A Realistic Lightweight PUF-based Mutual Authentication in RFID Environments

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Abstract—Radio frequency identification has been widely used in several fields based on its low-cost property. However, the wireless-based communication part in the radio frequency identification still suffers from several kinds of attacks such as impersonation attack, cloning attack, DoS attack, and tracking attack. To solve these problems in the radio frequency identification environment, this manuscript proposes a new authentication protocol that just uses limited resources. Moreover, both the informal and the formal analyses are used to ensure that the proposed scheme achieves the security features, withstands kinds of attacks, and has low computational complexity.

Index Terms— Radio Frequency Identification (RFID), Authentication protocol, informal and formal analyses, computational complexity.

I. INTRODUCTION

RADIO Frequency Identification (RFID) has been widely applied in several fields, such as, transportation system, supply chain, livestock management, patient medical caring system, e-payment system, and e-passport system. There are three main components in the RFID environment, namely Tag, Reader, and the Server.

The Tag transmits information to the reader where it is processed, then the reader forwards it to the server. The communication between the Tag and the reader is done via the public channel. However, the reader and server communicate via a private channel since both of them are in one unit. The attacker can fully control public channels in which he/she can eavesdrop, intercept, edit, and delete the message. Hence, to avoid these attacks, the authentication method, a security feature to ensure that both parties recognize the identity mutually, is needed in the RFID environment. Nevertheless, the limited resources in RFID make most of the existing cryptographic algorithms, such as public-key cryptosystems cannot be used in RFID. Thus, a new authentication method is needed in the RFID since the ones with these cryptographic algorithms cannot be directly used in the RFID environment.

Recently, the physical unclonable function (PUF) is used to ensure authentication in the RFID environment. A PUF is a unique property of a circuit that maps a set of Challenge C to a

set of the Response R in the chip manufacturing process [1][2][3]. Several authentication protocols based on the PUF in the RFID environment are proposed by [4]–[9]. Unfortunately, these protocols fail to achieve security features such as anonymity, untraceability, resolving desynchronization problem, perfect forward, and backward secrecy. Additionally, these protocols fail to withstand various kinds of attacks such as impersonation attack, DoS attack, and tracking attack. Additionally, the previous protocol [4]–[9] used ideal PUF hence it did not denote the realistic condition, in the real condition output of PUF has noisy. Subsequently [10] and [11] proposed protocol security in the RFID environment using realistic PUF. However, [12] and [13] point out that the protocols proposed by [10] and [11] fail to achieve scalability, untraceability. Subsequently, two popular PUF-based authentication protocols in the RFID environment are proposed by [12] and [13], their researches discuss ideal PUF and Non-ideal PUF. However, after we evaluate them deeply, both of them also fail to withstand impersonation attack, namely if the attacker stole the Tag by activating the PUF and Fuzzy Extractor with programming, the attacker can obtain response and fixed key and then the attacker is able to generate a new set of {response, fixed key, challenge, session key}. As result, the attacker impersonates the Tag as a legitimate user (see Section II for more detail of discussion the weaknesses of [12] and [13]).

Besides, both [12] and [13] cannot achieve perfect forward and backward secrecy for after the attacker obtains response, the attacker can obtain past and future secret such as new {response, challenge, session key}. On the other hand, their scheme cannot achieve untraceability as well because the attacker can compute a new challenge. The attacker searches for a new challenge in collected messages, if found, he learns that the owner of the two messages is the same (see Section II for more detail of discussion the weaknesses of [12] and [13]).

In this paper, we propose a new mutual authentication protocol for focusing on non-ideal PUF-based which is used for authentication. The proposed protocol can achieve mutual authentication, anonymity, untraceability, perfect forward, and backward secrecy. Further, the proposed protocol withstands various kinds of attacks such as impersonation attack, DoS

Attack, tracking attack, and cloning attack.

The rest of this paper is organized as follows. To support our point of view, Section II presents a brief review of two state-of-the-art protocols proposed by Gope et al. and Feng Zhu et al. and points out their problems. Section III presents our proposal in detail. To ensure that our scheme achieves security features and withstands any kinds of attacks, we present informal analysis in Section IV followed by formal analysis using BAN Logic, and Scyther Tool Section V, VI, respectively. Finally, we conclude our article in Section VII.

A. Related Works and Motivation

Several schemes in the RFID environment have been proposed, such as the schemes by [14]–[19] using Elliptic curve cryptography with exponential module operation in the algorithm, however, it is not suitable to be applied in a tiny Tag in an RFID environment.

The other research by [20]–[23] proposed the protocols using a symmetric-key cryptosystem. Unfortunately, their schemes cannot guarantee to withstand the cloning attack. [4]–[9] offer authentication PUF-based which is resilient to the cloning attack. However, these PUF-based authentication schemes [4]–[9] have weaknesses, e.g., [4] tree-based authentication scheme using PUF. [5] pointed out that the scheme proposed by [4] fails to withstand the DoS and impersonation attack.

[5] proposed a new scheme based on PUF to enhance security features. However, [7] presented that the scheme introduced by [4] is vulnerable against the cold boot attack, and then [7] showed the evidence that the attacker is easy to tamper and obtain all data after impersonating it as well as tracing previous and future communication. In other research, [6] came up with a scheme to enhance security features [5]. However, [7] raised awareness that the scheme previously suggested by [5] is vulnerable against cold boot attack. [8] also applied authentication PUF-based in an RFID environment, but the scheme does not achieve forward secrecy and is weak against the DoS attack. However, since cold-boot attacks will cause a defect in the data in Tag memory due to the Tag sensitivity, the attacker cannot obtain data in Tag memory. At the other time, [24], [25] proposed PUF-based authentication in RFID, yet, both of them cannot withstand the DoS attack.

[9] presented a PUF-based authentication in the RFID system. However, [12] P. Gope et al. showed that the scheme proposed by [9] cannot achieve forward secrecy. P.Gope [12] then came up with mutual PUF-based authentication. Feng Zhu et al. [13] presented a lightweight RFID mutual authentication protocol with PUF. However, after careful investigation, we found that both [12]–[13] have the problem to achieve perfect forward and backward secrecy in which the attacker can impersonate the Tag. Additionally, their scheme does not achieve untraceability.

This article resolves the problems in the previous schemes specified by [4]–[13]. We present the review and point out the weakness of two papers by [12] and [13] to support our scheme's perspective in Sections 3 and 4. The proposed scheme contributions are as follow:

1. Evaluating two popular authentication protocols in

RFID environment PUF-based and denote several weaknesses of them

2. Designing the new protocol in realistic conditions using non-ideal PUF. Our scheme achieves security features including mutual authentication, anonymity, untraceability, perfect forward secrecy, and backward secrecy, resolves the desynchronization problem, scalability.
3. Our proposal withstands various attacks such as impersonation attack, DoS attack, cloning attack, and Traceability attack.
4. A formal analysis using BAN Logic was carried out to ensure that our authentication protocol achieves secure mutual authentication.
5. The other analysis formally using the Scyther tool ensures that our protocol withstands various kinds of attacks.
6. A comparison of security features and computational complexity was conducted to ensure our proposal is not only secure but also has a low computational complexity

B. Preliminaries

This subsection briefly presents the preliminary background of the PUF and the capabilities of the attacker.

a. Physically Unclonable Function (PUF)

A PUF is a unique property of a circuit that maps a set of Challenge C to a set of the Response R in the chip manufacturing process [26]. Formally, inputting C into PUF to produce R where $R = \text{PUF}(C)$ is hard to clone [27]. We divide PUF into two types, namely ideal PUF and non-ideal PUF.

an ideal PUF will produce a similar response with similar challenges inputted into PUF even if the non-stable temperature factor occurs. In the last few years, researchers have developed an ideal PUF which ensures 0% Bit-Error Rate [28]–[31], however, the ideal PUF is not realistic due to the real condition output of PUF has noisy. Meanwhile, a non-ideal PUF may produce a different response with a similar challenge inputted into PUF due to temperature factors. The fuzzy extractor is used to obtain stable PUF output [32], [33]; Therefore, in this paper, we use the non-ideal PUF, where $R'_i = \text{PUF}(C)$.

b. Fuzzy Extractor.

The fuzzy extractor has two functions, namely $FE.Gen()$ and $FE.Rec()$. $FE.Gen()$ is the probabilistic function to generate the fixed key K_u and helper data hd from the input noisy response R'_i , where $(K_u, hd) = FE.Gen(R'_i)$. $FE.Rec()$ is the deterministic function to reconstruct K_u from helper data hd and noisy input R'_i , where $(K_u, hd) = FE.Gen(R'_i) \rightarrow K_u = FE.Rec(hd, R'_i)$. The successful FE is based on the similarity of original data and noisy data. Therefore, in this paper, we use the fuzzy extractor to obtain a fixed key, namely K_u from noisy response, where $(K_u, hd) = FE.Gen(R'_i)$ [32], [33].

c. The Adversary Model

The attacker's capabilities are summarized as follows; The proposed scheme could still remain secure under the attacks by attackers with the following capabilities. Our work adopts the research conducted by [34].

1. C1: the attacker has full control of the communication channel
2. C2: with a stolen RFID Tag the attacker can activate the PUF, and Fuzzy Extractor by programming

The steps of the attacker:

Step 1: The attacker intercepts the message based on C1

Step 2: Steal RFID Tag and obtains data from Tag's memory

Step 3: Activate PUF to compute $R'_i = PUF(C)$ based on C2

Step 3: Activate Fuzzy Extractor to compute $K_u = FE.Rec(hd, R'_i)$ based on C2

Step 4: If $R'_i = PUF(C)$ and $K_u = FE.Rec(hd, R'_i)$ can pass the verification, the attacker obtains correct K_u .

Step 5: The attacker can get all secret based on C1, C2.

II. STATE OF THE ART PROTOCOLS AND PROBLEMS

This section presents a brief review of two state-of-the-art protocols proposed by [12], [13], and points out their problems.

A. Gope et al.'s Protocol

This subsection presents a brief review of the authentication protocol proposed by [12], including notations, setup phase, mutual authentication, and the main weakness. Table 1 is the notations used throughout the authentication protocol proposed by [12].

TABLE I
NOTATIONS OF CRYPTOGRAPHY FUNCTIONS

Notation	Definition
TID_T^i	Temporary identity of the Tag for i-th round
$CRP(C_i, R'_i)$	Challenge-Response Pairs for the i-th round
K_i	Session Key for the i-th round
PUF_T	Physically Unclonable Function of the Tag
$h(\cdot)$	One-way hash function
$\oplus$	Exclusive-OR operation
$\parallel$	Concatenation operation
FE	Fuzzy Extractor for generating fixed-key from noisy-response, where Fixed key K_i and help data hd are generated from R'_i where $(K_i, hd) = FE.Gen(R'_i)$ Fixed key K_i is reconstructed from R'_i, hd where $(K_i) = FE.Rec(R'_i, hd)$

a. The setup phase

Step 1: The backend server generates Challenge C_i and sets the emergency challenge $C_{em} = \{c_1, c_2, \dots, c_n\}$ and then the backend server sends C_i, C_{em} to the Tag.

Step 2: Upon receiving C_i, C_{em} , the Tag produces the response R'_i, R'_{em} using PUF_T where $R'_i = PUF_T(C_i)$ and $R'_{em} = PUF_T(C_{em})$. The Tag sends R'_i, R'_{em} to the backend

server.

Step 3: The server generates the temporary identities TID_T^i for the i-th round, computes $(K_i, hd_i) = FE.Gen(R'_i)$ and $(K_{em}, hd_{em}) = FE.Gen(R'_{em})$. The server generates a set of the un-link pseudo identities $PID = \{pid_1, pid_2, \dots, pid_n\}$. The server copies and sends $TID_T^i, PID, (C_i, hd_i) (C_{em}, hd_{em})$ to the Tag and the backend server stores TID_T^i, PID as well along with $(C_i, C_{em}) (K_i, K_{em})$.

Step 4: The Tag stores $TID_T^i, PID, (C_i, hd_i) (C_{em}, hd_{em})$. The setup phase takes place via a secure channel.

b. The mutual authentication between tag and reader-server unit

Step 1: The Tag selects TID_T^i , generates COUNT, and sends $TID_T^i, COUNT$ to the backend server

Step 2: Upon receiving $TID_T^i, COUNT$, the server looks for TID_T^i in its database, if the server does not locate TID_T^i the communication will be terminated, otherwise, the server reads challenge-fixed key pairs CRP (C_i, K_i) , generates a nonce N_s , computes $N_s^* = K_i \oplus N_s$, and computes the verifier of the server $Res_s = h(COUNT + 1 || K_i || N_s^*)$. The server sends C_i, N_s^*, Res_s to the Tag.

Step 3: Upon receiving C_i, N_s^*, Res_s , the Tag generates $R'_i = PUF_T(C_i)$, selects hd_i , computes $K_i = FE.Rec(R'_i, hd_i)$, verifies Res_s , computes $N_s = K_i \oplus N_s^*$, $C_{i+1} = h(COUNT + 2 || N_s || K_i)$, $R'_{i+1} = PUF_T(C_{i+1})$, $R_{i+1}^* = K_i \oplus R'_{i+1}$, $Res_T = h(N_s || K_i || R_{i+1}^*)$. The Tag sends R'_{i+1}, Res_T to the backend server.

Step 4: Upon receiving R'_{i+1}, Res_T the server verifies Res_T . If the Res_T is not equal to Res_T the server will terminate the communication, otherwise computes $R'_{i+1} = K_i \oplus R_{i+1}^*$, generates $(K_{i+1}, hd_{i+1}) = FE.Gen(R'_{i+1})$, computes $C_{i+1} = h(COUNT + 2 || N_s || K_i)$, $hd_{i+1}^* = h(COUNT + 3 || K_i \oplus hd_{i+1})$, $V_s = h(hd_{i+1}^* || K_i)$, updates $TID_T^{i+1} = h(TID_T^i || K_{i+1})$ and stores $TID_T^{i+1}, (C_{i+1}, K_{i+1})$. The server sends hd_{i+1}^*, V_s to the Tag

Step 5: Upon receiving hd_{i+1}^*, V_s , the Tag verifies V_s . If the Res_T is not equal to Res_T the server will terminate the communication, otherwise computes $hd_{i+1} = h(COUNT + 3 || K_i \oplus hd_{i+1}^*)$, updates $TID_T^{i+1} = h(TID_T^i || K_{i+1})$. Finally, the Tag stores $TID_T^{i+1}, (C_{i+1}, hd_{i+1})$

c. The main weakness in [12].

Step 1: The attacker intercepts every message, namely $M_1: \{TID_T^i, COUNT\}$, $M_2: \{C_i, N_s^*, Res_s\}$, $M_3: \{R'_{i+1}, Res_T\}$, and $M_4: \{hd_{i+1}^*, V_s\}$ based on C1.

Step 2: Steal RFID Tag and obtains data from the Tag's memory

Step 3: Activate PUF to compute $R'_i = PUF_T(C_i)$, based on C2

Step 4: Activate Fuzzy Extractor to compute $K_i = FE.Rec(R'_i, hd_i)$, based on C2

Step 4: If the attacker passes verification Res_s by K_i , that is, the attacker obtains correct fixed key

Step 5: The attacker can compute secrets include current response R'_i , K_i , new challenge C_{i+1} , new response $R'_{i+1} = PUF^T(C_{i+1})$, new help data hd_{i+1} based on C1, C2.

d. The scheme [12] does not achieve untraceability

Since the attacker can compute correct R, and the attacker can compute new challenge C_{i+1} . The scheme [12] does not achieve untraceability, the proof is as follow:

Step 1: Compute $C_{i+1} = h(COUNT + 2||N_s||K_i)$

Step 2: Search C_{i+1} in his collected message

Step 4: If the attacker finds similar C_{i+1} in his/her collected message, he/she will know that the owner of the two messages is the same.

B. Feng Zhu et al.'s Protocol

This subsection presents a brief review of the authentication protocol in [13], including Notations, Setup phase, Mutual authentication, and the main weakness. Table 2 is the notations used throughout the authentication protocol proposed by [13].

a. The setup phase

TABLE I
NOTATIONS OF CRYPTOGRAPHY FUNCTIONS

Notation	Definition
TID_i^T	Temporary identity of the Tag for i-th round
$CRP(C_i, R'_i)$	Challenge-Response Pairs for the i-th round
K_i	Session Key for the i-th round
PUF_T	Physically Unclonable Function of the Tag
$h(\cdot)$	One-way hash function
$\oplus$	Exclusive-OR operation
$ $	Concatenation operation
FE	Fuzzy Extractor for generating fixed-key from noisy-response, where Fixed key K_i and help data hd are generated from R'_i where $(K_i, hd) = FE.Gen(R'_i)$ Fixed key K_i is reconstructed from R'_i , hd where $(K_i) = FE.Rec(R'_i, hd)$

Step 1: The server generates Challenge C_i and sends C_i to the Tag.

Step 2: The Tag generates $R'_i = PUF^T C_i$ and sends R'_i to the server

Step 3: The server generates SID_i^T , computes $(k_i, hd_i)FE.Gen(R'_i)$, sends SID_i^T, hd_i to the Tag, and stores: $\{SID_i^T, C_i, k_i\}$

Step 4: The tag stores SID_i^T, hd_i

The setup phase via secure channel.

b. The mutual authentication between the tag and reader-server unit

Step 1: The server generates Hello, and sends $M_1: \{Hello\}$ to the tag

Step 2: The tag reads SID_i^T, hd_i , and sends $M_2: SID_i^T$ to the server.

Step 3: upon receiving $M_2: SID_i^T$, the server finds SID_i^T in database, reads C_i, k_i , generates N , computes $N' = k_i \oplus N$,

$Auth_1 = h(N||k_i)$. The server sends $M_3: \{C_i, N', Auth_1\}$ to the Tag

Step 4: upon receiving $M_3: \{C_i, N', Auth_1\}$, the tag computes $R'_i = PUF^T C_i, k_i = FE.Rec(R'_i, hd_i)$,

$N = N' \oplus k_i$, verifies $Auth_1$, generates M , computes $C_{i+1} = h(N||M||C_i)$, $R'_{i+1} = PUF^T(C_{i+1})$, $R'' = R'_{i+1} \oplus N$, $M' = M \oplus N$, $Auth_2 = h(N||M + 1||R'_{i+1})$. The tag sends $M_4: \{R'', M', Auth_2\}$ to the server.

Step 5: upon receiving $M_4: \{R'', M', Auth_2\}$, the server computes $R'_{i+1} = R'' \oplus N$, $M = M' \oplus N$, verifies $Auth_2$, computes $(k_{i+1}, hd_{i+1})FE.Gen(R'_{i+1})$, $C_{i+1} = h(N||M||C_i)$, $SID_{i+1}^T = h(N||M + 2||SID_i^T)$, $hd' = h(M||k_i) \oplus hd_{i+1}$, $Auth_3 = h(N||M + 2||hd_{i+1})$, stores $SID_{i+1}^T, C_{i+1}, k_{i+1}$. The server sends $M_5: \{Auth_3\}$ to the tag.

Step 6: upon receiving $M_5: \{Auth_3\}$, the tag computes $hd_{i+1} = h(M||k_i) \oplus hd'$ verifies $Auth_3$, computes $SID_{i+1}^T = h(N||M + 2||SID_i^T)$ and stores SID_{i+1}^T, hd_{i+1}

c. The weakness of Feng Zhu et al.'s Scheme

This subsection presents the weakness of a scheme by [13] based on the stolen card, and the attacker can activate PUF by programming, [13] fails to achieve perfect forward and backward secrecy.

Step 1: The attacker intercepts every message namely $M_1: \{Hello\}, M_2: SID_i^T, M_3: \{C_i, N', Auth_1\}$, $M_4: \{R', M', Auth_2\}$ and based on C1.

Step 2: Steal RFID Tag and obtains data from the Tag's memory

Step 3: Activate PUF to compute $R'_i = PUF^T C_i$ based on C2

Step 4: Activate Fuzzy Extractor to compute $k_i = FE.Rec(R'_i, hd_i)$ based on C2

Step 5: If the attacker passes verification $Auth_1$ by k_i , that is, the attacker obtains correct fixed key k_i

Step 6: The attacker can compute all secrets include current response R'_i, k_i and then the attacker can compute new challenge C_{i+1} , new response R_{i+1} , new help data hd_{i+1} based on C1, C2.

d. The scheme [13] does not achieve untraceability

Based on the attacker's ability to compute correct k_i and a new challenge. [13] does not achieve untraceability, the proof is as the following:

Step 1: Can compute $C_{i+1} = h(N||M||C_i)$

Step 2: Search C_{i+1} in his collected message

Step 4: if the attacker finds a similar C_{i+1} in his/her collected message, he/she will know the owner of two messages is the same.

III. PROPOSED SCHEME

This section presents our proposed scheme starting from System structure, Assumptions, Notation, Setup phase between

Fig. 1. System Structure

Tag and backend server, and mutual authentication between Tag and the reader- server unit. For convenience, we use the notation in Table 3 throughout our scheme.

A. System structure

This sub section presents a brief description of the system structure

In Fig 1, the system structure consists of three participants, namely, Tag, Reader, and server. The Tag transmits information to the reader where it is processed, then the reader forwards it to the server. The communication between the Tag and the reader is done via the public channel. However, the reader and server communicate via a private channel since both of them are in one unit.

B. Assumptions

We have several assumptions as follows

- The RFID is equipped with PUF
- The RFID is able to resist side-channel attacks [35]
- Cold Boot Attack will cause data defect in Memory of Tag [35]

C. Notations of Cryptography Function

This subsection presents the notations of the cryptography function in table III throughout this paper. Additionally, based on the assumption aforesaid, the devices are equipped with PUF; hence our scheme uses this facility

D. Setup Phase between Tag and the Server

The setup phase between Tag and the server has 4 steps as follows:

Step 1: The tag sends ID_T, Reg_{Req} to the server.

Step 2: The server generates C_T, K_{TS}, PID_{TS} , computes $PID_{Syn} = \{pid_1, pid_2, \dots, pid_n\}$, $K_{Syn} = \{k_1, k_2, \dots, k_n\}$, $C_{Syn} = \{c_1, c_2, \dots, c_n\}$ and sends them to the tag.

Step 3: The tag computes $R'_T = PUF(C_T)$, $R'_{Syn} = PUF(C_{Syn})$. The tag sends R'_T, R'_{Syn} to the server. The tag stores $K_{TS}, PID_{TS}, PID_{Syn}, K_{Syn}$

Step 4: Finally, the server stores $C_T, R'_T, ID_T, PID_{TS}, K_{TS}, (C_{Syn}, R'_{Syn}) (PID_{Syn}, K_{Syn})$ and the tag stores $K_{TS}, PID_{TS}, PID_{Syn}, K_{Syn}$. setup phase via a secure channel.

On normal conditions the tag using PID_{TS}, K_{TS} is replaced by new values given by the server. When desynchronization occurs, PID_{TS}, K_{TS} are replaced by $(pid_1, k_1), \dots, (pid_n, k_n)$

TABLE III
NOTATIONS OF CRYPTOGRAPHY FUNCTIONS

Notation	Definition
ID_T	Identity of the Tag
K_{TS}	Shared key between server and Tag
PUF_T	Physically unclonable function of Tag
PID_{TS}	One-time Pseudonym of Tag to communicate with the server
C_T	Challenge for the i-th iteration
R'_T	The noisy Response of the respective PUF for C_T
$\parallel$	Concatenation operation
$\oplus$	Exclusive-OR operation
PID_{Syn}	Pseudo identity of synchronization is used if a loss of synchronization occurs where $PID_{Syn} = \{pid_1, \dots, pid_n\}$
K_{Syn}	Key of synchronization is used if a loss of synchronization occurs where $K_{Syn} = \{pk_1, \dots, pk_n\}$
FE	Fuzzy Extractor for generating fixed-key from response and help data, where Fixed key K_i and help data hd are generated from R'_i where $(K_i, hd) = FE.Gen(R'_i)$ Fixed key K_i is reconstructed from R'_i, hd where $(K_i) = FE.Rec(R'_i, hd)$

from $PID_{Syn} = \{pid_1, pid_2, \dots, pid_n\}$ and $K_{Syn} = \{k_1, k_2, \dots, k_n\}$, and uses $C_{Syn} = \{c_1, c_2, \dots, c_n\}$.

E. Mutual Authentication Phase between Tag and the reader-server unit.

Mutual authentication phase between Tag and The reader-server unit has steps as follows:

Step 1: The tag selects PID_{TS} , generates N_a , and then sends $M_1: \{PID_{TS}, N_a\}$ to the reader-server unit

Step 2: Upon receiving $M_1: \{PID_{TS}, N_a\}$, the reader-server unit verifies PID_{TS} in the database if the reader-server unit does not find PID_{TS} in the database, the communication will be terminated, otherwise, the reader-server-unit reads the $CRP(C_T, R'_T), K_{TS}$ in server's database, computes $C_T^* = C_T \oplus h(K_{TS} || N_a)$. The reader-server unit decides to compute $PID'_{TS} = PID_{TS}^{new} \oplus h(ID_T || R'_T)$, the reader-server unit copies and stores PID_{TS}^{new} . The reader-server unit computes authentication code $V_0 = h(ID_T || N_a || C_T^* || PID'_{TS})$. The reader-server unit sends $M_2: \{C_T^*, PID'_{TS}, V_0\}$ to the tag.

Step 3: Upon receiving $M_2: \{C_T^*, PID'_{TS}, V_0\}$ the tag verifies V_0 , computes $C_T = C_T^* \oplus h(K_{TS} || N_a)$, generates $R'_T = PUF_T(C_T)$, computes $(k_T, hd_T) = FE.Gen(R'_T)$, $hd_T^* = hd_T \oplus h(K_{TS} || N_a)$, new challenge where $C_T^{new} =$

Fig. 2. Setup phase between Tag and Server via secure channel

$h(C_T || k_T)$, computes $R_T^{new'} = PUF_T(C_T^{new})$, $N_1 =$
 $h(k_T || K_{TS}) \oplus R_T^{new'}$, $V_A =$
 $h(ID_T || k_T || C_T^{new} || R_T^{new'} || N_1 || hd_T)$ and then the tag sends $M_3: \{V_A, N_1, hd_T^*\}$ to the server. The tag updates $K_{TS}^{new} = h(K_{TS} || k_T)$, the tag computes $PID_{TS}^{new} = PID_{TS} \oplus h(ID_T || R'_T)$ and stores $K_{TS}^{new}, PID_{TS}^{new}$.

Step 4: Upon receiving $M_3: \{V_A, N_1, hd_T^*\}$, the reader-server unit computes $hd_T^* = hd_T \oplus h(K_{TS} || N_a)$, $k_T = FE.Rec(R'_T, hd_T)$, $R_T^{new'} = h(k_T || K_{TS}) \oplus N_1$, $C_T^{new} = h(C_T || k_T)$, then verifies V_A . The reader-server computes $K_{TS}^{new} = h(K_{TS} || k_T)$, Finally, the reader-server stores $K_{TS}^{new}, PID_{TS}^{new}, (C_T^{new}, R_T^{new'})$.

F. The Solution to Resolve the Loss of Synchronization and DoS Attack.

Step 1: When desynchronization occurs, the tag replaces PID_{TS}, K_{TS} , by pid_1, k_1 .

Step 2: Run the same step with the authentication phase.

IV. ANALYSIS INFORMAL AND COMPARISON

This section presents the informal analysis using intuitive reasoning to show that our scheme achieves security features. This section also compares capabilities to withstand kinds of attacks with the previous authentication protocol by [10], [11], [12], and [13].

A. Informal Analysis

This subsection presents the security feature analysis. The details are as follows:

a. Achieve Mutual Authentication

Both parties recognize the identity of the other party by the possession of a shared key K_{TS} , The tag checks N_a , and the reader-server unit checks N_1 to ensure the freshness. Therefore, the scheme achieves mutual authentication.

b. Achieve Strong Anonymity

The tag uses a one-time Pseudonym PID_{TS} to communicate with the reader-server unit. The adversary cannot obtain the original identity. Therefore, the scheme provides anonymity.

Fig. 3. Mutual Authentication between the Tag and the Reader-server Unit

c. Achieve Perfect Forward Secrecy

In our scheme, the message updates in every session include shared key K_{TS}^{new} , challenge C_T^{new} , and response R_T^{new} . Even if the attacker obtains the current shared key K_{TS} , the attacker cannot obtain past secrets since those are deleted from memory. Therefore, the scheme achieves perfect forward.

d. Achieve Perfect Backward Secrecy

Our scheme protected challenge C_T by a shared key K_{TS} where $C_T^* = C_T \oplus h(K_{TS} || N_a)$; Even if the attacker can obtain shared key K_{TS} and R_T' , the attacker cannot obtain fixed key k_T simultaneously because of k_T generated by the FE.Gen, where FE.Gen is the probabilistic function that produces different output if the attacker inserts the same response R_T' , and then the attacker cannot compute new challenge C_T^{new} and new response R_T^{new} . Therefore, our proposed scheme achieves perfect backward secrecy.

e. Achieve Untraceability

Because of the attacker cannot compute new challenge, since the attacker cannot know the owner of the challenge based on the collected message in the public channel. Therefore, the scheme achieves untraceability.

f. Resolve the Loss of Synchronization

When desynchronization occurs, the tag replaces PID_{TS} , K_{TS} , by pid_1 , k_1 . Run the same step with the authentication phase. Therefore, the scheme can resolve the loss of synchronization.

B. Attack analysis

This subsection presents that our scheme withstands various kinds of attacks including impersonation attack, Tracking attack, and DoS attack. The details are as follows:

a. Withstand against Impersonation Attack

The attacker can't reveal the current fixed key, new challenge

TABLE IV
COMPARISON OF SECURITY FEATURES

Schemes	SF1	SF2	SF3	SF4	SF5
Asyu et al.[10]	No	No	No	Yes	No
Huth et al.[11]	No	No	No	Yes	No
Gope et al. [12]	No	No	No	Yes	Yes
Feng Zhu et al. [13]	No	No	No	Yes	Yes
Our scheme	Yes	Yes	Yes	Yes	Yes

The details of notations are SF: Security Features, SF1: Perfect Forward Secrecy, SF2: Perfect Backward Secrecy, SF3: Untraceability, SF4: Anonymity SF5: Resolve the Desynchronization problem.

and new response even if the attacker stoles and activate PUF; hence, the attacker can't impersonate the Tag. Therefore, the scheme withstands Impersonation attack.

TABLE V
COMPARISON OF ATTACK RESISTANCE

Schemes	WA1	WA2	WA3	WA4
Asyu et al.[10]	No	No	No	Yes
Huth et al.[11]	No	No	No	Yes
Gope et al. [12]	No	No	Yes	Yes
Feng Zhu et al. [13]	No	No	Yes	Yes
Our scheme	Yes	Yes	Yes	Yes

The details of notations are WA: withstand against kinds of attacks, WA1: withstand against impersonation attack, WA2: withstand against tracking attack, WA3: withstand against the DoS attack, WA4: withstand against cloning attack.

b. Withstand Tracking Attack

Because the scheme achieves untraceability, hence, our propose withstands a tracking attack.

c. Withstand against the DoS Attack

Based on the security features analysis, our scheme solves the loss of synchronization; hence automatically, our proposed scheme withstands against the DoS attack as wells.

TABLE VI
COMPARISON OF COMPUTATIONAL COMPLEXITY

Protocol	Computation		Overall
	Tag	Reader-Server unit	
Asyu et al.[10]	$3T_H + 2T_{PUF} + T_{RNG} + T_{SKE} + T_{FE.Gen}$	$3T_H + T_{RNG} + T_{SKD} + T_{FE.Rec}$	$6T_H + 2T_{PUF} + 2T_{RNG} + T_{SKE} + T_{SKD} + T_{FE.Gen} + T_{FE.Rec}$
Huth et al.[11]	$3T_H + 2T_{PUF} + T_{RNG} + T_{SKE} + T_{CBKA} + T_{FE.Gen}$	$3T_H + T_{RNG} + T_{SKD} + T_{CBKA} + T_{FE.Rec}$	$6T_H + 2T_{PUF} + 2T_{RNG} + T_{SKE} + T_{SKD} + 2T_{CBKA} + T_{FE.Gen} + T_{FE.Rec}$
Gope et al. [12]	$5T_H + 2T_{PUF} + T_{RNG} + T_{FE.Rec}$	$5T_H + T_{RNG} + T_{FE.Gen}$	$10T_H + 2T_{PUF} + 2T_{RNG} + T_{FE.Gen} + T_{FE.Rec}$
Feng Zhu et al. [13]	$4T_H + 2T_{PUF} + T_{RNG} + T_{FE.Rec}$	$5T_H + T_{RNG} + T_{FE.Gen}$	$9T_H + 2T_{PUF} + 2T_{RNG} + T_{FE.Rec} + T_{FE.Gen}$
Our scheme	$4T_H + 2T_{PUF} + T_{RNG} + T_{FE.Gen}$	$3T_H + T_{RNG} + T_{FE.Rec}$	$7T_H + 2T_{PUF} + 2T_{RNG} + T_{FE.Gen} + T_{FE.Rec}$

The details of notations are T_H : Time of the one-way hash function, T_{PUF} : Time of PUF process, and T_{RNG} : Time of Random Number Generation, T_{SKE} : Time of Symmetric Key Encryption, T_{SKD} : Time of Symmetric Key Decryption, T_{CBKA} : Time of Channel-Based of Key Agreement Operations, $T_{FE.Gen}$: Time of Fuzzy Extractor Generation, $T_{FE.Rec}$: Time of Fuzzy Extractor Reconstruction.

TABLE VII
NOTATION OF BAN LOGIC

Symbol	Explanation
$P \models X$	P believes X
$P \Delta X$	P sees X
$P \vdash X$	P said X
$P \Rightarrow X$	P has jurisdiction over X
$\#(X)$	X is fresh
$P \overset{K}{\leftrightarrow} Q$	P and Q may use the shared K to communicate
$P \ni X$	P processes or is capable of processing, formula X
$\{X\}_K$	Formula X is encrypted under the key K

TABLE VIII
POSTULATES OF BAN LOGIC

Rule	Postulate
R1 is the rule of Message-meaning	$\frac{P \models P \leftrightarrow Q, \Delta \{X\}_K}{P \models Q \mid \sim X}$
R2 is the rule of Nonce-verification	$\frac{P \models \#(X), P \models Q \mid \sim X}{P \models Q \models X}$
R3 is the rule Jurisdiction	$\frac{P \models Q \models X, P \models Q \models X}{P \models X}$
R4 is the rule of Seeing	$\frac{P \Delta (X, Y)}{P \Delta X}, R5: \frac{P \models P \leftrightarrow Q, P \Delta \{X\}_K}{P \Delta X}$
R6 is the rule of Freshness	$\frac{P \models \#(X)}{P \models \#(X, Y)}$
R7 is the rule of Belief	$\frac{P \models (X, Y)}{P \models X}$

C. Comparison

The section presents a comparison between our proposed scheme with the previous protocol authentication by [10], [11], [12], and [13] in terms of security features and the capability to resist attack. The comparison is below:

Based on table 4, [10], and [11] only achieve SF4 and does not achieve SF1-SF3, SF5. [12] and [13] do not achieve SF1-SF3, however, both of them achieve SF4 and SF5. The proposed scheme achieves all security features covering Perfect Forward Secrecy and Perfect Backward Secrecy, untraceability, Anonymity, and resolve the Desynchronization problem, represented as SF1-SF5.

Based on table 5, [10], and [11] cannot resist W1-W3 but they are resilient to W4. [12] and [13] are vulnerable against WA1 and WA2 yet withstand W3 and W4. Only our proposed scheme can withstand all kinds of attacks, namely WA1-WA4.

Table 6. presents the computational complexity of the schemes respectively. [10] has a result in overall computational complexity, namely $6T_H + 2T_{PUF} + 2T_{RNG} + T_{SKE} + T_{SKD} + T_{FE.Gen} + T_{FE.Rec}$. [11] obtains total computational complexity of $6T_H + 2T_{PUF} + 2T_{RNG} + T_{SKE} + T_{SKD} + 2T_{CBKA} + T_{FE.Gen} + T_{FE.Rec}$. [12] gets total computational complexity of $9T_H + 2T_{PUF} + 2T_{RNG} + T_{FE.Rec} + T_{FE.Gen}$. [13] gets total computational complexity of $9T_H + 2T_{PUF} + 2T_{RNG} +$

$T_{FE.Rec} + T_{FE.Gen}$. Our scheme gets total complexity of $7T_H + 2T_{PUF} + 2T_{RNG} + T_{FE.Gen} + T_{FE.Rec}$. The final result shows that our scheme is lowest than [10], [11], [12] and [13]. Therefore, our proposal is secure and more efficient, suitable, and comfortable as well as practical to be applied in the RFID environment.

V. ANALYSIS FORMALLY USING BAN LOGIC

This subsection presents an analysis formally using BAN logic as evidence that our scheme achieves secure mutual authentication.

A. Brief explanation of BAN Logic

The BAN Logic has three objects [36], namely, participants, encryption keys, and logical formulas. In this paper participants are Tag and Reader-server unit, encryption keys are K_{TS} and k_T , logical formulas are based on Table VII and VIII.

B. Proof of the scheme's formal analysis using BAN Logic

This subsection presents the formal analysis of Mutual Authentication between Tag (T) and Reader- Server Unit (RS),

starting from the idealized protocol, the assumption and goal, and protocol analysis

1) Create the idealize protocol

We create the ideal protocol and omit the first process,

a. Message

Step2: $RS \rightarrow T: C_T^*, PID_{TS}'$, V_0

Step3: $T \rightarrow RS: V_A, N_1, hd_T^*$

b. Logical Formula

Step2: $RS \rightarrow T: \{C_T^*, PID_{TS}'\}_{K_{TS}}$

Step3: $T \rightarrow RS: \{N_1, R_T^{new'}, hd_T^*\}_{k_T, K_{TS}}$

2) The assumption or goals

This subsection presents the assumptions and goals including the belief of shared keys, the belief of freshness, and trust

a. Belief of shared keys

$T| \equiv T \xleftrightarrow{K_{TS}} RS$

The Tag believes that Tag and RS using shared K_{TS}

$RS| \equiv RS \xleftrightarrow{K_{TS}} T$

The RS believes that RS and Tag using shared K_{TS}

$T| \equiv T \xleftrightarrow{k_T} RS$

The Tag believes that Tag and RS using shared k_T

$RS| \equiv RS \xleftrightarrow{k_T} T$

The RS believes that RS and the Tag using shared k_T

b. Belief of freshness

$T| \equiv \#(N_a)$

The Tag believes that N_a is fresh

$RS| \equiv \#(N_a)$

The RS believes that N_a is fresh

$RS| \equiv \#(N_1)$

The RS believes that N_1 is fresh

$T| \equiv \#(N_1)$

The Tag believe that N_1 is fresh

c. Trust

$T| \equiv RS| \equiv RS \xleftrightarrow{K_{TS}} T$

the Tag believes that RS believes using shared key K_{TS}

$T| \equiv RS| \equiv RS \xleftrightarrow{k_T} T$

the Tag believes that RS believes using shared secret k_T

3) The protocol analysis

This subsection presents the protocol analysis in mutual authentication between Tag (T) and Reader server unit (RS), starting from step 2 then step 3.

Step2: $RS \rightarrow T: \{C_T^*, PID_{TS}'\}_{K_{TS}}$

a. Message meaning

$T| \equiv RS \xleftrightarrow{K_{TS}} T, T \triangleleft (\{C_T^*, PID_{TS}'\}_{K_{TS}}, RS \xleftrightarrow{K_{TS}} T)$

$T| \equiv RS| \sim ((C_T^*, PID_{TS}'), RS \xleftrightarrow{K_{TS}} T)$

Because T believes that RS and T share a key K_{TS} , T sees that $\{C_T^*, PID_{TS}'\}_{K_{TS}}$ is encrypted by K_{TS} , T believes that RS once said (C_T^*, PID_{TS}')

b. Nonce verification

$T| \equiv RS| \sim (RS \xleftrightarrow{K_{TS}} T, (C_T^*, PID_{TS}'))$, $T| \equiv \#(N_a)$

$T| \equiv \#(N_a, (C_T^*, PID_{TS}'))$

Because T believes that RS once said (C_T^*, PID_{TS}') and T believes that N_a is fresh, T believes that the $(N_a, (C_T^*, PID_{TS}'))$ is fresh

c. Belief

$T| \equiv RS| \sim (N_a, (C_T^*, PID_{TS}')), T| \equiv \#(N_a)$

$T| \equiv RS| \equiv (N_a, (C_T^*, PID_{TS}'))$

Because T believes that RS once said $(N_a, (C_T^*, PID_{TS}'))$ and T believes that N_a is fresh, T believes that RS believes $(N_a, (C_T^*, PID_{TS}'))$

$T| \equiv RS| \equiv (N_a, (C_T^*, PID_{TS}'))$

$T| \equiv RS| \equiv ((C_T^*, PID_{TS}'))$

Because T believes that RS believes $((N_a, (C_T^*, PID_{TS}'))$, T believes that RS believes (C_T^*, PID_{TS}')

Step3: $T \rightarrow RS: \{N_1, R_T^{new'}, hd_T^*\}_{k_T, K_{TS}}$

a. Message meaning

$RS| \equiv T \xleftrightarrow{k_T, K_{TS}} RS, RS \triangleleft (\{N_1, R_T^{new'}, hd_T^*\}_{k_T, K_{TS}}, RS \xleftrightarrow{k_T, K_{TS}} T)$

$RS| \equiv T| \sim (N_1, R_T^{new'}, hd_T^*), RS \xleftrightarrow{k_T, K_{TS}} T$

Because RS believes that RS and T using shared key k_T, K_{TS} , RS sees that $\{N_1, R_T^{new'}, hd_T^*\}_{k_T, K_{TS}}$ are encrypted by k_T, K_{TS} , RS believes that T once said $(N_1, R_T^{new'}, hd_T^*)$

b. Nonce verification

$RS| \equiv T| \sim (RS \xleftrightarrow{k_T, K_{TS}} T, (N_1, R_T^{new'}, hd_T^*))$, $RS| \equiv \#(N_1)$

$RS| \equiv \#(N_1, (N_1, R_T^{new'}, hd_T^*))$

Because RS believes that T once said $((N_1, R_T^{new'}))$ and RS believes that N_1 is fresh, RS believes that the $(N_1, (N_1, R_T^{new'}, hd_T^*))$ is fresh

c. Belief

$RS| \equiv T| \sim (N_1, (N_1, R_T^{new'}, hd_T^*)), T| \equiv \#(N_1)$

$RS| \equiv T| \equiv (N_1, (N_1, R_T^{new'}, hd_T^*))$

Because RS believes that T once said $(N_1, (N_1, R_T^{new'}, hd_T^*))$ and T believes that N_1 is fresh, the RS believes that T believes $(N_1, (N_1, R_T^{new'}, hd_T^*))$

$RS| \equiv T| \equiv (N_1, (N_1, R_T^{new'}, hd_T^*))$

$RS| \equiv T| \equiv (N_1, R_T^{new'}, hd_T^*)$

Because RS believes that T believes $(N_1, (N_1, R_T^{new'}, hd_T^*))$, RS believe that T believes $(N_1, R_T^{new'}, hd_T^*)$

Based on formal analysis using the BAN logic, our proposed scheme achieved mutual authentication with evidence that upon the receiving $\{C_T^*, PID_{TS}'\}_{K_{TS}}$, the Tag obtains C_T by computing $C_T = C_T^* \oplus h(K_{TS} || N_a)$, generates R_T' with $R_T' = PUF_T(C_T)$, $(k_T, hd_T) = FE.Gen(R_T')$ verifies V_0 to ensure the message from the reader-server unit. On the other hand, the reader-server unit also authenticates the Tag with evidence; upon receiving $\{R_T^{new'}\}_{k_T, K_{TS}}$, $\{hd_T\}_{K_{TS}, N_a}$ the reader-server unit computes

```

usertype String;
hashfunction H;
const XOR:Function;
const CON:Function;
const PUF:Function;
const FEGen:Function;

macro Ctenc=XOR(Ct,H(CON(Kts,Na)));
macro PIDtsenc=XOR(PIDtsnew,H(CON(IDt,Ct)));
macro V0=H(CON(CON(CON(CON(Ct,IDt),Na),Ctenc),PIDtsenc));
macro Rt=PUF(Ct);
macro kt =FEGen(Rt);
macro hdt =FEGen(Rt);
macro Ctnew=H(CON(Ct,kt));
macro Rnew = PUF(Ctnew);
macro N1=XOR(Rnew,H(CON(Kts,kt)));
macro hdtenc=XOR(hdt,H(CON(Kts,Na)));
macro VA=H(CON(CON(CON(CON(IDt,kt),Rnew),N1),hdtenc));

protocol realistic-PUF-RFID(Reader,Tag){

role Tag{
  secret PIDts, Rt, Ct, IDt, Kts, PIDtsnew,kt;
  var Rnew;
  fresh N1, Na;
  send_1(Tag,Reader,PIDts, Na);
  rcv_2(Reader,Tag,Ctenc, PIDtsenc, V0);
  send_3(Tag,Reader,VA,N1,hdtenc);
  claim(Tag,Secret,Rnew);
  claim(Tag,Secret,kt);
  claim(Tag,Niagree);
  claim(Tag,Nisynch);
  claim(Tag,Alive);
  claim(Tag,Weakagree);
}

role Reader{
  secret PIDts, Rt, Ct, IDt, Kts, PIDtsnew,kt;
  fresh Na;
  var PIDtsnew;
  rcv_1(Tag, Reader, PIDts, Na);
  send_2(Reader,Tag,Ctenc, PIDtsenc, V0);
  rcv_3(Tag,Reader,VA,N1,hdtenc);
  claim(Reader,Secret,Ct);
  claim(Reader,Secret,kt);
  claim(Reader,Niagree);
  claim(Reader,Nisynch);
  claim(Reader,Alive);
  claim(Reader,Weakagree);
}

}

```

Fig. 4. The modeling of the proposed protocol in SPDL

$hd_T = hd_T^* \oplus h(K_{TS} || N_a)$, reconstruction k_T from R'_T, hd_T , where $k_T = FE.Rec(R'_T, hd_T)$ and the reader computes $R_T^{new'} = h(k_T || K_{TS}) \oplus N_1$, then verifies V_A to ensure the message from the Tag. Therefore, all parties recognize the identity of the other party by the possession of the shared key K_{TS}, k_T and check freshness based on N_a, N_1

VI. ANALYSIS FORMALLY USING SCYTHYR TOOL

In this article, we also use the Scyther Tool for validating our proposed protocol. The Scyther Tool is implemented in Python programming, which is used to verify the protocol security [37]. This tool also follows Delov-Yao (DY) adversary model

[38]. There are two steps to evaluate a protocol using the Scyther Tool. First, we modeled our proposed protocol using Protocol Description Language (SPDL), and the second one ran the Scyther tool to validate the protocol's security claim.

Figure 3 denotes the result of the modeling of our protocol. There are two entities in the modeling, namely a tag and reader-server. Later, the verification result for our proposed protocol is shown in figure 4. Based on figure 4, the Scyther Tool denotes that it cannot find any attacks, which proved our security claim

Scyther results : verify					
Claim				Status	Comments
realistic_PUF_RFID	Tag	realistic_PUF_RFID,Tag1	Secret PUF(H(CON(Ct,FEGen(PUF(Ct))))))	ok	No attacks within bound
		realistic_PUF_RFID,Tag2	Secret FEGen(PUF(Ct))	ok	No attacks within bound
		realistic_PUF_RFID,Tag3	Niagree	ok	No attacks within bound
		realistic_PUF_RFID,Tag4	Nisynch	ok	No attacks within bound
		realistic_PUF_RFID,Tag5	Alive	ok	No attacks within bound
		realistic_PUF_RFID,Tag6	Weakagree	ok	No attacks within bound
Reader	realistic_PUF_RFID,Reader1	Secret Ct		ok	No attacks within bound
	realistic_PUF_RFID,Reader2	Secret FEGen(PUF(Ct))		ok	No attacks within bound
	realistic_PUF_RFID,Reader3	Niagree		ok	No attacks within bound
	realistic_PUF_RFID,Reader4	Nisynch		ok	No attacks within bound
	realistic_PUF_RFID,Reader5	Alive		ok	No attacks within bound
	realistic_PUF_RFID,Reader6	Weakagree		ok	No attacks within bound
Done.					

Fig. 5. The result of verification our proposed protocol using the Scyther Tool

VII. CONCLUSION

This article proposed a new lightweight realistic PUF-based and mutual authentication scheme to improve the security features and resolve the RFID environment problem. Based on the informal analysis, our proposed scheme fulfills security features such as Mutual Authentication, Perfect Forward, and Backward Secrecy, Untraceability, Anonymity, resolve Desynchronization (SF1-SF5), and withstand various kinds of attacks (WA1-WA4). Additionally, formal analysis using BAN Logic ensures our scheme achieves mutual authentication, and analysis formally using Scyther tool denotes that our scheme withstands various kinds of attacks. On the other hand, based on the computational complexity comparison, our protocol obtains lower computational cost compared to the scheme proposed by [10], [11], [12], and [13]. Therefore, our scheme is much suitable to be applied in the RFID environment.

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