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χperbp: a Cloud-based Lightweight Mutual Authentication Protocol

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Abstract Cloud-based RFID is gaining popularity in tandem with the growth of cloud computing and the Internet of Things (IoT). The cloud-based RFID system is developed with the intent of providing real-time data that can be sent into the cloud for easy access and interpretation. The security and privacy of constrained devices in these systems is a challenging issues for many applications. To deal with this problem, we first introduce χper, as a new hardware/software friendly component that can be implemented using bitwise operations and extensively analyze its security. Next, we propose χperbp, a lightweight authentication protocol based on χper component. To evaluate the performance efficiency of our proposed scheme, we implement the χperbp scheme on an FPGA module Xilinx Kintex-7 using the hardware description language VHDL. Our security and cost analysis of the proposed protocol shows that the proposed protocol provides desired security against various attacks, at a reasonable cost. Also, formal security evaluation using BAN logic and the Scyther tool indicates its security correctness. Besides, we analyze the security of a related protocol which has been recently proposed by Fan *et al.* It is a

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cloud-based lightweight mutual authentication protocol for RFID devices in an IoT system. The authors have claimed that their scheme is secure against active and passive attacks, however, our detailed security analysis in this paper demonstrates the major drawbacks of this protocol. More precisely, the proposed attack discloses the tag's secrets efficiently. Given the tag's secrets, any other attack will be trivial.

Keywords Internet of Things · Cloud · Authentication · Lightweight cryptography.

1 Introduction

Cloud computing is growing rapidly as the next-generation platform for computation, with applications in approximately any area because of its performance, high availability, least cost, and many others. On the other hand, in recent years, the use of radio frequency identification (RFID) has increased across a range of different industries such as the retail industry, healthcare, transportation, etc. due to its inherent benefits. However, the wide distribution of RFID systems may threaten the security of both businesses and consumers. A cloud-based RFID system, as depicted in Figure 1, is typically composed of three components, namely a tag, a reader, and a cloud server. The RFID tag is typically a small device that utilizes low-power radio waves to receive, store, and transmit data to nearby readers and allows users to automatically identify and track inventory and assets. It comprises a microchip or integrated circuit (IC) with a small memory to store the object's identity and data, a small antenna, and a low-power battery(inactive tags, and passive tags have no power). The RFID reader is a scanner that has more computation and storage resources than the tag and maybe is placed in a fixed location to interrogate the tag or be mobile. The cloud server has considerable resources and in fact, it is the main processing and storage source of an RFID system.

Providing secure communication between these components is regarded as one of the main issues in RFID systems. To satisfy this goal, the authentication protocol of a tag is used in the RFID systems. An authentication protocol is a method to authenticate a remote device like an RFID tag by a reader over an insecure communication channel. Cloud-based authentication is a solution that is quick to deploy, easily managed, and supports extensive authentication methods. The most common challenge to employing an authentication protocol in such systems is that the tags typically have limited storage and computing resources to support standard cryptographic algorithms such as RSA, ECC, etc. Hence, several ultra/lightweight protocols have been proposed in the literature, e.g. RAPP [42], R^2AP [47], RCIA [28] and UMAPSS [31]. However, all those solutions have been shown to be vulnerable [5,8,37,38].

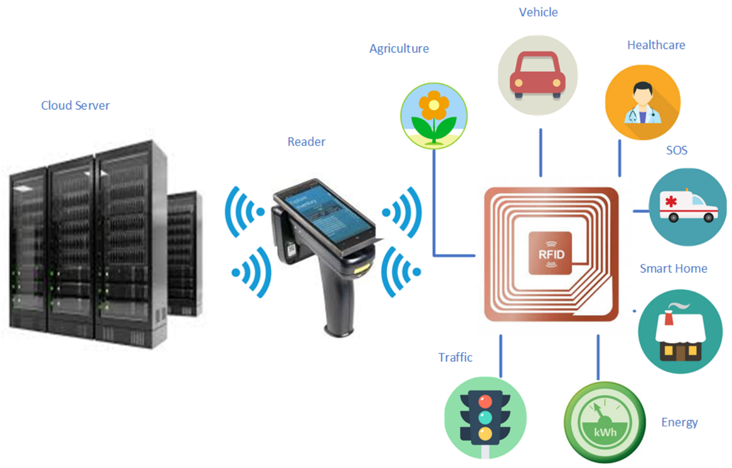


Fig. 1: A Cloud-Based RFID System

1.1 Problem statement and our contributions

The main drawback of the most compromised ultra-lightweight schemes is their cryptographic primitive which is commonly a very lightweight primitive based on bitwise operations. Recently, Fan *et al.* [22] proposed a scheme that belongs to this category and, we show that it is as insecure as its predecessors. Hence, the first challenge in designing a security solution for constrained environments, such as RFID tags and IoT edge devices, is to design an efficient and secure cryptographic primitive. To tackle this challenge, we design a new security module called χper. It is a symmetric primitive which can be used as a core to provide confidentiality in any security protocol. To ensure its security, we extensively analyzed its security properties such as differential and linear characteristics. Given such a primitive, we design a security protocol for a cloud-based RFID system. Besides that, to show the shortcoming of the previous studies, we also shed light on the security weakness of the Fan *et al.* [22] protocol. Hence, the contribution of this paper contains three main folds:

- First, to show the shortcoming of the previous works, we analyze the Fan *et al.* [22] scheme (called Timestamp-permutation) and show that the proposed scheme is vulnerable to secret disclosure attack. This attack discloses the value of ID_i and its encrypted value $E_1(ID_i)$. Given these values, an adversary can perform other known attacks such as de-synchronization, traceability, etc.
- Second, given that the main source of weakness in Fan *et al.* [22] scheme is its cryptographic primitive, we design a new security module called χper, which can be used as a security core in any symmetric protocol. Our security analysis supports its merits.

- Third, given χper, we proposed a lightweight authentication protocol(called χperbp) for IoT applications. We prove the security of the χperbp through formal and informal analysis. In the end, to evaluate the performance efficiency of our proposed scheme, we implement the χperbp scheme on an FPGA module Xilinx Kintex-7 using the hardware description language VHDL and compare the synthesis results with some lightweight schemes.

1.2 Related works

The evolution of IoT technology drives researchers to design secure and reliable authentication protocols for low-cost RFID systems. However, many challenges arise from using lightweight authentication protocols in RFID systems. For example, some of the proposed schemes are vulnerable to one or more security attacks [4, 43, 23] and some of them are inefficient in terms of processing time [36, 26].

Hoque *et al.* [25] proposed a serverless, forward-secure, and untraceable authentication protocol for RFID tags. They claimed that their scheme safeguards both tag and reader against almost all major attacks without the intervention of the server. However, Deng *et al.* [17] showed that the proposed scheme is vulnerable to de-synchronization attack. They addressed the weakness of the Hoque *et al.* scheme and proposed an improved serverless authentication scheme. In [30], Li *et al.* analyzed the Deng *et al.* scheme and pointed out that this scheme cannot resist location tracking attack, and also its tag searching method is low efficient. Tan *et al.* [41] proposed an authentication protocol that provides comparable protection against known attacks without needing a central authority. However recently, in [45], Wei *et al.* showed that the scheme is vulnerable to denial of service, de-synchronization, and tracking attacks.

In [18], Dhillon *et al.* proposed an authentication scheme for the Internet of Multimedia Things(IoMT) environments. They declared that the scheme is robust and can resist significant security attacks. However, Mahmood *et al.*[32] showed that it is vulnerable to user masquerading attacks and a stolen verifier attack. Besides, their scheme also violates the anonymity and traceability of a user.

More recently, Fan *et al.* [22] proposed a lightweight cloud-based authentication protocol called Timestamp-permutation for IoT systems. The proposed scheme uses only simple operations such as rotation, permutation, concatenation, and a symmetric encryption algorithm. Therefore, it's well suited for use in low-cost applications such as RFID systems. They claimed that the proposed scheme is secure against various known attacks, but in this paper, we show that it is vulnerable to disclosure attack. This attack can disclose the secret information stored in a tag such as the identity ID_i and its encrypted value $E_1(ID_i)$.

1.3 Paper organization

The rest of the paper is organized as follows. In section 2 we go through Fan *et al.*'s scheme and point out its security weaknesses. Next, we introduce χper in section 3, as a component that can be used in recent studies to design a security protocol for constrained environments. Using χper, we design χperbp as a security protocol for cloud-based RFID systems in section 4 and argue its security and efficiency in section 5. Finally, we conclude the paper in section 6.

2 Fan *et al.*'s protocol and its security

In this section, we give a brief description of the Timestamp-permutation protocol [22]. This protocol consists of two phases: 1-Initialization and 2-Authentication. We represent the notations used in this article in Table 1 and a brief description of the Timestamp-permutation scheme in Figure 2. The timestamps in this protocol are based on the reader's current time. Before considering this protocol, we need to introduce some definitions.

Definition 1 Let A, and B are two n-bits strings, where

$$A = a_1 a_2 ... a_n, a_i \in \{0, 1\}, i = 1, 2, ..., n$$

$$B = b_1 b_2 ... b_n, b_i \in \{0, 1\}, i = 1, 2, ..., n$$

and $C = A \oplus B$ where $C = c_1 c_2 ... c_n$, $c_i \in \{0, 1\}$, $i = 1, 2, ..., n$. Moreover, let

$$b_{k_1}, b_{k_2}, ..., b_{k_m} = 1$$

$$b_{k_{m+1}}, b_{k_{m+2}}, ..., b_{k_n} = 0$$

where $1 \leq k_1 < k_2 < ... < k_m \leq n$ and $1 \leq k_{m+1} < k_{m+2} < ... < k_n \leq n$. The function $Per(A, B)$ is defined as following:

$$Per(A, B) = c_{k_1} c_{k_2} ... c_{k_m} c_{k_n} c_{k_{n-1}} ... c_{k_{m+2}} c_{k_{m+1}}$$

Definition 2 Let $wt(B)$ is the Hamming weight [44] of B, where $0 \leq wt(B) \leq n$. The function $Rot(A, B)$ is defined as A is left routed $wt(B)$ bits.

Table 1: Notation used in this paper

Notation	**Description**
$\mathcal{T}_i$	the i-th RFID tag
$\mathcal{C}$	the cloud server
$\mathcal{R}$	the RFID reader
$\mathcal{A}$	the adversary
ID_i	the identity of $\mathcal{T}_i$
$Per(A, B)$	the permutation
$Rot(A, B)$	the rotation
$\theta()$	the obscuring the timestamp
$E_1()\backslash D_1()$	the symmetric encryption\decryption algorithm using a key shared between the readers
$E_2()\backslash D_2()$	the symmetric encryption\decryption algorithm using a key shared between the readers and cloud
$(X)_L$	the left half of X
$(X)_R$	the right half of X
$X \lll i$	rotate X left by i positions
$X \ggg i$	rotate X right by i positions
$\lfloor X \rfloor_i$	assuming $X = x_1x_2 \dots x_n$, then $\lfloor X \rfloor_i = x_{i+1} \dots x_n$
$\lceil X \rceil_i$	assuming $X = x_1x_2 \dots x_n$, then $\lceil X \rceil_i = x_1 \dots x_i$
$\bar{X}^i$	assuming $X = x_1x_2 \dots x_n$, then $\bar{X}^i = x_1 \dots x_{i-1}\bar{x}_i \dots x_n$

2.0.1 Initialization Phase

We suppose that this phase is conducted in a secure environment. This phase includes the following steps:

1. $\mathcal{T}_i$ stores timestamp T_t, the unique identity ID_i which is assigned by the system and its encryption value $E_1(ID_i)$.
2. $\mathcal{R}$ has the keys of two symmetric encryption algorithms E_1 and E_2.
3. $\mathcal{C}$ stores the encrypted value of each tag's identity and the corresponding timestamps which are followed by a bit "0" or "1". This mark bit is exploited to record which timestamp is more likely to be synchronized with the tag. $\mathcal{C}$ only has the key of the second symmetric encryption algorithm E_2.

2.0.2 Authentication Phase

1. The reader $\mathcal{R}$ generates a timestamp T_r and sends it to the tag $\mathcal{T}_i$.
2. Upon receiving T_r, the tag computes

$$M_1 = Rot(E_1(ID_i), E_1(ID_i) \oplus T_t)$$

$$M_2 = Per(M_1, E_1(ID_i) \oplus T_r)$$

and sends the messages $\{M_2, \theta(T_t), T_r\}$ to $\mathcal{R}$. Then the reader forwards the messages to $\mathcal{C}$.

3. The cloud $\mathcal{C}$ searches in its database for timestamp T_t which matches $\theta(T_t)$. Then it looks for $E_1(ID_i)$ which matches $Per(M_1, E_1(ID_i) \oplus T_r)$ in the result of the first search. If $E_1(ID_i)$ exists, two states may occur:
   - If the mark bit of T_t is "1", the timestamp marked "0" will be replaced by T_r.
   - If the mark bit of T_t is "0", the last certification may not end normally. T_r will be stored and the previous timestamps will not be deleted.

   Then $\mathcal{C}$ computes $M_3 = E_2(E_1(ID_i)\|T_t\|T_r)$ and sends it to $\mathcal{R}$.
4. $\mathcal{R}$ computes $D_2(E_1(ID_i)\|T_t\|T_r)$ to get $\{E_1(ID_i), T_t, T_r\}$. If it matches with $Per(M_1, E_1(ID_i) \oplus T_r)$ then $\mathcal{R}$ authenticates $\mathcal{C}$. Then the reader decrypts $E_1(ID_i)$ and computes $M_4 = Rot(ID_i, ID_i \oplus T_t)$, $M_5 = Per(M_4, ID_i \oplus T_r)$ and sends $(M_5)_L$ to $\mathcal{T}_i$.
5. Upon receiving, $\mathcal{T}_i$ compares $(M_5)_L$ with $(M_5')_L = (Per(M_4, ID_i \oplus T_r))_L$, if it matches, the tag authenticates the reader and replaces timestamp T_t with T_r. Then it sends $(M_5')_R = (Per(M_4, ID_i \oplus T_r))_R$ to $\mathcal{R}$.
6. If $(M_5')_R$ matches with $(M_5)_R$ then $\mathcal{R}$ authenticates $\mathcal{T}_i$ and sends $M_6 = E_2(E_1(ID_i)\|T_r)$ to $\mathcal{C}$.
7. $\mathcal{C}$ computes $E_2(E_1(ID_i)\|T_r)$ and compares it with M_6. If they matches, $\mathcal{C}$ authenticates $\mathcal{R}$ and updates its database as following:
   - Change the mark bit of timestamp T_r to "1".
   - Delete the timestamps except for T_r.

Tag $\mathcal{T}_i$		**Reader** $\mathcal{R}$		**Cloud** $\mathcal{C}$
ID_i,$E_1(ID_i)$,T_t		T_r,E_1,E_2		T_t,T_t',E_2
		Generate T_r		
	$\xleftarrow{Query,T_r}$			
$M_1 = Rot(E_1(ID_i), E_1(ID_i) \oplus T_t)$ $M_2 = Per(M_1, E_1(ID_i) \oplus T_r)$				
	$\xrightarrow[\theta(T_t),T_r]{M_2}$		$\xrightarrow[\theta(T_t),T_r]{M_2}$	
				$M_3 = E_2(E_1(ID_i) \Vert T_t \Vert T_r)$
			$\xleftarrow{M_3}$	
		decrypt M_3 to get $\{E_1(ID_i), T_t, T_r\}$ $M_2 \stackrel{?}{=} Per(M_1, E_1(ID_i) \oplus T_r)$ $M_4 = Rot(ID_i, ID_i \oplus T_t)$ $M_5 = Per(M_4, ID_i \oplus T_r)$		
	$\xleftarrow{(M_5)_L}$			
$m_4' = Rot(ID_i, ID_i \oplus T_t)$ $M_5' = Per(m_4', ID_i \oplus T_r)$ $(M_5')_L \stackrel{?}{=} (M_5)_L$ replace T_t with T_r				
	$\xrightarrow{(M_5')_R}$			
		$(M_5')_R \stackrel{?}{=} (M_5)_R$ $M_6 = E_2(E_1(ID_i) \Vert T_r)$		
			$\xrightarrow{M_6}$	
				$M_6' = E_2(E_1(ID_i) \Vert T_r)$ $M_6' \stackrel{?}{=} M_6$

Fig. 2: Timestamp-permutation protocol

2.1 Cryptanalysis of Fan *et al.* protocol

In this section, we analyze the security of the Timestamp-permutation protocol against various attacks. The proposed attacks are based on the observations below:

1. $\mathcal{T}_i$ does not contribute to the session randomness. Hence, as far as it has not updated its timestamp, its response to the identical challenge will be the same.
2. On a session of protocol between a legitimate $\mathcal{R}$ and $\mathcal{T}_i$, in Step 1, $\mathcal{R}$ generates a timestamp T_r and sends it to $\mathcal{T}_i$ and in Step 5, $\mathcal{T}_i$ stores it as a new T_t. Hence, a passive adversary $\mathcal{A}$ who monitors the transferred messages of a session over a public channel knows the next value of T_t which is used by $\mathcal{T}_i$.

3. Let $A = a_1a_2 \dots a_n$, $B = b_1b_2 \dots b_n$ and $wt(B) = w$. Given $Per(A, B) = x_1x_2 \dots x_n$, then :

$$if\ b_1 = 1 : Per(A, \bar{B}^1) = x_2 \dots x_w x_{w+1} \dots x_n \bar{x}_1$$
$$if\ b_1 = 0 : Per(A, \bar{B}^1) = \bar{x}_n x_1 x_2 \dots x_w x_{w+1} \dots x_{n-1}$$

On the other word:

$$if\ b_1 = 1 : Per(A, \bar{B}^1) = (Per(A, B) \lll 1) \oplus 1$$
$$if\ b_1 = 0 : Per(A, \bar{B}^1) = (Per(A, B) \oplus 1) \ggg 1$$

Following this property, given $Per(A, B)$ and $Per(A, \bar{B}^1)$, one can determine the value of b_1.

2.1.1 Secret disclosure attack

Following the observation 1, $\mathcal{T}_i$ does not generate any random number. Therefore, the values of T_t and $M_1 = Rot(E_1(ID), E_1(ID) \oplus T_t)$ remains unchanged until $\mathcal{T}_i$ participates in a success session with the reader. According to the observation 2, assume that $\mathcal{A}$ has eavesdropped the last successful session between $\mathcal{T}_i$ and $\mathcal{R}$ and knows the stored value T_t. Then the adversary $\mathcal{A}$ can retrieve $E_1(ID)$ as following:

1. Let $E_1(ID) = e_1e_2...e_n$ and $ID = id_1id_2...id_n$
2. $\mathcal{A}$ impersonates $\mathcal{R}$ by selecting $T_r \in \{0, 1\}^n$ and sending it to $\mathcal{T}_i$.
3. Upon receiving T_r, the tag computes M_1, M_2 and sends the messages $\{M_2, \theta(T_t), T_r\}$ to $\mathcal{R}$.

$$M_1 = Rot(E_1(ID), E_1(ID) \oplus T_t)$$

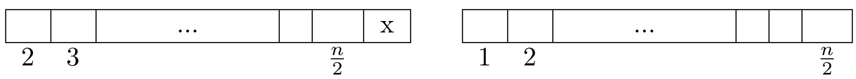
$$M_2 = Per(M_1, E_1(ID) \oplus T_r)$$

4. $\mathcal{A}$ stores M_2, and sends $\bar{T}_r^1$ to $\mathcal{T}_i$.
5. Upon receiving $\bar{T}_r^1$, the tag computes M_1 and $M_2' = Per(M_1, E_1(ID) \oplus \bar{T}_r^1)$ and returns $\{M_2', \theta(T_t), \bar{T}_r^1\}$.
6. if $M_2' = M_2 \lll 1$ then $e_1 = 1$ otherwise if $M_2' = M_2 \ggg 1$ then $e_1 = 0$.
7. Following this approach, given the value of $\lceil E_1(ID) \rceil_{i-1}$, $\mathcal{A}$ determines e_i as follows:
   (a) $\mathcal{A}$ impersonates the reader by selecting $T_r \in \{0, 1\}^n$ such that $\lceil T_r \rceil_{i-1} \oplus \lceil E_1(ID) \rceil_{i-1} = \{1\}^{i-1}$ and sending it to $\mathcal{T}_i$.
   (b) Upon receiving T_r, the tag computes M_1 and $M_2 = Per(M_1, E_1(ID) \oplus T_r)$ and returns $\{M_2, \theta(T_t), T_r\}$ to the expected $\mathcal{R}$.
   (c) $\mathcal{A}$ stores M_2, and sends $\bar{T}_r^i$ to $\mathcal{T}_i$.
   (d) Upon receiving $\bar{T}_r^i$, the tag computes M_1 and $M_2' = Per(M_1, E_1(ID) \oplus \bar{T}_r^i)$ and returns $\{M_2', \theta(T_t), \bar{T}_r^i\}$ to $\mathcal{R}$, which is indeed $\mathcal{A}$.

(e) if $\lfloor M_2' \rfloor_{i-1} = (\lfloor M_2 \rfloor_{i-1} \lll 1) \oplus 1$ then $e_i = 1$ otherwise if $\lfloor M_2' \rfloor_{i-1} = (\lfloor M_2 \rfloor_{i-1} \oplus 1) \ggg 1$ then $e_i = 0$.

In the following, we describe how an adversary $\mathcal{A}$ can retrieve the whole bits of ID.

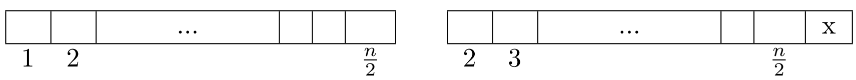
1. $\mathcal{A}$ eavesdrops N information sessions of the protocol between $\mathcal{T}_i$ and legitimate $\mathcal{R}$ and blocks the response message $(M_5)_L$. Hence, the T_t is not updated and the adversary $\mathcal{A}$ has $\{T_r^j, T_t, E_1(ID), M_2^j, (M_5^j)_L\}_{j=1}^{j=N}$, where
$$M_5^j = Per(Rot(ID, ID \oplus T_t), ID \oplus T_r^j) \tag{1}$$
2. Given $(M_5)_L$, T_t and T_r, the only unknown value in Equation 1 is the ID's bits. To simplify the index formulation, we remove the indices r, *5* and L for T_r and $(M_5)_L$ respectively. Let
$$T = t_1 t_2 ... t_n \ \ and \ \ \mathbb{T} = \{T_1, ..., T_N\}$$
$$M = m_1 m_2 ... m_{\frac{n}{2}} \ \ and \ \ \mathbb{M} = \{M_1, ..., M_N\}$$
Hence, $\mathcal{A}$ can find the ID's bits as following:
   - Suppose that the LSB bit of the $\mathbb{T}_1^1 = \{T_{k_1}, ..., T_{k_{l_1}}\}$ is "1" and the LSB bit of the $\mathbb{T}_1^0 = \{T_{k_{l_1+1}}, ..., T_{k_N}\}$ is "0". We know that the LSB bit of the values $Rot(ID, ID \oplus T_t)$ and ID are fixed, therefore if the LSB bit of $\mathbb{M}_1^1 = \{M_{k_1}, ..., M_{k_{l_1}}\}$ all are the same or the LSB bit $\mathbb{M}_1^0 = \{M_{k_{l_1+1}}, ..., M_{k_N}\}$ are not the same, then we conclude that the $id_1 = 0$, otherwise the $id_1 = 1$.
   Given $t_1 \oplus id_1$, there are only two possible bit positions in M that can be occupied due to $t_2 \oplus id_2$. To make the process easier to understand, we modify the elements of the set $\mathbb{M}$ as the following:
     - If $id_1 = 0$ then we shift the elements of the set $\mathbb{M}_1^1 = \{M_{k_1}, ..., M_{k_{l_1}}\}$ one position to the left and put an indicator "x" into their MSB.



(a) Elements of the set $\mathbb{M}_1^1$ (b) Elements of the set $\mathbb{M}_1^0$

Fig. 3: Case $id_1 = 0$

     - Otherwise, if $id_1 = 1$, we do that for elements of the set $\mathbb{M}_1^0 = \{M_{k_{l_1+1}}, ..., M_{k_N}\}$.



(a) Elements of the set $\mathbb{M}_1^1$ (b) Elements of the set $\mathbb{M}_1^0$

Fig. 4: Case $id_1 = 1$

We remain the name of elements of the set $\mathbb{M}$ unchanged after this modification.

- Let assume that the the second bit of the $\mathbb{T}_2^1 = \{T_{k'_1}, ..., T_{k'_{l_2}}\}$ is "1" and the second bit of the $\mathbb{T}_2^0 = \{T_{k'_{l_2+1}}, ..., T_{k'_N}\}$ is "0". Given that second bit of the values $Rot(ID, ID \oplus T_t)$ and ID are fixed, therefore if the LSB bit of $\{M_{k'_1}, ..., M_{k'_{l_2}}\}$ all are the same or the LSB bit $\{M_{k'_{l_2+1}}, ..., M_{k'_N}\}$ are not the same, then we conclude that the $id_2 = 0$, otherwise the $id_2 = 1$. Similarly, if $id_2 = 0$ then we shift the elements of the set $\mathbb{M}_2^1 = \{M_{k'_1}, ..., M_{k'_{l_2}}\}$ one position to the left and put an indicator "x" into their MSB. Otherwise, if $id_2 = 1$ we do that for elements of the set $\mathbb{M}_2^0 = \{M_{k'_{l_2+1}}, ..., M_{k'_N}\}$. We remain the name of elements of the set $\mathbb{M}$ unchanged after this modification.
- We continue this method until the left half bits of the ID are determined(because according to the Timestamp-permutation protocol, we only have the left half of the M_5). To determine the half-right bits, we remove the M_js from the set $\mathbb{M}$ which the whole of bit positions are occupied with "x" and replace them with new session information $(M_5)_L$s. On average we expect to still have $\frac{N}{2}$ of Ms in the set $\mathbb{M}$ where we are determining the value of id_n.

Given ID and $E_1(ID)$, any other attacks such as tag/reader impersonation attack, traceability attack, de-synchronization attack, and so on will be trivial.

Algorithm 1: Disclosure attack algorithm to find the encrypted value $E_1(ID)$

Data: Timestamp T_r

Result: The encrypted value $E_1(ID) = e_1 e_2 ... e_n$

Select T_r ;

Send T_r and $\bar{T}_r^1$ to $\mathcal{T}_i$ and store its response M_2 and M'_2 respectively;

if $(M'_2 = (M_2 \lll 1) \oplus 1)$ **then**

  $e_1 = 1$;

else

  $e_1 = 0$;

for *i=2 to 128* **do**

  Select $T_r \in \{0,1\}^n$ such that $\lceil T_r \rceil_{i-1} \oplus \lceil (E_1(ID) \rceil_{i-1} = \{1\}^{i-1}$ and send it and $\bar{T_r}^i$ to $\mathcal{T}_i$;

  if $(\lfloor M'_2 \rfloor_{i-1} = (\lfloor M_2 \rfloor_{i-1} \lll 1) \oplus 1)$ **then**

    $e_i = 1$;

  else

    $e_i = 0$;

Algorithm 2: Disclosure attack algorithm to find the identity ID

Data: Timestamp $T_r, (M_5)_L$
Result: The identity $ID = id_1 id_2 ... id_n$

Eavesdrop $\{(T_r^j, (M_5^j)_L)\}_{j=1}^{j=N}$;
for *i=1 to* $\frac{n}{2}$ **do**
  Construct the sets $(\mathbb{T}_i^1, \mathbb{M}_i^1)$,$(\mathbb{T}_i^0, \mathbb{M}_i^0)$;
  if *(the LSB bits of* $\mathbb{M}_i^1$ *all are the same or the LSB bits of* $\mathbb{M}_i^0$ *are not the same)* **then**
    $id_i = 0$;
    shift the elements of the set $\mathbb{M}_i^1$ one position to the left ;
  else
    $id_i = 1$;
    shift the elements of the set $\mathbb{M}_i^0$ one position to the left ;

3 χperbp, a lightweight cryptographic module

The main drawback of the Fan *et al.* [22] scheme which leads to the disclosure attack, is the lack of a nonlinear function. Hence, it can not provide enough confusion, as a criterion to design a secure primitive. Following Shannon's idea, any secure primitive should provide confusion and diffusion [6]. However, the proposed $Per(Rot(.))$ function only provides diffusion property. To add the confusion property into the previous scheme, we use a nonlinear function χ which is used in the Keccak [9] algorithm in our improved scheme. Keccak was standardized as SHA-3 hash function by NIST. χ function is an adjustable permutation for any odd value and we use a variant with 3 bits of input-output. Using this nonlinear component, we introduce $\chi per(A, B) : \{0,1\}^{3w} \times \{0,1\}^{3w} \rightarrow \{0,1\}^{3w}$, as depicted in Figure 6, where each variable consist of 3 words and w denotes a word length. One can also consider the $\chi per(.)$ function as three layers. Add-key, Non-linear (it is described with three AND and three XOR operations), and Mix-shift layers, according to the general structures of symmetric ciphers (see Figure 6). We can use $\chi per(.)$ to design a general cipher (function) called $\chi per^z(.)$. Algorithm 3 describes $\chi per^z(.)$, which includes z call to $\chi per(.)$. Here, z shows the number of rounds of the cipher. The variables z and w provide a trade-off between efficiency and security. Our recommendations for w and z are $w = 32$ and $z \geq 16$. $\chi per^z(.)$ is strong and immune against both linear and differential cryptanalysis attacks and has a sufficient margin of defense against these attacks. In Appendix A, the security of $\chi per^z(.)$ function has been investigated against several known attacks. In addition, $\chi per^z(.)$ offers excellent performance on hardware and software platforms as will be described in subsection 5.4. Now, we can propose a lightweight protocol based on the $\chi per^z(.)$ cipher.

4 χperbp: a χper based authentication protocol

Given $\chi per^z(.)$, we design a lightweight protocol and call it χperbp, stands for χper based protocol.

4.1 Initialization Phase of χperbp

This phase of the improved protocol includes the following steps:

1. $\mathcal{T}_i$ stores the timestamp T_t, the unique identity ID_i which is assigned by the system, and its secret key value K_i, shared by $\mathcal{C}$. We also assume that each tag is equipped with a $\chi per^z(.)$ function.
2. $\mathcal{R}$ has its identifier RID and its key K_r, shared with $\mathcal{C}$. The reader is equipped with $\chi per^z(.)$, a 48-bit $PRNG(.)$ and a secure hash function $H(.)$, e.g., PHOTON [24].
3. $\mathcal{C}$ stores the key and the identifier of $\mathcal{R}$ and $\mathcal{T}_i$.

4.2 Authentication Phase of χperbp

The authentication phase of χperbp is defined as below:

1. The reader $\mathcal{R}$ generates a random number R_r and sends it to the tag $\mathcal{T}_i$.
2. Upon receiving R_r, the tag computes two values $R_t = \chi per^z((T_t \| R_r), K_i)$ and $M_t = \chi per^z(ID_i \oplus (R_r \| (R_t)_R), K_i)$ and then sends the messages $\{M_t, (R_t)_R\}$ to $\mathcal{R}$. Afterward, it replaces the value T_t with $(R_t)_L$ and stores it in its local memory.
3. The reader $\mathcal{R}$ extracts its timestamp T_r and computes $MAC_r = H(M_t \| (R_t)_R \| R_r \| K_r \| T_r \| RID)$. Then it sends $\{M_t, (R_t)_R, R_r, T_r, MAC_r\}$ to $\mathcal{C}$.
4. The cloud $\mathcal{C}$ checks timestamp T_r to make sure it's in a reasonable delay time and searches in its database for the RID, based on the received MAC_r to authenticate the reader $\mathcal{R}$. Then, it searches in its database for a record of a tag that is matched to M_t to authenticate the tag $\mathcal{T}_i$. Next, $\mathcal{C}$ extracts its timestamp T_c, computes $M_c = \chi per^z(ID_i, K_i \oplus (T_c \| (R_t)_R))$, $DI_i = ID_i \oplus RID \oplus \chi per^z(T_c \| T_r, K_r)$ and $MAC_c = H(M_c \| M_t \| R_r \| (R_t)_R \| RID \| ID_i \| T_c)$ and sends $\{MAC_c, DI_i, M_c, T_c\}$ to $\mathcal{R}$.
5. $\mathcal{R}$ extracts the value ID_i from DI_i and verifies the received T_c and MAC_c to authenticate $\mathcal{C}$ and $\mathcal{T}_i$. Then, it computes $M_r = \chi per^z(M_t \oplus M_c, ID_i)$ and sends $\{M_c, M_r, T_c\}$ to $\mathcal{T}_i$.
6. Once received the message, $\mathcal{T}_i$ verifies whether $M_c \stackrel{?}{=} \chi per^z(ID_i, K_i \oplus (T_c \| (R_t)_R))$ to authenticate $\mathcal{C}$. Then it authenticates the reader $\mathcal{R}$ using M_r.

Tag $\mathcal{T}_i$		**Reader** $\mathcal{R}$		**Cloud** $\mathcal{C}$
ID_i,K_i,T_t		RID,K_r		ID_i,K_i,RID,K_r
		Generate R_r		
	$\xleftarrow{Query,R_r}$			
$R_t = \chi per^z((T_t \| R_r), K_i)$ $M_t = \chi per^z(ID_i \oplus (R_r \| (R_t)_R), K_i)$ Replace T_t with $(R_t)_L$				
	$\xrightarrow{M_t,(R_t)_R}$	Extract T_r $MAC_r = H(M_t \| (R_t)_R \| R_r \| K_r \| T_r \| RID)$		
			$\xrightarrow[M_t,R_r,(R_t)_R]{MAC_r,T_r}$	Verify T_r Authenticate $\mathcal{R}$ based on MAC_r Authenticate $\mathcal{T}_i$ based on M_t Extract T_c $M_c = \chi per^z(ID_i, K_i \oplus (T_c \| (R_t)_R))$ $MAC_c = H(M_c \| M_t \| R_r \| (R_t)_R \| RID \| ID_i \| T_c)$ $DI_i = ID_i \oplus RID \oplus \chi per^z(T_c \| T_r, K_r)$
		Verify T_c and extract ID_i Verify MAC_c, authenticate $\mathcal{C}$ and $\mathcal{T}_i$ $M_r = \chi per^z(M_t \oplus M_c, ID_i)$	$\xleftarrow[T_c,M_c]{MAC_c,DI_i}$	
	$\xleftarrow[M_r]{T_c,M_c}$			
Verify M_c and M_r Authenticate $\mathcal{C}$ based on M_c Authenticate $\mathcal{T}_i$ based on M_r				

Fig. 5: Illustration of the authentication phase of χperbp

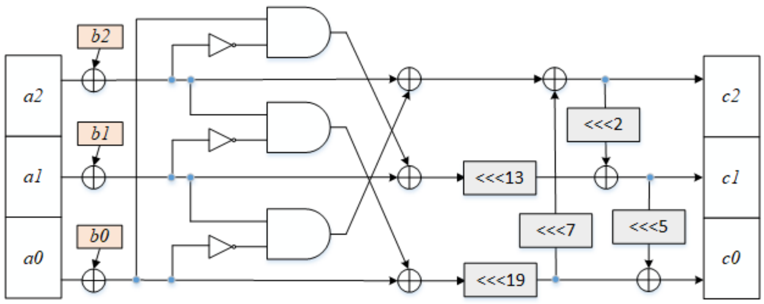


Fig. 6: $C = \chi per(A, B)$

Algorithm 3: $\chi per^z(A, B)$ based on $\chi per(A, B)$

Data: $A = a_0 \| a_1 \| a_2$ and $B = b_0 \| b_1 \| b_2$

Result: $\chi per^z(A, B)$

for *i=0 to 2* **do**

  $x_{i,0} = a_i$ and $y_{i,0} = b_i$;

for *i=0 to z-1* **do**

  $X_i = x_{0,i} \| x_{1,i} \| x_{2,i}$, $Y_i = y_{0,i} \| y_{1,i} \| y_{2,i}$;

  $X_{i+1} \leftarrow \chi per(X_i, Y_i)$;

  $Y_{i+1} \leftarrow (Y_i \lll 95) \oplus 0x243f6a8823ac08e1cb7a0379$;

Return X_z.

5 Security Analysis of the χperbp Protocol

In this section, firstly we analyze the informal security of our proposed scheme against the attacks proposed in this paper, and then, using formal security analysis under the broadly-accepted Burrows-Abadi-Needham (BAN) logic and an automated security analysis tool Scyther, we show that the χperbp protocol is secure against various known attacks. At the end of this section, we show the security comparison of the improved scheme with some relevant schemes in Table 4.

5.1 Informal security analysis

5.1.1 Replay attack

In this attack, an adversary tries to eavesdrop on some communication information and resend them to the tag, reader, or server at another time. In the improved scheme χperbp, we use two random numbers R_t, R_r along with two timestamps T_r, T_c for each session to prevent the replay attack.

5.1.2 Impersonation attack

Assume an adversary tries to impersonate himself/herself as a legal tag to a cloud server. He/she is not able to produce a valid request message M_t because the adversary needs to know the user's identity ID_i and shared password key K_i between the tag and the cloud. Also, the adversary cannot impersonate himself/herself as a legal cloud server because he/she is not able to produce M_c. Therefore the χperbp scheme is secure against impersonating attacks.

5.1.3 Traceability and anonymity

In χperbp scheme, all transferred messages between three parties tag, reader, and the cloud server include at least one of the random numbers R_t, R_r or timestamps T_r, T_c which are updated in each session. Therefore an adversary cannot trace a particular tag since the tag's responses to a fixed query are always different at the valid sessions.

5.1.4 Secret disclosure attack

The weakness of the Fan *et al.* scheme that deals with disclosure attack is the lack of a nonlinear function. In χperbp scheme, we use $\chi per^z(.)$ function which satisfies the confusion property significantly. Therefore, an adversary cannot carry out a disclosure attack as described in subsection 2.1.

5.1.5 De-synchronization attack

In χperbp scheme, we use two timestamps T_r and T_c to synchronize the reader and cloud. The T_r value concatenates with $\{M_t, (R_t)_R, R_r, K_r, RID\}$ and the T_c value concatenates with $\{M_c, M_t, R_r, (R_t)_R, RID, ID_i\}$, then both of them are hashed. Therefore the attacker can not change the values T_r and T_c, because he/she must compute the MAC_r and MAC_c, but he/she doesn't know the values of the ID_i, RID, and K_r.

5.1.6 A man-in-the-middle attack

The communications between the reader and the cloud are hashed, therefore if the attacker intercepts the messages $\{T_r, M_t, R_r, (R_t)_R\}$ or $\{DI_i, T_c, M_c\}$, he/she cannot compute the MAC_r and MAC_c because he/she doesn't know the values of the ID_i, RID and K_r. Also, the tag verifies the received messages with χper function, so the χperbp is secure against a man-in-the-middle attack.

5.1.7 Ephemeral secret leakage attack

Suppose that an adversary obtain the random number R_r and, T_t. He/she cannot disclose the secret key K_i from the messages R_t and M_t, because the χper is a secure cryptographic primitive. Also, $(T_c \| T_r)$ is encrypted with the secret key K_r. Therefore an adversary cannot disclose K_r when he/she obtains T_c and T_r. Therefore, χperbp scheme is secure against an ephemeral secret leakage attack.

5.1.8 Stolen verifier attack

There are two cases: First, if an adversary steals the RID that is stored in the reader, he/she cannot masquerade as a legitimate user in a user authentication execution, because the messages are encrypted by K_r and K_i. Therefore the χperbp is secure against a stolen verifier attack. Second, suppose an adversary steals verification data ID_i and RID stored in the cloud server. In that case, he/she can not impersonate him/herself as a legitimate user, because he/she doesn't have the secret key K_i. In this case, χperbp is secure against a stolen verifier attack.

5.2 Formal security analysis using BAN logic

To correctly evaluate the χperbp scheme, we use BAN Logic [13] proposed by Burrows, Abadi, and Needham. The BAN logic provides a formal method for reasoning about the beliefs of principals in cryptographic protocols. From a practical viewpoint, the analysis of a protocol is performed as follows:

- Transform message into an idealized logical formula
- State assumptions about the original message
- Make annotated idealized protocols for each protocol statement with assertions
- Apply logical rules to assumptions and assertions
- Deduce beliefs held at the end of the protocol

We present the notations and rules used in BAN logic proof in Table 2 and Table 3. The steps of our formal security analysis are as follows:

Table 2: BAN logic notations

Notation	Description
$A\| \equiv X$	A believes X
$A \triangleleft X$	A receives X
$A\| \sim X$	A sends X
$\#(X)$	X is fresh
$A \overset{k}{\leftrightarrow} B$	A and B have a shared secret k
$\{X\}_k$	X is encrypted by the secret key k
$A\| \Rightarrow X$	A regulates X
$< X >_k$	X is exclusive OR-ed with k
$H(X)$	Hash of X

Table 3: BAN logic rules

Rule	Description
$R1 : \frac{A\|\equiv A \overset{k}{\leftrightarrow} B, A \triangleleft \{X\}_k}{A\|\equiv B\|\sim X}$	A believes that B has sent X to him/her when A believes that he/she shared key k with B and received the encrypted message $\{X\}_k$
$R2 : \frac{A\|\equiv B\|\sim H(X), A \triangleleft X}{A\|\equiv B\|\sim X}$	A believes that B has sent X to him/her when A believes that B has sent hashed value $H(X)$
$R3 : \frac{A\|\equiv B\|\sim (X,Y)}{A\|\equiv B\|\sim X}$	A believes that X has been sent by B when he/she believes B has sent (X,Y)
$R4 : \frac{A\|\equiv \#(X)}{A\|\equiv \#(X,Y)}$	A believes that if X is fresh then (X,Y) is fresh

- **Step 1. All transmitted messages of the protocol**: In this step, we list all transmitted messages of the χperbp scheme as below:
  $M1 : \mathcal{R} \rightarrow \mathcal{T}_i : R_r, Query.$
  $M2 : \mathcal{T}_i \rightarrow \mathcal{R} : (R_t)_R = \chi per^z((T_t\|R_r), K_i), M_t = \chi per^z(ID_i \oplus (R_r\|(R_t)_R), K_i).$
  $M3 : \mathcal{R} \rightarrow \mathcal{C} : MAC_r = H(M_t\|(R_t)_R\|R_r\|K_r\|T_r\|RID), M_t, R_r, (R_t)_R, T_r.$
  $M4 : \mathcal{C} \rightarrow \mathcal{R} : M_c = \chi per^z(ID_i, K_i \oplus (T_c\|(R_t)_R)), MAC_c = H(M_c\|M_t\|R_r \|(R_t)_R\|RID\|ID_i\|T_c), DI_i = ID_i \oplus RID \oplus \chi per^z(T_c\|T_r, K_r), T_c.$
  $M5 : \mathcal{R} \rightarrow \mathcal{T}_i : M_c, M_r = \chi per^z(M_t \oplus M_c, ID_i), T_c.$
- **Step 2. Idealizing the messages of the protocol**: In this step, using the BAN logic notations, we express the idealized form of the messages in the previous step.
  $IM1 : \mathcal{T}_i \triangleleft R_r, Query.$
  $IM2 : \mathcal{R} \triangleleft \{(R_t)_R, M_t\}_{K_i}.$

$IM3 : \mathcal{C} \triangleleft H(M_t, (R_t)_R, R_r, K_r, T_r, RID), \{M_t, (R_t)_R\}_{K_i}, T_r, R_r.$
$IM4 : \mathcal{R} \triangleleft \{M_c\}_{K_i}, \{DI_i\}_{K_r}, H(M_c, M_t, R_r, (R_t)_R, RID, T_c, ID_i), T_c.$
$IM5 : \mathcal{T}_i \triangleleft \{M_c\}_{K_i}, \{M_r\}_{ID_i}, T_c.$

- **Step 3. Explicit assumptions**: The explicit assumptions of the χperbp scheme are listed as following:
  $A1 : \mathcal{R}| \equiv \#(R_r).$
  $A2 : \mathcal{T}_i| \equiv \#(R_t).$
  $A3 : \mathcal{R}| \equiv \#(T_r).$
  $A4 : \mathcal{C}| \equiv \#(T_c).$
  $A5 : \mathcal{T}_i| \equiv \mathcal{T}_i \overset{K_i}{\longleftrightarrow} \mathcal{C}.$
  $A6 : \mathcal{C}| \equiv \mathcal{C} \overset{K_i}{\longleftrightarrow} \mathcal{T}_i.$
  $A7 : \mathcal{R}| \equiv \mathcal{R} \overset{K_r}{\longleftrightarrow} \mathcal{C}.$
  $A8 : \mathcal{C}| \equiv \mathcal{C} \overset{K_r}{\longleftrightarrow} \mathcal{R}.$

- **Step 4. Security goals of the protocol**: The security goals that the χperbp scheme must meet are as follows:
  $G1 : \mathcal{C}| \equiv \mathcal{T}_i| \sim ID_i.$
  $G2 : \mathcal{C}| \equiv \mathcal{R}| \sim RID.$
  $G3 : \mathcal{R}| \equiv \mathcal{C}| \sim RID.$
  $G4 : \mathcal{R}| \equiv \mathcal{C}| \sim ID_i.$
  $G5 : \mathcal{T}_i| \equiv \mathcal{C}| \sim ID_i.$
  $G6 : \mathcal{T}_i| \equiv \mathcal{R}| \sim ID_i.$

- **Step 5. Proving the security goals of the protocol**:
  *Result*1: According to $M2$ and $M3$, we have $IM2$ and $IM3$ respectively. Based on $A3$, $\mathcal{C}$ checks T_r to prevent a replay attack. Next, according to $H(M_t, (R_t)_R, R_r, K_r, T_r, RID)$, $\mathcal{C}$ authenticates $\mathcal{R}$, and according to assumption $A5$ and the message $\{M_t, (R_t)_R\}_{K_i}$, $\mathcal{C}$ authenticates $\mathcal{T}_i$. According to $A6$, only $\mathcal{C}$ and $\mathcal{T}_i$ are able to compute the message $M_t = \chi per^z(ID_i \oplus (R_r \| (R_t)_R), K_i)$. Therefore, based on rule $R1$, we deduce the goal $G1$.
  *Result*2: According to message $M3$, we have $IM3$. Based on the assumption $A8$, the reader $\mathcal{R}$ and the cloud $\mathcal{C}$ can only compute the message $H(M_t, (R_t)_R, R_r, K_r, T_r, RID)$. Therefore, based on the rule $R2$, the goal $G2$ is proved.
  *Result*3: $\mathcal{C}$ sends message $M4$ to $\mathcal{R}$. According to assumption $A4$, the reader $\mathcal{R}$ thwarts a replay attack. According to $A7$, the reader extracts RID from DI_i and verifies it by using MAC_c. Therefore, based on the rule $R2$, we prove the goal $G3$.
  *Result*4: According to assumption $A4$, the reader $\mathcal{R}$ checks T_c to prevent replay attack. According to the $IM4$ and $A7$, only the reader $\mathcal{R}$ can compute $\chi per^z(T_c \| T_r, K_r)$ and extract the value ID_i from DI_i. Therefore, based on the rules $R1$, $R2$ and $R3$, the goal $G4$ is proved.
  *Result*5: Given the $IM5$, and the assumption $A5$, The tag $\mathcal{T}_i$ can compute $\chi per^z(ID_i, K_i \oplus (T_c \| (R_t)_R))$ and verify it with M_c. Therefore, based on

the rule $R1$, we prove the goal $G5$.
Result6: According to $IM5$, the tag $\mathcal{T}_i$ checks T_c to prevent a replay attack. It computes $\chi per^z(M_t \oplus M_c, ID_i)$ and verifies it with M_r. Therefore, based on the rules $R1$ and $R3$, the goal $G6$ is proved.

5.3 Automated verification through Scyther tool

We use Scyther tool [14] to verify the correctness and security of the χperbp scheme. Scyther is an automated security protocol analysis tool under the perfect cryptography assumption, in which it is assumed that the adversary learns nothing from the encrypted or hashed data. We describe the specification of a security protocol by a set of roles such as the tag's role, reader's role, and server's role. Roles are defined by a sequence of events such as sending or receiving of terms. Scyther's input language is SPDL, therefore we write χperbp scheme in SPDL language as depicted in Appendix B. To learn more about the Scyther tool and SPDL language, we refer the reader to [15,14]. Report of Scyther tool, as depicted in Figure 7, shows that the χperbp scheme is secure against known attacks.

Table 4: Security comparison

	SDA	ImA	DeA	RA	TA	FBSA	MIMA	AA
Ref [3]	✓	✓	✓	✓	×	×	✓	✓
Ref [34]	✓	✓	✓	✓	×	×	×	×
Ref [20]	×	×	✓	✓	×	✓	✓	✓
Ref [21]	×	×	×	✓	✓	✓	✓	×
Ref [22]	×	×	×	×	×	×	×	×
χperbp	✓	✓	✓	✓	✓	✓	✓	✓

SDA : secret disclosure attack
ImA : impersonation attack
DeA : de-synchronization attack
RA : replay attack
TA : traceability attack
FBSA : forward-backward security attack
MIMA : man-in-middle attack
AA : anonymity attack

Improved	Tag	Improved,Tag1	Secret IDi	Ok	No attacks within bounds.
		Improved,Tag2	Secret Ki	Ok	No attacks within bounds.
		Improved,Tag3	Niagree	Ok	No attacks within bounds.
		Improved,Tag4	Nisynch	Ok	No attacks within bounds.
		Improved,Tag5	Alive	Ok	No attacks within bounds.
		Improved,Tag6	Weakagree	Ok	No attacks within bounds.
	Reader	Improved,Reader1	Secret IDi	Ok	No attacks within bounds.
		Improved,Reader2	Secret Kr	Ok	No attacks within bounds.
		Improved,Reader3	Secret RID	Ok	No attacks within bounds.
		Improved,Reader4	Niagree	Ok	No attacks within bounds.
		Improved,Reader5	Nisynch	Ok	No attacks within bounds.
		Improved,Reader6	Alive	Ok	No attacks within bounds.
		Improved,Reader7	Weakagree	Ok	No attacks within bounds.
	CloudServer	Improved,CloudServer1	Secret IDi	Ok	No attacks within bounds.
		Improved,CloudServer2	Secret Ki	Ok	No attacks within bounds.
		Improved,CloudServer3	Secret Kr	Ok	No attacks within bounds.
		Improved,CloudServer4	Secret RID	Ok	No attacks within bounds.
		Improved,CloudServer5	Niagree	Ok	No attacks within bounds.

Done.

Fig. 7: Scyther tool results

5.4 Performance analysis

The χperbp scheme uses two main security functions: the $\chi per^z(.)$ function and a hash function. In the tag side, which has limited resources, the $\chi per^z(.)$ function only needs to be implemented. We implement the $\chi per^z(.)$ function on the FPGA module Xilinx Kintex-7 [1] using the hardware description language VHDL [7]. Synthesis and simulation of the HDL code are executed using Vivado v2018.3 [2]. As mentioned in section 3, security and performance of the $\chi per^z(.)$ function depend on the two parameters w and z. We recommend $w = 32$ and $z \geq 16$, therefore, based on these values, we calculate the throughput, *tp*, and the throughput-area ratio, *tp-area* of the $\chi per^z(.)$ algorithm by the following formula:

$$tp = \frac{Block\, size}{Cycles\, per\, block} \times Frequency(Mhz)$$

$$tp\text{-}area = \frac{tp}{Slice\, LUTs}$$

The throughput and implementation cost comparison of the $\chi per^z(.)$ function with some lightweight encryption functions which are used in the lightweight authentication schemes is shown in Table 5. Furthermore, we also implement the $Per(Rot(.))$ function which acts as a major function in the Timestamp-permutation protocol.

As shown in Table 5, the device utilization of the simulation after synthesis of the $\chi per^z(.)$ is 460 look-up-tables (LUTs) and its clock rate (frequency) is 680(Mhz). Moreover, $\chi per^z(.)$ function has the highest $tp/area$ which shows that it is more lightweight than the others.

An RTL schematic of the $\chi per(.)$ function is depicted in Figure 8. In this figure, the $\chi per(.)$ function is represented in terms of logic gates such as AND, NAND, and OR. In this diagram, 96-bit plaintext ($A = a1\|a2\|a3$) and 96-bit secret key ($B = b1\|b2\|b3$) are inputs, and 96-bit C is the output.

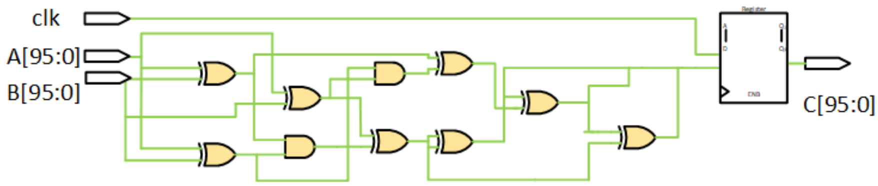


Fig. 8: Logic diagram of the synthesized $\chi per(.)$ function

Table 5: Throughput and implementation cost for various functions [19][27]

Function	Area (LUT)	Frequency (Mhz)	Throughput (Mbps)	Throughput/Area (Mbps/LUT)
SIMON-96	435	564	1041	2.39
SPECK-96	452	473	1622	3.59
PRESENT-80	311	542	1084	3.49
Blake	251	211	477	1.90
Keccak	393	159	864	2.19
Per(Rot(.))-80	904	244	81	0.08
$\chi per^z(.)$-96	460	680	10880	23.65

6 Conclusion

In this paper, we analyzed the Timestamp-permutation protocol proposed by Fan *et al.* for IoT applications and showed that their scheme is vulnerable to disclosure attack. This attack can disclose all the secret information stored on a tag such as the identity of the tag ID_i and its encryption value $E_1(ID_i)$. This attack is practical because it requires at most 128 session information. These values can be used for other attacks such as impersonate attack, desynchronization attack, replay attack and etc. The permutation function used in the Timestamp-permutation scheme has not had good confusion properties and this weakness lead to the disclosure attack. To address this vulnerability, we use a nonlinear function called $\chi per^z(.)$ and redesign the Timestamp-permutation scheme. We implement the $\chi per^z(.)$ function on a Xilinx Kintex-7 FPGA using VHDL language and compare the implementation cost with some lightweight encryption functions. The security and performance comparison results of the χperbp show that this protocol is well suited for resource-constrained environments such as RFID tags and sensor nodes.

As a limitation of χperbp, we should mention that to find the tag through the authentication phase, the server should search the whole database. Although, the server could have enough computation resources, however, it is a shortcoming in any application for which scalability is important. Hence, as future work, we suggest improving this feature of the protocol. In addition, χper is a new primitive which can be used in any other protocol independent of χperbp. In this paper, we have shown its security against various attack, but we encourage other researchers to investigate its security independently.

Declarations

Ethical Approval and Consent to participate

Not applicable.

Human and Animal Ethics

Not applicable.

Consent for publication

Not applicable.

Availability of supporting data

All the required data has been included in the manuscript.

Competing interests

The authors declare no conflict of interest/competing interests.

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Authors' contributions

Morteza Adeli: Experimentation, Methodology, Validation, Writing; **Nasour Bagheri:** Conceptualization, Experimentation, Validation, Writing - review, Supervision, Funding& editing; **Sadegh Sadeghi:** Experimentation, Validation, review & editing; **Saru Kumari** Conceptualization, Methodology, Designing, Experimentation, Validation, Supervision, review & editing.

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A Security Analysis of χper function

In this section, we present the results of our security analysis of χper against differential [11], linear [33], impossible differential [29,10] and zero-correlation [12] attacks. To investigate these attacks, we consider the χper function as three layers. Add-key, Non-linear (it is described with three AND and three XOR operations), and Mix-shift layers (see Figure 6). Note that to find a differential and linear characteristic the Add-key layer has no effect. Therefore, in these analyzes, we can ignore it. Also, the action of the Non-linear layer can be described as parallel with a 3×3 S-box. This S-box in hexadecimal notation is given by Table 6.

x	0	1	2	3	4	5	6	7
$S(x)$	0	3	6	1	5	4	2	7

Table 6: The 3-bit S-box used in χper in hexadecimal form.

A.1 Differential/Linear Cryptanalysis

In order to argue for the resistance of χper against differential and linear attacks, we applied Mixed Integer Linear Programming (MILP) method as explained in [46,35,40] to search for differential and linear characteristics. The results are listed in Table 7.

	♯ rounds	1	2	3	4	5	6	7	8
$w = 32$	Linear	1	3	6	11	19	24	28	32
	Differential	1	3	6	11	18	24	(32)	(37)

Table 7: Lowerbounds on the number of active S-boxes in χper. In case the MILP optimization was too long, we provide upper bounds between parentheses.

A.2 Impossible Differential characteristics

Impossible differential attack [29,10] finds two internal state differences Δ_i, Δ_o such that Δ_i is never propagated to Δ_o. The attacker then finds many pairs of plaintext/ciphertext and key values leading to (Δ_i, Δ_o). Those key values are wrong values, thus key space can be reduced. To search for impossible characteristics we applied the MILP method based on the [16,39].

Our MILP model shows the longest impossible differential characteristics reach 6 rounds. The details of one of these characteristics can be seen in Table 8. Note that in this 8, the Input differential, Middle differential, and Output differential show the differentials before the S-box layer, after the S-box layer, and after the Mix-Shift layers, respectively. Also, the bits "0", "1", and "?" shows zero, active, and unknown differentials, respectively. To prove the impossibility of this differential, we use the following property that can be derived from the Differential Distribution Table (DDT) of χper S-box.

Fact 1 The S-box of χper has the following property:

- *If the input difference of the S-box is* $0x1 = 001$, $0x2 = 010$, *and* $0x3 = 100$, *then the output difference must be as* $??1, ?1?$, *and* $1??$, *respectively, where the* ? *shows an unknown difference bit.*

Round	Input differential	Middle differential	Output differential
	00000000000000000000000000000000	000000000000000?0000000000000000	000000000000000?0000010000000000
↓ 1	00000000000000000000000000000000	000000000000000?0000000000000000	00?0000000000?000001000000000000
	00000000000000010000000000000000	00000000000000010000000000000000	00000000?00000100000000000001?00
	000000000000000?0000010000000000	00?00000?0000???000?01000000??00	00??0000?0000???000?1?000?0???00
2	00?0000000000?000001000000000000	00?00000?0000???00010?000000??00	???00010?00???0???1?0?0?0???0000
	00000000?00000100000000000001?00	00?00000?0000?1?000?0?0000001?00	01??00???1???1???0?0???000????00
	00??0000?0000???000?1?000?0???00	????00??????????????????0?????00	
3	???00010?00???0???1?0?0?0???0000	????00??????????????????0?????00	
	01??00???1???1???0?0???000????00	????00???1??????????????0?????00	
		???????????????0????????????????	???0?????0?????0?????00????0?0??
		????????0???????????????????????	???0?????0?????0?????00????0?0??
		?????????0??????????????????????	???0?????0?????0?????00????0?0??
	???0?????0?????0?????00????0?0??	?0000????0?1???0?????00????000??	?0000??0000010000?0??00?0??0000?
3	???0?????0?????0?????00????0?0??	???0????00????00????00010?00?0??	?0000??00000?0000?0??0010??0000?
	???0?????0?????0?????00????0?0??	0??0?1???0?0???000???000???0000?	?0000??00000?0000?0??00?0??0000?
	?0000??0000010000?0??00?0??0000?	?0000??0000010000000000000?00001	000000?0000010000000000000000000
2	?0000??00000?0000?0??0010??0000?	00000000000000000?0?00010?000000	000000?00000?0000000000000000000
	?0000??00000?0000?0??00?0??0000?	00000000000000000000?00001?0000?	000000100000?0000000000000000000
	000000?0000010000000000000000000	00000000000010000000000000000000	00000000000000000000000000000000
↑ 1	000000?00000?0000000000000000000	00000000000000000000000000000000	00000000000000000000000000000000
	000000100000?0000000000000000000	00000010000000000000000000000000	00000000000000000001000000000000

Table 8: An impossible differential characteristic for 6 rounds χper when $w = 32$.

A.3 Zero-Correlation Linear Approximation

The zero-correlation attack is one of the cryptanalytic methods introduced by Bogdanov and Rijmen [12]. The attack is based on linear approximations with zero correlation. To search for zero-correlation linear approximations, we applied the MILP method for χper. The longest zero-correlation linear approximation was obtained for 6 rounds of χper when $w = 32$. Table 9 shows an example of this zero-correlation linear approximation. Note that in this table, the Input mask, Middle mask, and Output mask show the linear masks before the S-box layer, after the S-box layer, and after the Mix-Shift layers, respectively. Also, the bits "0", "1", and "?" shows zero, active, and unknown masks, respectively.

In the same way with impossible differential characteristics, Fact 1 is also true in linear mode and we have used it in Table 9.

Round	Input mask	Middle mask	Output mask
	00000000000000000000000000000000	0000?000000000000000000000000000	0000?0000000000000000?0000000000
↓ 1	00000000000000000000000000000000	0000?000000000000000000000000000	0000000000001000000000??0000000
	00001000000000000000000000000000	00001000000000000000000000000000	00000000000000001000000000000?00
	0000?0000000000000000?0000000000	0000?0000000?0000?000?0??0000?00	00?0?0?0??00?0?00?000?0??0000?00
2	0000000000001000000000??0000000	0000?000000010000?000?0??0000?00	?000??00?????000??00?00??1000?0?
	00000000000000001000000000000?00	0000?0000000?00001000?0??0000?00	00?0??0000?000?0??0000?00?000?10
	00?0?0?0??00?0?00?000?0??0000?00	0?0?0???0?????0?0??00??????000???	???0?????????0????0?????????????
3	?000??00?????000??00?00??1000?0?	?0?0???0?????0?0??00??????000???	??????1?????????0???????????????
	00?0??0000?000?0??0000?00?000?10	?0?0???0?????0?0??00??????000?1?	0???????0??1????????0?????0?0???
	??????0?????????????????????????	?0????0?0????0????00????1?0?0??0	?0?0??000?0??0?0??0000??10000100
3	??????0?????????????????????????	?00???00?0?0??0?0????0?0??0?0??1	?0?0??000?0?10?0??0000???0000?00
	??????0?????????????????????????	??????0?0????0????0?0????0??????	?0?0??00010??0?0??0000?1?0000?00
	?0?0??000?0??0?0??0000??10000100	00?0?000000000000?0000?010000100	0000?000000000000000000010000000
2	?0?0??000?0?10?0??0000???0000?00	?0000?00000010000?00000000000000	0000?0000000000000000000?0000000
	?0?0??00010??0?0??0000?1?0000?00	00?01000010?00?0?000000100000?00	00001000000000000000000?0000000
	0000?000000000000000000010000000	00000000000000000000000010000000	00000000000000000000000010000000
↑ 1	0000?0000000000000000000?0000000	00000000000000000000000000000000	00000000000000000000000000000000
	00001000000000000000000?0000000	00001000000000000000000000000000	00000000000000000000000000000000

Table 9: A zero-correlation linear approximation for 6 rounds χper when $w = 32$.

B Security Protocol Description Language model of the χperbp scheme

```
usertype Timestamp;
const XOR: Function;
const Concatenate: Function;
const Right: Function;
const Left: Function;
const Xper: Function;
hash function H;

    protocol Xperbp(Tag,Reader,CloudServer){
role Tag {
const IDi, Ki;
var Mr, Mc;
fresh Rr: Nonce;
var Tr, Ts, Tt: Timestamp;
recv-!Tt(Tag,Tag,Tt);
recv-1(Reader,Tag,Rr);
macro Rt={Concatenate(Tt,Rr)}Ki;
macro RRt= Right(Rt);
macro Mt={XOR(IDi,Concatenate(Rr,RRt))}Ki;
send-2(Tag,Reader,Mt,RRt);
recv-5(Reader,Tag,Mc,Ts,Mr);
macro Mc'={IDi}XOR(Ki,Concatenate(Ts,RRt));
macro Mr'={XOR(Mt,Mc)}IDi;
match(Mc,Mc');
match(Mr,Mr');
claim(Tag,Secret,IDi);
claim(Tag,Secret,Ki);
claim(Tag,Niagree);
claim(Tag,Nisynch);
claim(Tag,Alive);
claim(Tag,Weakagree);
}
    role Reader {
const RID, Kr, Ki, IDi;
var RRt,RtR,RtL,Mc,Mt,MACc,DIi;
fresh Rr: Nonce;
var Tt, Ts,Tr: Timestamp;
recv-!Tr(Reader,Reader,Tr);
send-1(Reader,Tag,Rr);
recv-2(Tag,Reader,Mt,RRt);
macro MACr=H(Concatenate(Mt,RRt,Rr,Kr,Tr,RID));
send-3(Reader,CloudServer,MACr,Tr,Mt,Rr,RRt);
recv-4(CloudServer,Reader,Mc, DIi,Ts, MACc);
macro IDi'=XOR(DIi,RID,{Concatenate(Ts,Tr)}Kr);
macro MACc'=H(Concatenate(Mc,Mt,RRt,Rr,Ts,IDi',RID));
match(MACc,MACc');
macro Mr={XOR(Mt,Mc)}IDi;
send-5(Reader,Tag,Mc,Ts,Mr);
claim(Reader,Secret,IDi);
claim(Reader,Secret,Kr);
claim(Reader,Secret,RID);
claim(Reader,Niagree);
claim(Reader,Nisynch);
claim(Reader,Alive);
```

```
claim(Reader,Weakagree);
}
    role CloudServer{
const RID,Kr,IDi,Ki ;
var RRt,RtR,RtL,Mt,MACr,DIi;
fresh Rr : Nonce;
var Ts,Tt,Tr: Timestamp;
recv-!Ts(CloudServer,CloudServer,Ts);
recv-3(Reader,CloudServer,MACr,Tr,Mt,Rr,RRt);
macro Mt'={XOR(IDi,Concatenate(Rr,RRt))}Ki;
macro MACr'=H(Concatenate(Mt,RRt,Rr,Kr,Tr,RID));
match(Mt,Mt');
match(MACr,MACr');
macro Mc={IDi}XOR(Ki,Concatenate(Ts,RRt));
macro MACc=H(Concatenate(Mc,Mt,RRt,Rr,Ts,IDi,RID));
macro DIi=XOR(IDi,RID,{Concatenate(Ts,Tr)}Kr);
send-4(CloudServer,Reader,Mc,DIi,Ts,MACc);
claim(CloudServer,Secret,IDi);
claim(CloudServer,Secret,Ki);
claim(CloudServer,Secret,Kr);
claim(CloudServer,Secret,RID);
claim(CloudServer,Niagree);
claim(CloudServer,Nisynch);
claim(CloudServer,Alive);
claim(CloudServer,Weakagree);
} }
```