H_{V1} &= H_3(ID_V \| IDD_U \| X \| M_{U2V_1}), \end{aligned} \quad (31)$$

$$Y = r_{V1} \cdot P_V + H_{V1} \cdot S_V.$$

Then, V transmits the message $M_{V2S} = \{ID_V, X, Y, M_{U2V_1}\}$ to the server S .

A3 ($S \rightarrow V: \{M_{S2V}\}$). When the server received the message, it computes

$$H'_{V1} = H_3(ID_V \| IDD_U \| X \| M_{U2V_1}) \quad (32)$$

and checks whether $e(P, Y)$ is equal to $e(P_V, X + H'_{V1} \cdot P_S)$. If this holds, the device V is authenticated by S . Otherwise, this authentication request is rejected. Then, S computes

$$\begin{aligned} K_U &= H_2(sH_1(IDD_U)), \\ r'_{U1} &= D_{K_U}(E_{K'_U}(r_{U1})), \\ PWD'_U &= D_{r'_{U1}}(E_{r_{U1}}(PWD_U)), \\ Q_U &= H_2(sH_1(PWD'_U)) \end{aligned} \quad (33)$$

and checks whether M_{U1} is equal to $H_2(K_U \oplus Q_U \oplus r'_{U1})$. If this holds, the user U is authenticated by S . Otherwise, this authentication request is rejected. After that, the server S generates a random string r_{S1} . Then S computes

$$\begin{aligned} k_{SV} &= s \cdot X = (k_{SVx}, k_{SVy}), \\ S_V &= s \cdot H_1(ID_V) = (S_{Vx}, S_{Vy}), \\ M_{S1} &= k_{SVx} \oplus k_{SVy} \oplus r_{S1}, \\ M_{S2} &= H_2(r'_{U1} \| K_U) \oplus r_{S1}, \\ M_{S3} &= H_2(r'_{U1} \oplus K_U \oplus M_{S2}), \\ M_{S4} &= H_2(k_{SVx} \| k_{SVy} \| S_{Vx} \| S_{Vy} \| M_{S1} \| M_{S3}). \end{aligned} \quad (34)$$

Finally, the S replies with the message $M_{S2V} = \{M_{S1}, M_{S2}, M_{S3}, M_{S4}\}$ to the device V .

A4 ($V \rightarrow U: \{M_{V2U}\}$). After receiving the message, V computes

$$k'_{SV} = r_{V1} \cdot P_S = (k'_{SVx}, k'_{SVy}) \quad (35)$$

ALGORITHM 2: The login phase and the key agreement phase.

ALGORITHM 3: The password update phase of our scheme.

and checks whether M_{S4} is equal to $H_2(k'_{SVx} \| k'_{SVy} \| S_{Vx} \| S_{Vy} \| M_{S1} \| M_{S3})$. If this holds, the S is authenticated by the device V . Otherwise, this authentication procedure fails. Then, V generates a random number r_{V2} and computes

$$\begin{aligned}
 r'_{S1} &= M_{S1} \oplus k'_{SVx} \oplus k'_{SVy}, \\
 R_V &= r_{V2} \cdot P = (R_{Vx}, R_{Vy}), \\
 H_{V2} &= H_2(R_{Vx} \| R_{Vy} \| r'_{S1}).
 \end{aligned} \tag{36}$$

Finally, the device V transmits the message $M_{V2U} = \{R_V, H_{V2}, M_{S2}, M_{S3}\}$ to the user U .

A5 ($U \rightarrow V: \{M_{U2V2}\}$). The user U checks whether M_{S3} is equal to $H_2(r_{U1} \oplus K'_U \oplus M_{S2})$. If this holds, the user U authenticates the S . Otherwise, this authentication procedure fails. After that, U computes

$$r''_{S1} = M_{S2} \oplus H_2(r_{U1} \| K'_U). \tag{37}$$

Then, the user U checks whether H_{V2} is equal to $H_2(R_{Vx} \| R_{Vy} \| r''_{S1})$. If this holds, the device V is authenticated

by the user U . Otherwise, this authentication procedure fails. U generates a random number r_{U2} and computes

$$\begin{aligned}
 R_U &= r_{U2} \cdot P = (R_{Ux}, R_{Uy}), \\
 H_U &= H_2(R_{Ux} \| R_{Uy} \| r'_{S1}),
 \end{aligned} \tag{38}$$

$$R_{UV} = r_{U2} \cdot R_V,$$

$$k_{UV} = H_2(R_U \| R_V \| R_{UV}),$$

where k_{UV} is the session key shared between the user U and the device V . Finally, U sends the message $M_{U2V2} = \{R_U, H_U\}$ back to the device V .

A6. After obtaining the message sent by the user, the device V checks whether H_U is equal to $H_2(R_{Ux} \| R_{Uy} \| r'_{S1})$. If this holds, the user U is authenticated by the device V . Otherwise, this authentication procedure fails. Then, V computes

$$\begin{aligned}
 R'_{UV} &= r_{V2} \cdot R_U, \\
 k'_{UV} &= H_2(R_U \| R_V \| R'_{UV}).
 \end{aligned} \tag{39}$$

The k'_{UV} is the session key between the user U and the device V .

5.4. Password Update Phase. When the user requests to update his/her password PW_U to a new PW_{new} , he/she should perform the next procedures.

$CI(U \rightarrow S : \{IDD_U, E_{K'_U}(r_{C1}), E_{r_{C1}}(PWD_U), M_{UC1}, M_{UC2}\})$. U inserts his/her smart card into a smart card reader and inputs his/her identity ID_U , old password PW_U , and new password PW_{new} . Then the smart card checks whether P_U is equal to $H_2(S_U \oplus H_2(PW_U \oplus r_U) \oplus M_U \oplus ID_U)$. If this holds, it will authenticate the identity and password of the user. Otherwise, this user's password update request procedure is rejected. After this, the smart card generates a secret string r_{C1} randomly and computes

$$\begin{aligned} K'_U &= S_U \oplus H_2(PW_U \oplus r_U) \oplus H_2(ID_U), \\ Q'_U &= M_U \oplus ID_U, \\ IDD_U &= H_2(ID_U \oplus r_U), \\ PWD_{new} &= H_2(PW_{new} \oplus r_U), \\ M_{UC1} &= PWD_{new} \oplus S_U \oplus H_2(ID_U), \\ M_{UC2} &= H_2(K'_U \oplus Q'_U \oplus r_{C1} \oplus PWD_{new}). \end{aligned} \quad (40)$$

Next U transmits the message $\{IDD_U, E_{K'_U}(r_{C1}), E_{r_{C1}}(PWD_U), M_{UC1}, M_{UC2}\}$ to the S .

$C2(S \rightarrow U : \{M_{SC1}, M_{SC2}\})$. Once obtaining the message sent by the user, the S computes

$$\begin{aligned} K_U &= H_2(sH_1(IDD_U)), \\ r'_{C1} &= D_{K_U}(E_{K'_U}(r_{C1})), \\ PWD'_U &= D_{r'_{C1}}(E_{r_{C1}}(PWD_U)), \\ Q_U &= H_2(sH_1(PWD'_U)), \\ PWD'_{new} &= M_{UC1} \oplus K_U \oplus PWD'_U \end{aligned} \quad (41)$$

and checks whether M_{UC2} is equal to $H_2(K_U \oplus Q_U) \oplus r'_{C1} \oplus PWD'_{new}$. If this holds, S will accept the user's request. Otherwise, this request procedure is rejected. Then, the server S computes

$$\begin{aligned} Q_{U_{new}} &= H_2(sH_1(PWD'_{new})), \\ M_{SC1} &= Q_{U_{new}} \oplus H_2(K_U \oplus r'_{C1}), \\ M_{SC2} &= H_2(Q_{U_{new}}) \oplus H_2(PWD'_{new} \parallel r'_{C1}) \end{aligned} \quad (42)$$

and sends the message $\{M_{SC1}, M_{SC2}\}$ back to the user U .

C3. When the user received the message from the server, he/she computes

$$Q'_{U_{new}} = M_{SC1} \oplus H_2(K'_U \oplus r_{C1}) \quad (43)$$

and checks whether M_{SC2} is equal to $H_2(Q'_{U_{new}}) \oplus H_2(PWD_{new} \oplus r_{C1})$. If not, the request is rejected. Otherwise, the user computes

$$\begin{aligned} S_{U_{new}} &= K'_U \oplus PWD_{new} \oplus H_2(ID_U), \\ P_{U_{new}} &= H_2(K'_U \oplus Q'_{U_{new}}), \\ M_{U_{new}} &= Q'_{U_{new}} \oplus ID_U \end{aligned} \quad (44)$$

and replaces S_U , P_U , and M_U with $S_{U_{new}}$, $P_{U_{new}}$, and $M_{U_{new}}$, which are all saved in the smart card.

6. Security Model and Proof

In this part, the provable secure method will be employed to prove that our proposed protocol is provable secure in the models in [18].

6.1. Security Model. In 2005, Abdalla et al. proposed a security model AFP05, which is suitable for the three-party authenticated key agreement scenario. It contains two types of participants, such as the client and the trusted server [18]. But there are three types of participants in our proposed protocol, a user, a trusted device, and a trusted server. So we add a query *SendDevice* in our security model. During the execution of the protocol, U and V have many instances, respectively. U_i and V_j denote the i th instance of U and the j th instance of V . There exists one state of accept, reject, and $\perp$ in an oracle. If the oracle gets correct message, it turns the accept state; otherwise, it turns reject. $\perp$ means that no decision has been reached or no result has been returned. The adversary A , which is abstracted as a probabilistic polynomial time Turing Machine, interacts with other participants through a bounded number of queries which model the capabilities of the adversary in an actual attack. The queries are listed as follows.

SendClient(U_i, m). After receiving message m sent by the adversary, the U_i generates a message and outputs as the result of this query. A query *SendClient*(U_i , Start) begins a new key agreement process.

SendDevice(V_j, m). After receiving message m sent by the adversary, the V_j generates a message and output.

SendServer(S, m). After receiving message m sent by the adversary, the S generates a message and output.

Reveal(U_i/V_j). If no session key is defined for instance U_i/V_j or if either U_i/V_j or its partner is asked a *Test* query, the result of this query is the invalid symbol $\perp$. Otherwise the session key generated by the instance U_i/V_j is returned.

Test(U_i/V_j). If no session key is defined for instance U_i/V_j or if either U_i/V_j or its partner is asked a *Reveal* query, the result of this query is the invalid symbol $\perp$. Otherwise, the oracle flips a coin b . If $b = 1$, the session key is output. Otherwise, a value randomly chosen from the distribution space of session key is output.

The queries defined in our improved AFP05 security model can be simulated using the *SendClient*, *SendDevice*, and *SendServer* queries repeatedly if we assume that there is at least one benign adversary which faithfully relays message flows. In our improved AFP05 security model, the notion of freshness is already embedded in the definition of the oracles. A Find-Then-Guess (FTG) model exists in our improved AFP05 security model, in which the semantic security is defined by a game with two phases. In the first phase, the adversary is able to adaptively execute *SendClient*, *SendDevice*, *SendServer*, *Reveal*, and *Test* query. In the second, A executes a single *Test* query and guesses a bit b' for b , where b is selected in the *Test* query. If $b' = b$, the adversary wins the game. Let Succ denote the event that the adversary correctly guesses the bit b , and the advantage of A that attacks the protocol S is defined as

$$\text{Adv}_S^{\text{FTG-3PAKA}}(A) = |2 \Pr[\text{Succ}] - 1|. \quad (45)$$

A 3PAKA protocol S is considered semantically secure in FTG model if and only if $\text{Adv}_S^{\text{FTG-3PAKA}}(t, Q) = \max_A \{\text{Adv}_S^{\text{FTG-3PAKA}}(A)\}$ is negligible, where the maximum time executed by all the adversaries with time-complexity at most t and the number of queries at most Q .

6.2. Mathematical Computational Problems [10]. Let p, r be two large prime numbers and $r \mid (p - 1)$. Let G be a multiplicative subgroup of Z_p^* , with prime number r order and element g_0 generator.

Computational Diffie-Hellman Problem (CDH). Given $\{g_0, g_0^a, g_0^b \in G\}$ and $a, b \in_R Z_r^*$, it is hard to compute $g_0^{ab} \bmod p$.

The probabilistic polynomial time Turing Machine denoted as Δ , the probability of which could successfully solve CDH problem in G , is defined as

$$\text{Succ}_G^{\text{CDH}}(\Delta) = \Pr[\Delta(g^a, g^b) = g^{ab} \bmod p : a, b \in_R Z_r^*]. \quad (46)$$

CDH Assumption. For any probabilistic Turing Machine Δ , the probability of $\text{Succ}_G^{\text{CDH}}(\Delta)$ is negligible.

Elliptic Curve Computational Diffie-Hellman (ECCDH) Assumption. Let G_1 be an additive point group with an elliptic curve by the generator P and aP and bP are elements of G_1 . A is able to compute the value of abP only with aP and bP in time t at most

$$\text{Succ}_{G_1}^{\text{ECCDH}}(\Delta, t) = \Pr[\Delta(aP, bP) = abP : a, b \in_R Z_q^*]. \quad (47)$$

The fact $\text{Succ}_{G_1}^{\text{ECCDH}}(\Delta, t)$ is negligible means that the ECCDH assumption holds.

6.3. Security Proof

Theorem 1. The hash functions $H_1(\cdot)$, $H_2(\cdot)$, and $H_3(\cdot)$ are modeled as random oracles. Let A be an adversary against our protocol S within time t . We denote that q_1 , q_2 , and q_3 ,

respectively, represent the number of $H_1(\cdot)$, $H_2(\cdot)$, and $H_3(\cdot)$ oracle queries executed by A , and q_{sc} , q_{sv} , and q_{ss} denote the number of *SendClient* queries, *SendDevice* queries, and *SendServer* queries. Then,

$$\begin{aligned} \text{Adv}_S^{\text{FTG-DRM}}(t, Q) \leq & \frac{q_1^2 + q_3^2 + q_{ss} + 10q_2 + 2q_3}{q - 1} \\ & + \frac{q_2^2 + 2q_{ss} + 4q_{sc} + 4q_{sv}}{2^l} \\ & + 2q_2 \text{Succ}_{P, G_1}^{\text{CDH}}(t'), \end{aligned} \quad (48)$$

where $Q = \{q_1, q_2, q_3, q_{sc}, q_{sv}, q_{ss}\}$ and $t' \leq t + (q_{sc} + q_{sv} + q_{ss})T_s$, with T_s denoting the computational time of one scalar multiplication in G_1 .

Proof. We define several attack games from Game GM_0 to Game GM_6 . For each game GM_i , Succ_i denotes the event that A has successfully guessed the bit b in the test session. The games are listed as follows.

Hash, Reveal, Test Queries.

(i) For a hash query $H(i, *, h)$, $i \in \{1, 2, 3\}$, we proceed as follows:

(a) Rule $H^{(1)}$: If a record $(i, *, h)$ exists on list L_h , h is returned. Otherwise, $h \leftarrow G_1(i = 1)/\{0, 1\}^l$ ($i = 2$)/ Z_q^* ($i = 3$) and h is returned. Record $(i, *, h)$ is added to list L_h . If the adversary directly issues this query, the record $(i, *, h)$ is added to list L_A .

(ii) For a query *Reveal* (U_i/V_j), we proceed as follows:

(a) If no session key is defined for instance U_i/V_j or if either U_i/V_j or its partner is asked a *Test* query, the output is $\perp$. Otherwise the output of this query is k_{UV} which is defined for the instance U_i/V_j .

(iii) For a query *Test* (U_i/V_j), we proceed as follows:

(a) If no session key is defined for instance U_i/V_j or if either U_i/V_j or its partner is asked a *Reveal* query, the output is $\perp$. Otherwise, the oracle flips a bit b . If $b = 1$, the session key is output. Otherwise, a value randomly chosen from the distribution space of session key is output.

Game GM_0 . This is the actual attack game. According to the definition, we have

$$\text{Adv}_P^{\text{FTG-DRM}}(A) = |2 \Pr[\text{Succ}_0] - 1|. \quad (49)$$

Otherwise, we randomly generate a bit b' if the game aborts or stops without answer from A or A has not finished the game.

Game GM_1 . We simulate all the oracles for each query and keep three lists to store the oracles answers. L_h stores answers

of random oracles $H_1(\cdot)$, $H_2(\cdot)$, and $H_3(\cdot)$. L_A is denoted for random oracle query asked by A . L_S is for the transcripts in the channel. We simulate the *SendClient*, *SendDevice*, *SendServer*, *Reveal*, and *Test* queries as in the actual attack. We list hash, *Reveal*, *Test* queries in *Hash*, *Reveal*, *Test Queries* and *SendClient*, *SendDevice*, *SendServer Queries*. Obviously, game GM_0 and game GM_1 are indistinguishable. So we have

$$\Pr [\text{Succ}_1] = \Pr [\text{Succ}_0]. \quad (50)$$

Game GM_2 . In this game, all the oracles simulated are almost the same as in the game GM_1 , but here, we avoid some collisions in the transcripts. The hash oracles $H_1(\cdot)$, $H_2(\cdot)$, and $H_3(\cdot)$ may collide with different input values. We use the following rule.

Rule $H^{(2)}$. If this query is directly issued by the adversary, and $(i, *, h)_{i \in \{1,2,3\}} \in L_A$, the game abort; Otherwise, h is returned.

Given that hash value h is selected from a random uniform distribution, the probability of collisions is at most $(q_1^2/2(q-1)) + (q_2^2/2^{l+1}) + (q_3^2/2(q-1))$ [22].

Game GM_2 and game GM_1 are perfectly indistinguishable unless the abovementioned rule causes the game abort. Hence,

$$|\Pr [\text{Succ}_2] - \Pr [\text{Succ}_1]| \leq \frac{q_1^2}{2(q-1)} + \frac{q_2^2}{2^{l+1}} + \frac{q_3^2}{2(q-1)}, \quad (51)$$

Game GM_3 . The game GM_3 is defined by aborting the executions in which the adversary has obtained a valid authenticator without asking the corresponding hash query by guessing Y , M_{U1} , M_{S4} , M_{S3} , H_{V2} , or H_U . The following rules are used.

Rule $S1^{(3)}$: $H'_{V1} \leftarrow H_3(\text{ID}_V \| \text{IDD}_U \| X \| M_{U2V1})$. We check the equation $e(P, Y) = e(P_V, X + H'_{V1} \cdot P_S)$. If it does not hold, S terminates without accepting; else we verify whether $\{(\text{IDD}_U, *, *, *), (\text{ID}_V, *, Y, *), (*, *, *, *), (*, *, *, *)\} \in L_S$ or $(3, (\text{ID}_V \| \text{IDD}_U \| X \| M_{U2V1}), H_{V1}) \in L_A$. If the two tests fail, S rejects the authenticator and terminates without accepting; otherwise, S accepts and continues.

Rule $S2^{(3)}$: $K_U \leftarrow H_2(sH_1(\text{IDD}_U))$, $r'_{U1} \leftarrow D_{K_U}(E_{K'_U}(r_{U1}))$, $\text{PWD}'_U \leftarrow D_{r'_{U1}}(E_{r_{U1}}(\text{PWD}_U))$, $Q_U \leftarrow H_2(sH_1(\text{PWD}'_U))$. We check the equation $H_2(K_U \oplus Q_U \oplus r'_{U1}) = M_{U1}$. If it does not hold, S terminates without accepting; else we verify whether $(2, (K_U \oplus Q_U \oplus r'_{U1}), M_{U1}) \in L_A$ or $\{(\text{IDD}_U, *, *, M_{U1}), (\text{ID}_V, *, *, *), (*, *, *, *), (*, *, *, *), (*, *, *)\} \in L_S$. If the two tests fail, S rejects the authenticator and terminates without accepting; Otherwise, S accepts and continues.

SendClient, SendDevice, SendServer Queries.

(i) For a query *SendClient*(U_i , Start), we proceed as follows:

(a) Rule $U1^{(1)}$: $r_{U1} \leftarrow \{0, 1\}^l$, $M_{U1} \leftarrow H_2(K'_U \oplus Q'_U \oplus r_{U1})$, $\text{IDD}_U \leftarrow H_2(\text{ID}_U \oplus r_U)$ and

$M_{U2V1} = \{\text{IDD}_U, E_{K'_U}(r_{U1}), E_{r_{U1}}(\text{PWD}_U), M_{U1}\}$ is returned. Then, instance U_i proceeds to an expecting state.

(ii) For a query *SendClient*(U_i , M_{V2U}), we proceed as follows if instance U_i is in an expecting state:

- (a) Rule $U2^{(1)}$: We check whether $H_2(r_{U1} \oplus K'_U \oplus M_{S2}) = M_{S3}$. If the equation does not hold, instance U_i terminates without accepting. Otherwise, instance U_i accepts and applies the following rule.
- (b) Rule $U3^{(1)}$: $r'_{S1} \leftarrow M_{S2} \oplus H_2(r_{U1} \| K'_U)$, and we check whether $H_2(R_{Vx} \| R_{Vy} \| r'_{S1}) = H_{V2}$. If the equation does not hold, instance U_i terminates without accepting. Otherwise, instance U_i accepts and applies the following rule.
- (c) Rule $U4^{(1)}$: $r_{U2} \leftarrow Z_q^*$, $R_U \leftarrow r_{U2} \cdot P$, $H_U \leftarrow H_2(R_{Ux} \| R_{Uy} \| r'_{S1})$, and instance U_i accepts and applies the following rule.
- (d) Rule $U5^{(1)}$: $R_{UV} \leftarrow r_{U2} \cdot R_V$, $k_{UV} \leftarrow H_2(R_U \| R_V \| R_{UV})$, and $M_{U2V2} = \{R_U, H_U\}$ is returned. Then, instance U_i terminates and record $\{(\text{IDD}_U, E_{K'_U}(r_{U1}), E_{r_{U1}}(\text{PWD}_U), M_{U1}), (\text{ID}_V, X, Y, M_{U2V1}), (M_{S1}, M_{S2}, M_{S3}, M_{S4}), (R_V, H_{V2}, M_{S2}, M_{S3}), (R_U, H_U)\}$ is added to list L_S .

(iii) For a query *SendDevice*(V_j , M_{U2V1}), we proceed as follows:

- (a) Rule $V1^{(1)}$: $r_{V1} \leftarrow Z_q^*$, $X \leftarrow r_{V1} \cdot P$, $H_{V1} \leftarrow H_3(\text{ID}_V \| \text{IDD}_U \| X \| M_{U2V1})$, $Y \leftarrow r_{V1} \cdot P_V + H_{V1} \cdot S_V$, and $M_{V2S} = \{\text{ID}_V, X, Y, M_{U2V1}\}$ is returned. Then, instance V_j proceeds to an expecting state.

(iv) For a query *SendDevice*(V_j , M_{S2V}), we proceed as follows if instance V_j is in an expecting state:

- (a) Rule $V2^{(1)}$: $k'_{SV} \leftarrow r_{V1} \cdot P_S = (k'_{SVx}, k'_{SVy})$, and we check whether $M_{S4} = H_2(k'_{SVx} \| k'_{SVy} \| S_{Vx} \| S_{Vy} \| M_{S1} \| M_{S3})$. If the equation does not hold, instance V_j terminates without accepting. Otherwise, instance V_j accepts and applies the following rule.
- (b) Rule $V3^{(1)}$: $r_{V2} \leftarrow Z_q^*$, $r'_{S1} \leftarrow M_{S1} \oplus k'_{SVx} \oplus k'_{SVy}$, $R_V \leftarrow r_{V2} \cdot P$, $H_{V2} \leftarrow H_2(R_{Vx} \| R_{Vy} \| r'_{S1})$, and $M_{V2U} = \{R_V, H_{V2}, M_{S2}, M_{S3}\}$ is returned. Then, instance V_j proceeds to an expecting state.

(v) For a query *SendDevice*(V_j , M_{U2V2}), we proceed as follows if instance V_j is in an expecting state:

- (a) Rule $V4^{(1)}$: We check whether $H_2(R_{Ux} \| R_{Uy} \| r'_{S1}) = H_U$. If the equation does not hold, instance V_j terminates without accepting. Otherwise, instance V_j accepts and applies the following rule.

- (b) Rule $V5^{(1)}$: $R'_{UV} \leftarrow r_{V_2} \cdot R_U$, $k'_{UV} \leftarrow H_2(R_U \| R_V \| R'_{UV})$, and instance V_j terminates.
- (vi) For a query $SendServer(S, M_{V_2S})$, we proceed as follows:

- (a) Rule $S1^{(1)}$: $H'_V \leftarrow H_3(ID_V \| IDD_U \| X \| M_{U2V_1})$, and we check whether $e(P, Y) = e(P_V, X + H'_{V_1} \cdot P_S)$. If the equation does not hold, instance S terminates without accepting. Otherwise, instance S accepts and applies the following rule.
- (b) Rule $S2^{(1)}$: $K_U \leftarrow H_2(sH_1(IDD_U))$, $r'_{U1} \leftarrow D_{K_U}(E_{K'_U}(r_{U1}))$, $PWD'_{U1} \leftarrow D_{r'_{U1}}(E_{r_{U1}}(PWD_U))$, $Q_U \leftarrow H_2(sH_1(PWD'_{U1}))$ and we check whether $H_2(K_U \oplus Q_U \oplus r'_{U1}) = M_{U1}$. If the equation does not hold, instance S terminates without accepting. Otherwise, instance S accepts and applies the following rule.
- (c) Rule $S3^{(1)}$: $r_{S1} \leftarrow \{0, 1\}^l$, $k_{SV} \leftarrow s \cdot X$, $S_V \leftarrow s \cdot H_1(ID_V)$, $M_{S1} \leftarrow k_{SVx} \oplus k_{SVy} \oplus r_{S1}$, $M_{S2} \leftarrow H_2(r'_{U1} \| K_U) \oplus r_{S1}$, $M_{S3} \leftarrow H_2(r'_{U1} \oplus K_U \oplus M_{S2})$, $M_{S4} \leftarrow H_2(k_{SVx} \| k_{SVy} \| S_{Vx} \| S_{Vy} \| M_{S1} \| M_{S3})$, and $M_{S2V} = \{M_{S1}, M_{S2}, M_{S3}, M_{S4}\}$ is returned. Then, instance S terminates.

Rule $V2^{(3)}$: $k'_{SV} \leftarrow r_{V_1} \cdot P_S = (k'_{SVx}, k'_{SVy})$. We check the equation $M_{S4} = H_2(k'_{SVx} \| k'_{SVy} \| S_{Vx} \| S_{Vy} \| M_{S1} \| M_{S3})$. If it does not hold, V_j terminates without accepting; else we verify whether $(2, (k'_{SVx} \| k'_{SVy} \| S_{Vx} \| S_{Vy} \| M_{S1} \| M_{S3}), M_{S4}) \in L_A$ or $\{(IDD_U, *, *, *), (ID_V, *, *, *), (*, *, *, M_{S4}), (*, *, *, *)\} \in L_S$. If the two tests fail, V_j rejects the authenticator and terminates without accepting; otherwise, V_j accepts and continues.

Rule $U2^{(3)}$. We check the equation $H_2(r_{U1} \oplus K'_U \oplus M_{S2}) = M_{S3}$. If it does not hold, U_i terminates without accepting; else we verify whether $\{(IDD_U, *, *, *), (ID_V, *, *, *), (*, *, M_{S3}, *), (*, *, M_{S2}, *), (*, *)\} \in L_S$ or $(2, (r_{U1} \oplus K'_U \oplus M_{S2}), M_{S3}) \in L_A$. If the two tests fail, U_i rejects the authenticator and terminates without accepting; otherwise, U_i accepts and continues.

Rule $U3^{(3)}$: $r''_{S1} \leftarrow M_{S2} \oplus H_2(r_{U1} \| K'_U)$. We check the equation $H_2(R_{Vx} \| R_{Vy} \| r''_{S1}) = H_{V_2}$. If it does not hold, U_i terminates without accepting; else we verify whether $\{(IDD_U, *, *, *), (ID_V, *, *, *), (*, *, *, *), (*, H_{V_2}, *, *)\} \in L_S$ or $(2, (R_{Vx} \| R_{Vy} \| r''_{S1}), H_{V_2}) \in L_A$. If the two tests fail, U_i rejects the authenticator and terminates without accepting; otherwise, U_i accepts and continues.

Rule $V4^{(3)}$. We check the equation $H_2(R_{Ux} \| R_{Uy} \| r'_{S1}) = H_U$. If it does not hold, V_j terminates without accepting; else we verify whether $\{(IDD_U, *, *, *), (ID_V, *, *, *), (*, *, *, *), (*, *, *, *), (*, H_U)\} \in L_S$ or $(2, (R_{Ux} \| R_{Uy} \| r'_{S1}), H_U) \in L_A$. If the two tests fail, V_j

rejects the authenticator and terminates without accepting; otherwise, instance V_j accepts and continues.

Game GM_3 and Game GM_2 are almost indistinguishable only if the rules mentioned above cause the instance to reject a valid authenticator. Because the adversary deduces the authenticator without issuing the corresponding hash queries, the probability of guessing is at most $(q_{ss}/2(q-1)) + (q_{ss}/2^l) + (q_{sv}/2^l) + (q_{sc}/2^l) + (q_{sv}/2^l)$. Hence,

$$|\Pr[\text{Succ}_3] - \Pr[\text{Succ}_2]| \leq \frac{q_{ss} + 2q_{sc} + 2q_{sv}}{2^l} + \frac{q_{ss}}{2(q-1)}. \quad (52)$$

Game GM_4 . We define game GM_4 by aborting the executions in which the adversary may have obtained valid authenticator Y , M_{U1} , M_{S4} , M_{S3} , H_{V_2} , or H_U by guessing the corresponding secret messages and querying the corresponding hash function. We use the following rules.

Rule $S1^{(4)}$: $H'_V \leftarrow H_3(ID_V \| IDD_U \| X \| M_{U2V_1})$. We check the equation $e(P, Y) = e(P_V, X + H'_{V_1} \cdot P_S)$. If it does not hold, S terminates without accepting; else we confirm whether $\{(IDD_U, *, *, *), (ID_V, *, *, *), (*, *, *, *), (*, *, *, *)\} \in L_S$. If the test fails, S rejects the authenticator and terminates without accepting; otherwise, we check whether $(3, (ID_V \| IDD_U \| X \| M_{U2V_1}), H_{V_1}) \in L_A$. If this is the case, we abort the game.

Rule $S2^{(4)}$: $K_U \leftarrow H_2(sH_1(IDD_U))$, $r'_{U1} \leftarrow D_{K_U}(E_{K'_U}(r_{U1}))$, $PWD'_{U1} \leftarrow D_{r'_{U1}}(E_{r_{U1}}(PWD_U))$, $Q_U \leftarrow H_2(sH_1(PWD'_{U1}))$. We check the equation $H_2(K_U \oplus Q_U \oplus r'_{U1}) = M_{U1}$. If it does not hold, S terminates without accepting; else we confirm whether $\{(IDD_U, *, *, M_{U1}), (ID_V, *, *, *), (*, *, *, *), (*, *, *, *)\} \in L_S$. If the test fails, S rejects the authenticator and terminates without accepting; otherwise, we check whether $(2, (K_U \oplus Q_U \oplus r'_{U1}), M_{U1}) \in L_A$. If this is the case, we abort the game.

Rule $V2^{(4)}$: $k'_{SV} \leftarrow r_{V_1} \cdot P_S = (k'_{SVx}, k'_{SVy})$. We check the equation $M_{S4} = H_2(k'_{SVx} \| k'_{SVy} \| S_{Vx} \| S_{Vy} \| M_{S1} \| M_{S3})$. If it does not hold, V_j terminates without accepting; else we confirm whether $\{(IDD_U, *, *, *), (ID_V, *, *, *), (*, *, *, M_{S4}), (*, *, *, *), (*, *)\} \in L_S$. If the test fails, V_j rejects the authenticator and terminates without accepting; otherwise, we check whether $(2, (k'_{SVx} \| k'_{SVy} \| S_{Vx} \| S_{Vy} \| M_{S1} \| M_{S3}), M_{S4}) \in L_A$. If this is the case, we abort the game.

Rule $U2^{(4)}$. We check the equation $H_2(r_{U1} \oplus K'_U \oplus M_{S2}) = M_{S3}$. If it does not hold, U_i terminates without accepting; else we confirm whether $\{(IDD_U, *, *, *), (ID_V, *, *, *), (*, *, M_{S3}, *), (*, *, M_{S2}, *), (*, *)\} \in L_S$. If the test fails, U_i rejects the authenticator and terminates without accepting; otherwise, we check whether

$(2, (r_{U1} \oplus K'_U \oplus M_{S2}), M_{S3}) \in L_A$. If this is the case, we abort the game.

Rule U3⁽⁴⁾: $r'_{S1} \leftarrow M_{S2} \oplus H_2(r_{U1} \| K'_U)$. We check the equation $H_2(R_{Vx} \| R_{Vy} \| r'_{S1}) = H_{V2}$. If it does not hold, U_i terminates without accepting; else we confirm whether $\{(IDD_U, *, *, *), (ID_V, *, *, *), (*, *, *, *), (*, H_{V2}, *, *), (*, *)\} \in L_S$. If the test fails, U_i rejects the authenticator and terminates without accepting; otherwise, we check whether $(2, (R_{Vx} \| R_{Vy} \| r'_{S1}), H_{V2}) \in L_A$. If this is the case, we abort the game.

Rule V4⁽³⁾. We check the equation $H_2(R_{Ux} \| R_{Uy} \| r'_{S1}) \stackrel{?}{=} H_U$. If it does not hold, V_j terminates without accepting; else we confirm whether $\{(IDD_U, *, *, *), (ID_V, *, *, *), (*, *, *, *), (*, *, *, *), (*, H_U)\} \in L_S$. If the test fails, V_j rejects the authenticator and terminates without accepting; otherwise, we check whether $(2, (R_{Ux} \| R_{Uy} \| r'_{S1}), H_U) \in L_A$. If this is the case, we abort the game.

Games GM_4 and GM_3 are almost indistinguishable only if the rules mentioned above cause the game to abort. Because the secret messages corresponding to valid authenticators $M_{U1}, Y, M_{S4}, M_{S2}, H_{V2}$, and H_U are deduced by the adversary, the probability of guessing is at most $(q_3 + q_2 + q_2 + q_2 + q_2 + q_2)/(q - 1)$. Hence,

$$|\Pr[\text{Succ}_4] - \Pr[\text{Succ}_3]| \leq \frac{5q_2 + q_3}{q - 1}. \quad (53)$$

Game GM_5 . Here we simulate a private hash function $H_4(\cdot) : \{0, 1\}^* \mapsto \{0, 1\}^l$ and take place of random oracle $H_2(\cdot)$ with $H_4(\cdot)$. Then, we do not use the R_{UV} or R'_{UV} to generate session key k_{UV} or k'_{UV} . As the result, the session key is completely independent of $H_2(\cdot)$ and either R_{UV} or R'_{UV} .

Rule U5⁽⁵⁾: $R_{UV} \leftarrow r_{U2} \cdot R_V, k_{UV} \leftarrow H_2(R_U \| R_V)$, and $M_{U2V2} = \{R_U, H_U\}$ is returned. Then, instance U_i terminates and record $\{(IDD_U, E_{K'_U}(r_{U1}), E_{r_{U1}}(\text{PWD}_U), M_{U1}), (ID_V, X, Y, M_{U2V1}), (M_{S1}, M_{S2}, M_{S3}, M_{S4}), (R_V, H_{V2}, M_{S1}, M_{S2}), (R_U, H_U)\}$ is added to list L_S .

Rule V5⁽⁵⁾: $R'_{UV} \leftarrow r_{V2} \cdot R_U, k'_{UV} \leftarrow H_2(R_U \| R_V)$, and instance V_j terminates.

Games GM_5 and GM_4 are almost indistinguishable only if the following event AskH5 occurs: A queries the hash function $H_2(\cdot)$ on $(R_U \| R_V \| R_{UV})$ or on $(R_U \| R_V \| R'_{UV})$. Because the $H_4(\cdot)$ is a private oracle, the probability that A correctly guesses the value of b is $1/2$. Hence,

$$|\Pr[\text{Succ}_5] - \Pr[\text{Succ}_4]| \leq \Pr[\text{AskH5}], \quad (54)$$

$$\Pr[\text{Succ}_5] = \frac{1}{2}.$$

Game GM_6 . In this game, the random self-reducibility of the CDH problem is used to simulate the executions. Given

a CDH instance (A, B) , where $A, B \in G_1$, the next rules are listed.

Rule V3⁽⁶⁾: $a \leftarrow Z_q^*, r'_{S1} \leftarrow M_{S1} \oplus k'_{SVx} \oplus k'_{SVy}, R_V \leftarrow a \cdot A, H_{V2} \leftarrow H_2(R_{Vx} \| R_{Vy} \| r'_{S1})$. The message $M_{V2U} = \{R_V, H_{V2}, M_{S2}, M_{S3}\}$ is returned. Then, instance V_j proceeds to an expecting state.

Rule U4⁽⁶⁾: $b \leftarrow Z_q^*, R_U \leftarrow b \cdot B, H_U \leftarrow H_2(R_{Ux} \| R_{Uy} \| r'_{S1})$. Instance U_i accepts and proceeds.

By the definition of event AskH5, event AskH6 means that the adversary has issued a query to random oracle on $(R_U \| R_V \| \text{CDH}(R_U, R_V))$. The number of records, such as $(2, *, *)$ in the list L_A , is q_2 , and the probability of obtaining the $\text{CDH}(R_U, R_V)$ value from list L_A is $1/q_2$. Hence, the accumulated probability is $(1/q_2) \times \Pr[\text{AskH6}]$. Besides, the CDH problem is random characteristics of the self-reducibility, and the equation $\text{CDH}(R_U, R_V) = \text{CDH}(A, B)^{ab}$ holds. Thus,

$$\Pr[\text{AskH5}] = \Pr[\text{AskH6}], \quad (55)$$

$$\Pr[\text{AskH6}] = q_2 \text{Succ}_{P, G_1}^{\text{CDH}}(t').$$

Finally, we summarize all the relationships and complete the proof. $\square$

From (50) to (53), we could derive

$$|\Pr[\text{Succ}_0] - \Pr[\text{Succ}_4]| \leq \frac{q_1^2 + q_3^2 + q_{ss} + 10q_2 + 2q_3}{2(q - 1)} + \frac{q_2^2 + 2q_{ss} + 4q_{sc} + 4q_{sv}}{2^{l+1}}. \quad (56)$$

From (54) to (55), we obtain

$$|\Pr[\text{Succ}_4] - \frac{1}{2}| \leq q_2 \text{Succ}_{P, G_1}^{\text{CDH}}(t'). \quad (57)$$

From (56) and (57), we have

$$|\Pr[\text{Succ}_0] - \frac{1}{2}| \leq \frac{q_1^2 + q_3^2 + q_{ss} + 10q_2 + 2q_3}{2(q - 1)} + \frac{q_2^2 + 2q_{ss} + 4q_{sc} + 4q_{sv}}{2^{l+1}} + q_2 \text{Succ}_{P, G_1}^{\text{CDH}}(t'). \quad (58)$$

From (49) and (58), we obtain (48) and the Theorem 1.

7. Security Analysis of Our Scheme

To get over the problems existing in Yang et al.'s scheme, we proposed a provable secure and efficient authentication scheme using smart card based on elliptic curve cryptography. In this part, we will show that the scheme we proposed is secure against various attacks [23, 24].

7.1. Smart Card Loss Attack. The smart card of user U contains $\{r_U, S_U, P_U, M_U, P, H_2(\cdot), E_K(\cdot)/D_K(\cdot)\}$. If the smart card of the user U is stolen by the attacker, he/she could only get the secret data r_U, S_U, P_U , and M_U from it; other data in the smart card is public to all clients. However, he/she does not know the identity ID_U or the password PW_U of U . As a result, he/she cannot use the secret data r_U, S_U, P_U , and M_U to impersonate the user U to pass the authentication of the server and the device. As the result, our scheme can resist the smart card loss attack.

7.2. Denial of Service Attack. In some schemes [10, 25–27], both of the server and user need to update some shared data in their smart card or verifier table after the key agreement phase or the authentication phase. The attacker can eavesdrop, intercept, and modify any transmitted messages on the public channel. And the behavior of the attacker may cause the difference of the shared data between the user and the server. So, these schemes cannot resist the denial of service attack. In our proposed scheme, the user and the server have not needed to update some data in their smart card or verifier table. Thus, the attacker no longer can perform the denial of service attack.

7.3. Efficient Login Phase. To improve the efficiency of our proposed scheme, before the key agreement phase, the smart card checks the correctness of user's identity and password. In the login phase of our scheme, when the user U inputs his/her identity ID_U and password PW_U , the smart card checks the correctness of ID_U and PW_U firstly through the equation $P_U = H_2(S_U \oplus H_2(PW_U \oplus r_U) \oplus M_U \oplus ID_U)$. If it does not hold, the smart card reject U 's request. Otherwise, it authenticates the legality of the user U and turns to the key agreement phase.

7.4. Session Key Attack. Firstly, the security of the session key in our scheme is based on the computational Diffie-Hellman problem. Secondly, the session key is generated by the random numbers, which are randomly selected by the user and the device, respectively. At last, before computing a session key, both of them must authenticate each other [28]. Based on the reasons mentioned above, the attacker cannot perform the session key attack.

7.5. Insider Attack. Because of without verifier table in this system, the insider cannot acquire any secret data from the server's system. In addition, the insider cannot obtain K_U without the server's private key. And the adversary has no idea to derive the secret data K_U from all messages he/she can achieve. Thus, he/she cannot impersonate a legal user U' to pass the authentication of the server and the device, or the server S' to deceive a legal user. Therefore, the proposed scheme is able to withstand the insider attack.

7.6. Replay Attack. If the U 's message M_{U2V_1} is intercepted and resent to the device by the attacker, the message M_{V_2S} is computed and sent to the server by the device. Obviously the user and the device can through the server's certification,

and the server responses the message M_{S2V} to the device. After that, the device can authenticate the server and sends the message M_{V2U} to the attacker. The attacker can acquire nothing from M_{V2U} . So, he/she cannot send a legality message M_{U2V_2} to the device. The device must not establish a session key with the attacker [29]. In the same way, if the attacker replays the device's message, he/she also cannot pass the user's authentication.

8. Performance Comparisons

In this part, our proposed scheme's performance will be evaluated compared with some other schemes [10, 12]. The comparison is summarized in Table 1. We define seven parameters of time complexity which are adopted in the schemes mentioned above as follows.

- (i) T_{H1} : The time complexity of executing a hash function $H_1(\cdot)$.
- (ii) T_{H2} : The time complexity of executing a hash function $H_2(\cdot)$.
- (iii) T_{H3} : The time complexity of executing a hash function $H_3(\cdot)$.
- (iv) T_P : The time complexity of executing a pairings operation of point on elliptic curve.
- (v) T_M : The time complexity of executing a scalar multiplication operation of point on elliptic curve.
- (vi) T_A : The time complexity of executing an addition operation of point on elliptic curve.
- (vii) T_S : The time complexity of executing a symmetric key computation.

A comparison of our proposed scheme and that of Zhang et al. and Yang et al. is summarized in Table 1. It is known to all that one-way hash function is more efficient than the operation of scalar multiplication. Moreover, the pairing operation costs much more than the scalar multiplication operation. The effort of evaluating one pairing operation is approximately three times the effort of evaluating one scalar multiplication operation. Therefore our proposed scheme performs better than Zhang et al.'s scheme and Yang et al.'s scheme. Consequently, our proposed scheme is much more suitable for practical applications.

9. Conclusions

We have analyzed the scheme of Yang et al. and pointed out, except the attacks mentioned in Mishra et al. paper, their scheme suffers from the session key attack and has some mistakes. We propose a new provable secure and efficient digital rights management authentication scheme using smart card based on elliptic curve cryptography to surmount the problems in Yang et al.'s. And we demonstrate that the new scheme is provable secure under the model AFP05 introduced in this paper. Because hash function is used to replace the operations of point on elliptic curve and the symmetric key computation in our scheme, our scheme

TABLE 1: Performance comparisons.

	Our proposed scheme	Yang et al.'s scheme	Zhang et al.'s scheme
Registration phase			
U	$2T_{H2}$	$1T_{H2}$	—
S	$3T_{H1} + 3T_{H2} + 3T_M$	$2T_{H1} + 1T_{H2} + 2T_M$	$2T_{H1} + 4T_{H2} + 2T_M$
Login phase and key agreement phase			
U	$9T_{H2} + 2T_M + 2T_S$	$6T_{H2} + 6T_S$	$7T_{H2} + 7T_S$
V	$4T_{H2} + 1T_{H3} + 6T_M + 1T_A$	$2T_{H2} + 2T_{H3} + 3T_P + 6T_M + 2T_A + 3T_S$	$3T_{H2} + 2T_{H3} + 3T_P + 6T_M + 2T_A + 3T_S$
S	$3T_{H1} + 6T_{H2} + 1T_{H3} + 1T_P + 5T_M + 1T_A + 2T_S$	$1T_{H1} + 5T_{H2} + 2T_{H3} + 2T_P + 7T_M + 3T_A + 5T_S$	$5T_{H2} + 2T_{H3} + 2T_P + 7T_M + 3T_A + 6T_S$
Password update phase			
U	$9T_{H2} + 2T_S$	$4T_{H2}$	—
S	$3T_{H1} + 7T_{H2} + 3T_M + 2T_S$	$1T_{H1} + 3T_{H2}$	$4T_{H2}$
Total	$9T_{H1} + 40T_{H2} + 2T_{H3} + 1T_P + 19T_M + 2T_A + 4T_S$	$4T_{H1} + 22T_{H2} + 4T_{H3} + 5T_P + 15T_M + 5T_A + 8T_S$	$2T_{H1} + 23T_{H2} + 4T_{H3} + 5T_P + 15T_M + 5T_A + 9T_S$

is more efficient than Yang et al.'s scheme. As a result, our proposed scheme is more suitable for practical applications in ubiquitous computing.

Notations

U:	The user
S:	The server
V:	The device
A:	The attacker
ID _U :	The user U's identity
s:	The secret key of the server S
P _S :	The public key of the server S and $P_S = sP$
PW _U :	The user U's password
P _U :	The public key of the user U and $P_U = sH_1(\text{ID}_U)$
H ₁ (·):	$\{0, 1\}^* \mapsto G_1$, a one-way hash function maps an arbitrary length bit string into a member of group G_1 .
H ₂ (·):	$\{0, 1\}^* \mapsto \{0, 1\}^l$, a one-way hash function maps an arbitrary length bit string into a l -bits string.
H ₃ (·):	$\{0, 1\}^* \mapsto Z_q^*$, a one-way hash function maps an arbitrary length bit string into a random member in group Z_q^* .
E _K (·)/D _K (·):	The symmetric encryption/decryption algorithm using key K
⊕:	The bitwise XOR operation
:	String concatenation operation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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