PUF-based Mutual Authentication and Key-Exchange Protocol For Peer-to-Peer IoT Applications

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Abstract—Peer to Peer (P2P) or direct connection IoT has become increasingly popular owing to its lower latency and higher privacy compared to database-driven or server-based IoT. However, wireless vulnerabilities raise severe concerns on IoT device-to-device communication. This is further aggravated by the challenge to achieve lightweight direct mutual authentication and secure key exchange between IoT peer nodes in P2P IoT applications. Physical unclonable function (PUF) is a key enabler to lightweight, low-power and secure authentication of resource-constrained devices in IoT. Nevertheless, current PUF-enabled authentication protocols, with or without the challenge-response pairs (CRPs) of each of its interlocutors stored in the verifier's side, are incompatible for P2P IoT scenarios due to the security, storage and computing power limitations of IoT devices. To solve this problem, a new lightweight PUF-based mutual authentication and key-exchange protocol is proposed. It allows two resource-constrained PUF embedded endpoint devices to authenticate each other directly without the need for local storage of CRP or any private secrets, and simultaneously establish the session key for secure data exchange without resorting to public-key algorithm. The proposed protocol is evaluated using the Mao and Boyd logic as well as the automatic security analysis tool ProVerif to corroborate its mutual authenticity, secrecy, and resistance against replay and man-in-the-middle attacks. Using two Avnet Ultra96-V2 boards to emulate the two IoT endpoint devices of a network, a physical prototype system is also constructed to demonstrate and validate the feasibility of the proposed secure P2P connection scheme.

Index Terms—Peer-to-peer Internet of Things, IoT Security, Physical Unclonable Functions, Peer-entity Authentication Protocol, Key Exchange Protocol, Man-in-the-Middle Attacks

1 INTRODUCTION

THE Internet of Things (IoT) regime can be roughly classified into two categories, i.e., database-driven IoT and peer-to-peer (P2P) IoT [1]. For database-driven IoT, the connections between two IoT endpoint devices are established indirectly through a server, which is a common approach for IoT connection. Data collected from the IoT devices will be transmitted to and stored in the server's database and the retrieval of data can be achieved by sending a request to the server. By contrast, P2P IoT enables direct connection between two IoT endpoints, which provides lower-latency performance and higher-privacy level compared to server-centric database-driven IoT. As data collectors, IoT endpoints have access to high-value assets and confidential information. Since they are easily accessible and resource constrained, they are also alluring targets of attack, especially when the intelligent autonomous endpoint devices are allowed to interact or exchange sensitive data directly with each other endpoints in a smart environment. Authentication and secure key exchange between two end-

points are the crucial first line of defense to prevent fake endpoints from exfiltrating data and holding information hostage. Unfortunately, legacy security solutions, despite sufficiently mature, do not transfer convincingly to the P2P IoT scenarios due to the heterogeneity, and resource and memory constraints of IoT devices.

To this end, Physical Unclonable Function (PUF) stands out as a promising embodiment to facilitate secure authentication and key exchange of IoT devices [2], [3], [4], [5], [6]. A PUF can be viewed as a physical circuit realization of a random oracle by harnessing the minute variance in modern semiconductor manufacturing processes [7]. The lynchpin of PUF is the irreversible random mapping of a digital input (known as a challenge) to a digital output (known as a response). The challenge-response mapping is very similar to a cryptographic hash function except that the hardness to invert the function is originated from the physical disorder instead of the computational complexity theory. The chip-to-chip variances of a manufacturing process can be harvested by the PUF circuit. With enough basic PUF cells, many unique challenge-response pairs (CRPs) of arbitrary length can be generated from each chip for a huge number of manufactured chips. Although the PUF circuit itself is easy to make and the responses can be readily measured, it is practically infeasible to physically clone a PUF instance to reproduce the same CRPs. More importantly, no secret key needs to be stored locally on a device as the PUF can generate the device-specific secret (response) only upon request

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(by applying a challenge). Once the required number of CRPs have been successfully measured and enrolled into a secure server database, the external measurement interface of the PUF responses can be permanently disabled. Since the entire set of CRPs is intricately embodied in the nano-structure of the PUF, any active manipulation of the PUF circuit internals will cause dysfunction of the challenge-response mapping mechanism and destroy the secret. This tamper-evident property of PUF and its ability to securely identify a device by interrogation without the need for a permanent secret residence in anti-temper memory largely reduce the risks of a number of powerful hardware attack vectors such as reverse engineering, probing and fault injection attacks on seizable devices [8], [9], [10], [11].

Using PUF for device authentication requires the verifier to keep a copy of its prover's CRPs. This is a common practice in PUF-based authentication protocol in database-driven IoT as the server has the computing power and memory resources to securely store the database of the CRPs of all its interlocutors. However, this requirement becomes impractical when mutual authentication has to be performed directly between two end-devices for secure communication in P2P IoT applications. IoT end-devices are usually small, low cost and resource constrained, which render classical recipes [2], [5], [6] of PUF-based mutual authentication between device and server inapplicable, especially when one end-device needs to communicate with several other end-devices. Besides, storing the prover's CRPs in the verifier device allows the latter to impersonate the prover, which rules out the applicability of traditional PUF-based authentication scheme in the P2P IoT scenarios.

This paper presents a lightweight device-to-device PUF-based authentication protocol between IoT edge devices for P2P IoT connection without requiring the devices to store each other's CRPs. The concept was firstly proposed without implementation in our preliminary work [12]. That work still requires the server's participation during the authentication phase and is vulnerable to the two-time pad attack. The shortcomings and overly simplistic security analysis in [12] are addressed in this paper. Our major contributions are:

- 1 The proposed mutual authentication scheme enables secure direct communication between any two IoT endpoints in a network. This enables the IoT data to be shared directly between a pair of endpoints. The server only helps to create the connection in the enrolment and update phase, and is then completely released from the authentication and communication phase of the system.
- 2 The proposed PUF-based scheme requires no keys or CRPs to be stored in the IoT endpoints. No extra intermediate "verifier" node is required, which is unlike the scheme in [13]. This makes it possible for a resource-constrained PUF-embedded device to directly authenticate any other PUF-embedded devices in the same local area network.
- 3 The proposed scheme also achieves a secure key exchange as a byproduct of the protocol. The session keys for exchanging messages by symmetric-key cryptography between two devices are directly derived from their PUF responses. The shared keys are automatically established upon successful authentication, which of-

floods the complexity of managing and storing the keys for IoT devices.

- 4 The security of the protocol is formally verified using the Mao and Boyd Logic [14] and the professional security verification tool ProVerif [15]. The proposed scheme is proved to possess robust reachability and secrecy, mutual authenticity, and high resilience against multiple attacks such as replay and man-in-the-middle attacks.
- 5 The proposed scheme has also been evaluated physically by a prototype system using Avnet Ultra96-V2 boards to emulate the IoT endpoints equipped with the required hardware primitive. Hardware overhead, computational complexity and other system performance are analyzed and compared with related existing works.

The rest of the paper is organized as follows. Sec. 2 introduces the related works and preliminaries; Sec. 3 presented the proposed protocol design, which includes an enrolment and update phase, and a mutual authentication and key exchange phase. The security of the protocol is analyzed in Sec. 4 while the implementation and comparison are presented in Sec. 5. Finally, Sec. 6 concludes the paper.

2 RELATED WORKS AND PRELIMINARIES

In this section, two pitfalls in using traditional authentication protocols for securing P2P IoT applications are discussed. In the same light, the limitations of existing PUF-based device authentication schemes in IoT setting are also identified. In addition, inference rules of Mao and Boyd Logic that can be used for the formal security analysis of P2P IoT device authentication protocol are introduced.

2.1 P2P IoT

Two necessary steps and the potential issues of adopting typical authentication protocols for securing P2P IoT connection are identified as follows. Firstly, the authenticity of the two IoT endpoints has to be assured before a secure direct connection between them can be established. A common approach is to involve a trusted server to authenticate the two IoT devices individually. Once both devices are authenticated, the communication is then handed over to the two devices without involving the server any more. This approach requires two mutual authentications to be performed independently between the server and the devices. The extra authentication through a proxy server incurs transmission bandwidth overhead and authentication delay owing to the need to protect any sensitive secret that cannot be sent in plaintext. Besides, the establishment and relay of shared secret through the server for each authentication request also increase the vulnerability of man-in-the-middle (MITM) and chosen-plaintext or chosen-ciphertext attacks. Secondly, end-to-end encryption is required to ensure secure data transmission between the two interlocutors. Either a symmetric key or a public key cryptographic (PKC) algorithm can be utilized for data encryption. Both cases require a secret key to be safely stored in both endpoints. If the secret keys are stored in the non-volatile memory (NVM) of the inexpensive endpoint devices with limited room for

sophisticated key protection, they can be relatively easily extracted by powerful commercial data extraction tools like Graykey [16] of Grayshift and UFED [17] of Cellebrite.

The abovementioned issues of P2P IoT can be avoided if the two IoT endpoints can directly authenticate each other without the need to store the secret key persistently and locally on the endpoint device to achieve end-to-end encryption.

2.2 Existing PUF-based Authentication Schemes

PUF as a “device fingerprint” has been widely used for individual device authentication [2], [5], [6]. A typical PUF-based authentication process is shown in Fig. 1. An enrolment phase is required to be carried out securely in a controlled environment once before the PUF can be deployed in the field for device authentication. During the enrolment phase, an adequate number of CRPs of the PUF has to be collected and stored in the verifier’s database. In the authentication phase, the verifier randomly selects a CRP from its database and then transmits the challenge to the prover. The prover obtains a response by applying this challenge to its PUF and sends the response back to the verifier. By comparing the received PUF response with the enrolled one, the verifier can authenticate the prover’s device.

Fig. 1. A typical PUF-based device authentication scheme. Here the PUF is a strong PUF with exponential number of CRPs. Each CRP is used only once for secure authentication.

As shown from Fig. 1, a typical PUF-based authentication scheme requires the verifier to safely store a CRP database of the prover’s PUF. This is easier to achieve if the verifier is a powerful server. If direct authentication of P2P IoT devices is to be achieved without a proxy server as discussed in Sec. 2.1, this scheme is infeasible as the verifier, an IoT endpoint, has limited resources to ensure the secure storage of the CRPs. As a result, PUF-based authentication schemes without the CRP storage in both endpoint devices of the verifier and the prover are desperately needed in such P2P IoT applications.

Several relevant solutions have been proposed in the literature [13], [18], [19], [20]. They are briefly reviewed as follows.

The protocol of [13] combines the PUF with a certificate-less identity based encryption. It requires a verifier node to act as the proxy to authenticate the two IoT endpoints. It also requires the presence of a Security Association

Provider (SAP) during the authentication phase to manage the authentication helper data. Besides, the protocol requires the verifier to store a secret hash key in an NVM. This requirement has completely defeated the fundamental tenet of using PUF to avoid keeping the secret in local memory.

On the other hand, the Babel-chain PUF-based mutual authentication protocol (BC-PHEMAP) [18] applies the PUF response iteratively to the PUF to create PUF chains for authentication. Since multiple PUF operations (8 in the text example) are required and each PUF operation has to be 100% reliable in order to preserve the enrolled chain result, this scheme is not practical due to the inevitable unreliability of PUF responses in the field. What is more, the BC-PHEMAP scheme reveals raw PUF responses during the protocol executions. The scheme requires strong PUF to ensure the chain or its subset is never reused to pair different devices but this also provides an opportunity for the adversary to collect a large number of used raw responses for modelling attack.

The scheme in [19] also requires a trusted third party server during the mutual authentication of two IoT endpoints. The server is responsible for providing the authentication message and generating the session keys. The protocol trades message exchange times (delays) for zero-storage in the device side and reduced storage requirement in the server side. Two rounds of mutual authentication between the server and the device and one round of mutual authentication between devices are required for a complete protocol run. On a par with [18], it does not take into account the practical PUF reliability issues.

Similar to [13], the work [20] relies on the combination of PUF with a PKC on elliptic curve to achieve mutual authentication between IoT nodes without the need for a local CRP storage. Each IoT node will obtain its public and private key pair after an enrolment phase with the server in a secure environment. The public keys are stored in the device’s memory while the private keys are recovered with the help of the PUF during the authentication phase. 14 rounds of elliptic curve scalar multiplications are required to complete the protocol runs, which increases the computational cost of the protocol significantly.

In short, existing PUF-based authentication schemes, either with or without requiring a CRP storage in the verifier, cannot be used to instantiate a low-cost, key-less, directly authenticated and directly connected P2P IoT network.

2.3 The Mao and Boyd Logic

The Mao and Boyd (MB) logic [14] is a formal logical approach towards the security analysis of peer-entity authentication protocols. It adopts the basic notational framework of the Burrows, Abadi and Needham (BAN) logic [21], but has overcome its limitations, such as providing only partial correctness proof and lacking complete formality. This section provides a brief introduction of the MB Logic.

Table 1 lists some basic logical formulas. In this table, P with or without any subscript represents a principal, M with or without any subscript represents a message and F with or without any subscript represents a formula. K represents a secret key, which is also a type of message.

The first step to analyze a protocol using the MB logic is to perform a protocol message idealization. Message

TABLE 1
Logical Formulas in the MB logic and Their Explanations

Formulas	Explanations
$M_1 \Re M_2, M_1 M_2$	Combined message; $\Re$ combines different types of messages while $ $ combines the same type of messages
$F_1 \wedge F_2$	Boolean conjunction of sub-formulas F_1 and F_2
$P \models F$	P believes the correctness of F
$P \stackrel{K}{\sim} M$	P send out K -encrypted M
$P \triangleleft^K M$	P sees M by using the decipherment key K
$P_1 \xleftrightarrow{K} P_2$	K is a good shared key between P_1 and P_2
$sup(P)$	P is a super-principal who has to be trusted unconditionally. IoT devices can be a super-principal for its PUF CRPs and the nonces it generated.
$\#(M)$	M is fresh
$S^{c\triangleleft} \parallel M$	Those principals that in the complement set of the set S cannot see M

idealization interprets the implicit protocol messages and transcribes them into explicit specifications. The following formalized terms are defined and used in the idealization rules:

- 1) Atomic message: a message without any “,” “|”, “ $\Re$ ”, “(”, “)”, “{”, “}” appears in its construction.
- 2) Challenge: an atomic message sent or received in different protocol lines by the same principal (i.e., the originator, which can be a person, a server, or a device). A timestamp is not considered as a challenge.
- 3) Replied challenge: a challenge sent to its originator.
- 4) Response: an atomic message that appears in a protocol line with a replied challenge and itself sent together by the sender of that line. A timestamp is not considered as a response.
- 5) Nonsense: an atomic message if it is not a challenge, a response or a timestamp.

With the definitions of the above formalized terms, the rules for idealization can be described as follows:

- 1) Delete any nonsense.
- 2) Treat an atomic message as response if it appears in a line not only as a challenge but also as a response.
- 3) Use the operator “|” to combine multiple factors in a line that belongs to the same type, e.g., “challenge | challenge”, “response | response”.
- 4) Use the operator “ $\Re$ ” to combine multiple factors in a line that belong to different types, e.g., “response $\Re$ replied challenge”, “message $\Re$ timestamp”.

Next, a set of inference rules or the logics of belief are defined for reasoning about the beliefs of principals and logical formulas. For simplicity, only the inference rules that are related to and used in this work are introduced.

- 1) The authentication rule:
if P and Q share a good key K , and P can see M using the key K , then P can believe Q has sent out the K -

encrypted M .

$$\frac{P \models P \xleftrightarrow{K} Q \wedge P \triangleleft^K M}{P \models Q \stackrel{K}{\sim} M} \quad (1)$$

- 2) The confidentiality rule:
if P and Q share a good key K , and P believes that only the principles in the set S is able to see M , and P has sent out the K -encrypted M , then P can believe that M is available to only the set S and Q except itself.

$$\frac{P \models P \xleftrightarrow{K} Q \wedge P \models S^{c\triangleleft} \parallel M \wedge P \stackrel{K}{\sim} M}{P \models (S \cup Q)^{c\triangleleft} \parallel M} \quad (2)$$

- 3) The nonce-verification rule:
If P believes that M is fresh and P believes that Q has sent out the K -encrypted M , then P can believe that Q believes K is a good shared key between P and Q .

$$\frac{P \models \#(M) \wedge P \models Q \stackrel{K}{\sim} M}{P \models Q \models P \xleftrightarrow{K} Q} \quad (3)$$

- 4) The super-principal rule:
If P believes that Q is a super principal, then P believes what Q believes.

$$\frac{P \models Q \models X \wedge P \models sup(Q)}{P \models X} \quad (4)$$

- 5) The fresh rule:
 P can believe that N is fresh if he receives N with a fresh M together in a message.

$$\frac{P \models \#(M) \wedge P \triangleleft N \Re M}{P \models \#(N)} \quad (5)$$

- 6) The good-key rule:
If P believes that K is fresh and available only to P and Q , then P can believe that K is a good shared key between P and Q .

$$\frac{P \models \{P, Q\}^{c\triangleleft} \parallel K \wedge P \models \#(K)}{P \models P \xleftrightarrow{K} Q} \quad (6)$$

- 7) The derived rule:
By combining the following belief axiom

$$\frac{P \models X \wedge P \models Y}{P \models (X \wedge Y)} \quad (7)$$

with the confidentiality rule (2), a derived rule can be obtained as follows:

$$\frac{P \models Q \models Q \xleftrightarrow{K} P \wedge P \models Q \models S^{c\triangleleft} \parallel M \wedge P \models Q \stackrel{K}{\sim} M}{P \models Q \models (S \cup \{P\})^{c\triangleleft} \parallel M} \quad (8)$$

Finally, the pre-conditions (initial beliefs) of a security protocol can be obtained by reversely applying the inference rules to the expected protocol achievements. If the pre-conditions obtained are reasonable or is satisfiable by a protocol run, then the protocol is construed to be provably secure based on the logical theory of belief (doxastic logic).

Fig. 2. System model. The server is only present in the enrolment and update phase to create/update the authentication mask and helper data. Once this is completed, the IoT endpoints can freely and directly authenticate and exchange data among themselves.

3 PROPOSED PUF-BASED SCHEME

3.1 Models and Assumptions

Fig. 2 shows the system model. The objective of the system is to establish direct mutual authentication and direct communications between IoT peer nodes by utilizing the on-the-fly key generation property of PUF while avoiding the shortfalls of existing PUF-based authentication schemes. The end-devices are assumed to be embedded with a PUF, a lightweight hash function (for example, sponge-like construction) [22] and a lightweight block cipher optimized for performance in hardware implementation like SIMON [23]. We assume that the CRPs of the devices have already been securely collected in the design house and securely transmitted to a legal local server. The end-devices have limited storage capacity and are incapable of protecting the secrets stored in their NVM. In contrast, the server can afford expensive anti-tamper storage to secure any secret and is powerful enough to perform complex computations.

The threat model assumes the presence of an attacker who can connect to the network and is able to eavesdrop the communication channel during the authentication process. It is also assumed that the attacker can initiate an unbound number of authentication requests. The attacker cannot break into the server's database but can have access to an IoT end-device to retrieve any stored secrets in the device. The objective of the attacker is to impersonate any end-devices and steal the secret session key without being detected.

The proposed protocol consists of two phases, i.e., an enrolment and update phase, and a mutual authentication and key-exchange phase. As shown in Fig. 2, the IoT end-devices only have to communicate with the server in the enrolment and update phase. After which, the IoT peer nodes can connect and authenticate each other directly. The notations used in our proposed protocol are described in Table 2.

3.2 Enrolment and Update Phase

The enrolment phase is firstly conducted in the design house, where the CRPs of each PUF-embedded chip are collected after fabrication. After which, the direct CRP access path are permanently removed. Once the customer identity is authenticated, the CRPs will be transferred to the customer's local server for the intended applications. Note that the CRP collection is assumed to be conducted

TABLE 2
Notations used by the proposed protocol

Notation	Description
$PUF(C)$	Apply the challenge C to the PUF
$H(X)$	Hash of X
$\oplus$	Exclusive OR
$\parallel$	Concatenation
$ENC(X, k)$	Encrypt X using the key k
$DEC(X, k)$	Decrypt X using the key K
ϕ	A key mask
$h = ECC_gen(X)$	Error correction code (ECC) generation phase. It generates the helper data h for the recovery of X
$ECC_rep(X, h)$	ECC reproduction phase. It corrects the noisy X with the helper data h

in a secure environment and the transfer of CRPs is also securely completed with the help of various supply chain authentication protocols.

The main idea is to utilize a one-time pad (OTP) to generate a key mask for a dedicated device pair. The mask can be publicly stored in the device side without compromising the security. Its purpose is to help with the retrieval of the secrets during the authentication process. Specifically, as shown in Fig. 3, for each intended pair of edge devices in an IoT network, A and B for example, a challenge $C_{A,B}$ is generated. The corresponding responses, R_A and R_B , can be retrieved from the server's CRP database for A and B accordingly. Helper data h_A and h_B are generated by the ECC [24] for the recovery of R_A and R_B , respectively, from the noisy responses reproduced by the PUF in the field. The server calculates a pair of random intermediary secrets, P_1 and P_2 , from the response R of each device. A lightweight cryptographic hash function H is used to boost the entropy of PUF responses and prevent the direct use of raw responses. Then, a OTP mask ϕ is generated by the XOR operation. ϕ needs not be kept private and it can be stored in the device memory. Due to the OTP, the knowledge of ϕ does not help to reveal P_1 and P_2 . Hence, both P_1 and P_2 can serve as the keys to decrypt a pair of secrets designated for a device with the help of its PUF. Specifically, for device A , P_{1A} is first calculated by hashing its reproduced PUF response R_A . P_{2A} is then obtained by hashing P_{1A} . P_{1B} and P_{2B} are similarly obtained from hashing R_B of device B consecutively. These private data are concealed in ϕ_1 and ϕ_2 by the OTP construction, $P_{1A} \oplus P_{1B}$ and $P_{2A} \oplus P_{2B}$, respectively.

Note that a OTP can achieve perfect secrecy, if the length of the random key is at least as long as the plaintext. Besides, the random key must be kept completely secret and never be reused in whole or in part. Most of the requirements can be easily achieved in our proposed scheme as the random keys (or plaintexts) defined by the PUF response can be generated by the device when needed. However, the one-time use policy of OTP requires that "a device should

never be paired with multiple other edge devices for the same challenge". Assume that there are N devices in the network and each device can pair with any other device to form a direct communication pair. To avoid the same challenge from being used in multiple pairs involving the same device, the challenges are allocated at the server side by Algorithm 1, where $I_{i,j}$ denotes the index of the challenge $C_{i,j}$ used for the paired devices, i and j . After running Algorithm 1 for a specific application, the server is able to randomly generate M number of challenges and allocates them to each device pair according to the challenge index allocation list CL .

A device should only accept the authentication mask from an authorized server that possesses the correct PUF CRPs of the device. To ensure this, the server packs the mask ϕ_2 with the key P_{1A} , a timestamp T and the device B 's identity ID_B together. The message package is encrypted with the key P_{1A} . The encrypted message is concatenated with the challenge $C_{A,B}$ and the helper data h_A to form a message M_A for sending to the device A . Upon receiving M_A , the device A applies $C_{A,B}$ to generate the key $\tilde{P}_{1A}$. If the key is correct, the message can be successfully decrypted. If the retrieved timestamp is fresh and the decrypted P_{1A} matches $\tilde{P}_{1A}$, the device A can believe the enrolment or updated message ($ID_B, C_{A,B}, h_A, \phi_2$) is indeed from a trusted local server. The timestamp T in M_A and M_B ensures the freshness of the message and prevents the replay of a compromised M_A or M_B . Each edge device can store $N - 1$ masks if it would like to establish a secure authenticated connection with all other devices in the network. The same process can be performed whenever the mask data in the device's side need to be updated. Due to the allocation of unique challenges to device pairs, although the authorized device can retrieve the hashed PUF response to the allocated challenge for any of its interlocutor, it still cannot impersonate as its interlocutor to communicate with other devices.

3.3 Mutual Authentication and Key-Exchange Phase

If an IoT end-device A wants to communicate with another end-device B , it will send a request message containing the current timestamp T_1 and its identity ID_A to the device B , as shown in Fig. 4. B checks the identity of A in its database. If it exists, it fetches the enrolled challenge $C_{A,B}$, helper data h_B and mask ϕ_1 corresponding to A from its memory. B applies the challenge $C_{A,B}$ to its embedded PUF to generate a reliable PUF response with the help data h_B . Using the mask ϕ_1 , B is able to recover the hashed PUF response $\tilde{P}_{1A}$ of A to the challenge $C_{A,B}$ by XORing ϕ_1 with P_{1B} . The latter is the hash of R_B . B then generates a nonce n_A that satisfies $n_A \neq \tilde{P}_{1A}$. A plaintext m_A is generated for A by XORing n_A with P_{1B} . Using the recovered $\tilde{P}_{1A}$ as the encryption key, a puzzle Q_A is created by the device B for the device A by encrypting the concatenated message of m_A and the received T_1 . To decrypt the received Q_A , A calculates P_{1A} directly from its clean PUF response R_A reproduced with the help of h_A . If $\tilde{T}_1$ obtained from the decrypted Q_A is equal to T_1 , A will hash the recovered plaintext $\tilde{m}_A$ to $\tilde{V}_A$ and send it to B as a proof of successfully solving the puzzle Q_A . Meantime, B also calculates V_A from the hashed m_A and compares it with the received $\tilde{V}_A$. If they match, B validates

Fig. 3. Enrolment and update phase. The device only accepts the authentication mask data from the server. Here, the hat on a response denotes the response is noisy while the tilde on a variable is used to emphasize that the private variable is recovered at the device side instead of being received by a transmission. Similarly for Fig. 4.

Algorithm 1: Challenge allocation for enrolment

Input: The number of IoT devices: N

Output: Challenge index allocation list: CL ; Number of challenges needed: M

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1   $CL = \{\};$ 
2   $x = \{1, 2, \dots, N-1\};$ 
3  for  $i = 1$  to  $N-1$  do
4      for  $j = i + 1$  to  $N$  do
5          if  $i == 1$  then
6               $I_{i,j} = j - 1;$ 
7          else
8              Find a subset  $CL'$  for challenges  $C_{m,n}$  in
               $CL$ , s.t.  $m = i$  or  $j$  OR  $n = i$  or  $j$ ;
9              if  $set(CL) == set(CL')$  then
10                  $I_{i,j} = length(x)+1;$ 
11                 Append  $I_{i,j}$  to  $x$ ;
12             else
13                  $I_{i,j} = \min(set(CL)-set(CL'));$ 
14                  $\triangleright I_{i,j}$  is the minimum index number in
                 the difference of set  $CL$  and set  $CL'$ 
15             Append  $I_{i,j}$  to  $CL$ ;
16   $M = length(x);$ 

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that the protocol initiator is indeed the authentic device A as it is claims.

By reversing the roles of the prover and the verifier, similar flow can be reciprocated by the initiator to validate if the interlocutor is indeed the one it wants to communicate with. The device A retrieves $\tilde{P}_{2B}$ with the help of ϕ_2 . Using

Fig. 4. Mutual authentication and key-exchange process. After the successful mutual authentication, P_{2A} and P_{2B} can be used as the session keys for message encryption by the devices, A and B, respectively ($n_A \neq \tilde{P}_{1A}$ and $n_B \neq \tilde{P}_{2B}$).

$\tilde{P}_{2B}$ as a key, a message m_B and T_2 is encrypted into a puzzle Q_B for the device B to solve. Following the same procedure, B can decrypt the received ciphertext Q_B using P_{2B} obtained by hashing its PUF response R_B twice. The recovered plaintext $\tilde{m}_B$ is hashed to generate a proof $\tilde{V}_B$. The proof is sent to A for verification. A compares its received $\tilde{V}_B$ with its generated V_B to complete the mutual authentication between them. Upon successful mutual authentication, A can use P_{2A} as the session key to send encrypted message to B and B can use P_{2B} as the session key to send encrypted message to A. This is because the device B can calculate P_{2A} by hashing its recovered $\tilde{P}_{1A}$ and uses it to decrypt the message sent by the device A. Vice versa, A can also calculate P_{2B} to decrypt the message sent by B.

4 SECURITY ANALYSIS

In this section, the MB logic introduced in Sec. 2.3 and an automatic security verification tool ProVerif [15] are used to formally analyze the security of the proposed protocol. The formal security analysis is based on some assumptions

about the properties of the security primitives discussed below.

Firstly, the PUF is assumed to be secure against micro-probing and physical attacks. This is because the key is not permanently present in digital form like the NVM key. It is derived by the PUF within the hardware only whenever it is required. The CRP generation mechanism cannot be derived by invasive attack or probing into the internal cell structure of the PUF. Doing so will leave a permanent tamper evidence and destroy the PUF functionality, which can be detected easily. As a natural byproduct of the semiconductor manufacturing process variations, the CRPs of the PUF are assumed to have a very high entropy. Although its generation mechanism is inexpensive, such physical disorder is the very hard to be fully characterized. In other words, it is practically infeasible for the adversary to physically clone a PUF, nor guess an unseen response of a PUF by any brute-force approach if the bitlength of the PUF response is sufficiently long. Besides, we assume that the PUF can also be made resilient against side channel attacks using several countermeasures proposed in the literature [25], [26].

Secondly, the hash function used is assumed to be a one-way hash function that possesses perfect pre-image and collision resistances. Pre-image resistance refers to the difficulty of finding any correct input given the output of the hash function, whereas collision resistance refers to the computational complexity of finding two different inputs that hash to the same output value. It should be noted that collision resistance also implies second pre-image resistance. The latter is a property of a hash function to ensure that given an input, it is difficult to find another input that has the same hash output.

4.1 The MB logic Analysis

Upon device deployment, the objective of the enrolment or update phase is to generate authentication mask data ϕ for the device pairs. The MB logic can be used to prove the authenticity and freshness of ϕ . Taking the enrolment/update of the device A for example, the idealized protocol statement is formally described as follows:

$$S \rightarrow A : C_{A,B} \mathcal{R} \text{ENC}(T \mathcal{R} P_{1A} \mathcal{R} ID_B \mathcal{R} \phi_2, P_{1A})$$

ϕ_2 can be proved to be a good shared key between the server S and A after the enrolment and update session: $S \models A \xleftrightarrow{\phi_2} S$, $A \models A \xleftrightarrow{\phi_2} S$. As shown in the tableaux of Figs. 5 (a) and (b), to prove the correctness of $S \models A \xleftrightarrow{\phi_2} S$, the good key rule (6) can be applied first, which leads to two pre-conditions, $S \models \{A, S\}^{c \Delta} \parallel \phi_2$ and $S \models \#(\phi_2)$. Since the protocol is meant for the server to enrol or update the device with a new ϕ_2 , $S \models \#(\phi_2)$ is reasonable. As for the other pre-condition $S \models \{A, S\}^{c \Delta} \parallel \phi_2$, the confidentiality rule (2) can be used and the three resulting assumptions are: 1) $S \models A \xleftrightarrow{P_{1A}} S$; 2) $S \models \{S\}^{C \Delta} \parallel \phi_2$; and 3) $S \models \phi_2$. All the three assumptions are reasonable as the server stores the correct CRP of the device and it indeed transmits its generated ϕ_2 in an encrypted form to A as indicated in the idealized message. Therefore, the correctness of $S \models A \xleftrightarrow{\phi_2} S$ is proved. Similar analysis can be conducted to show the correctness of $A \models A \xleftrightarrow{\phi_2} S$. Note

$$\begin{array}{c}
\frac{S \models A \leftrightarrow S \wedge S \models \{S\}^C \triangleleft \phi_2 \wedge S \models \phi_2}{(2) \quad S \models \{A, S\}^C \triangleleft \phi_2} \wedge S \models \#(\phi_2) \\
(6) \quad S \models A \leftrightarrow S \\
(a)
\end{array}$$

$$\begin{array}{c}
\frac{A \models \#(T) \wedge A \triangleleft \phi_2 \mathbb{R} T \quad A \models A \leftrightarrow S \wedge A \triangleleft \phi_2}{(5) \quad A \models \#(\phi_2) \quad (1) \quad A \models S \models \phi_2} \wedge A \models S \models \{S\}^C \triangleleft \phi_2 \wedge \frac{A \models A \leftrightarrow S \wedge A \triangleleft \phi_2}{(1) \quad A \models S \models \phi_2} \\
(3) \quad A \models S \models A \leftrightarrow S \\
(8) \quad A \models S \models \{A, S\}^C \triangleleft \phi_2 \\
(4) \quad A \models \{A, S\}^C \triangleleft \phi_2 \\
(6) \quad A \models A \leftrightarrow S \\
(b)
\end{array}$$

$$\begin{array}{c}
\frac{A \models \#(T_1) \wedge A \triangleleft m_A \mathbb{R} T_1 \quad A \models A \leftrightarrow B \wedge A \triangleleft m_A}{(5) \quad A \models \#(m_A) \quad (1) \quad A \models B \models m_A} \wedge A \models B \models \{B\}^C \triangleleft m_A \wedge \frac{A \models A \leftrightarrow B \wedge A \triangleleft m_A}{(1) \quad A \models B \models m_A} \\
(3) \quad A \models B \models A \leftrightarrow B \\
(8) \quad A \models B \models \{A, B\}^C \triangleleft m_A \\
(4) \quad A \models \{A, B\}^C \triangleleft m_A \\
(6) \quad A \models A \leftrightarrow B \\
(c)
\end{array}$$

$$\begin{array}{c}
\frac{B \models A \leftrightarrow B \wedge B \models \{B\}^C \triangleleft m_A \wedge B \models m_A}{(2) \quad B \models \{A, B\}^C \triangleleft m_A} \wedge B \models \#(m_A) \\
(6) \quad B \models A \leftrightarrow B \\
(d)
\end{array}$$

$$\begin{array}{c}
\frac{A \models A \leftrightarrow B \wedge A \models \{A\}^C \triangleleft m_B \wedge A \models m_B}{(2) \quad A \models \{A, B\}^C \triangleleft m_B} \wedge A \models \#(m_B) \\
(6) \quad A \models A \leftrightarrow B \\
(e)
\end{array}$$

$$\begin{array}{c}
\frac{B \models \#(T_2) \wedge B \triangleleft m_B \mathbb{R} T_2 \quad B \models A \leftrightarrow B \wedge B \triangleleft m_B}{(5) \quad B \models \#(m_B) \quad (1) \quad B \models A \models m_B} \wedge B \models A \models \{A\}^C \triangleleft m_B \wedge \frac{B \models A \leftrightarrow B \wedge B \triangleleft m_B}{(1) \quad B \models A \models m_B} \\
(3) \quad B \models A \models A \leftrightarrow B \\
(8) \quad B \models A \models \{A, B\}^C \triangleleft m_B \\
(4) \quad B \models \{A, B\}^C \triangleleft m_B \\
(6) \quad B \models A \leftrightarrow B \\
(f)
\end{array}$$

(1): The authentication rule; (2): The confidentiality rule; (3): The nonce-verification rule; (4): The super-principal rule; (5): The fresh rule; (6): The good-key rule; (8): The derived rule.

Fig. 5. The Mao and Boyd logic based security proof of (a) S believes ϕ_{2B} is only available to A and S ; (b) A believes ϕ_{2B} is only available to A and S ; (c) A believes m_A is only available to A and B ; (d) B believes m_A is only available to A and B ; (e) A believes m_B is only available to A and B ; (f) B believes m_B is only available to A and B .

that the secrecy of ϕ_2 is not required. What is important is to ensure that ϕ_2 is provided afresh by a legal server. Therefore, the good-key security analysis that proves the secrecy, authenticity and freshness of ϕ_2 is more than enough to ensure the correctness of the statement.

Next, the security analysis is performed in the mutual authentication phase of the proposed protocol. The following two properties are expected to be satisfied by the protocol:

- 1) Authentication of A to B : B believes A is the correct device with its challenge $C_{A,B}$ and mask ϕ_1 recorded in B . In this case, a honest device B can correctly retrieve the device's PUF secret P_{1A} of A , i.e., $\tilde{P}_{1A} = P_{1A}$.

Therefore, for the honest A and B , we have $A \models A \xrightarrow{P_{1A}} B$ and $B \models A \xleftarrow{P_{1A}} B$.

- 2) Authentication of B to A : A believes B is the correct device with its helper information $C_{A,B}$ and mask ϕ_2 recorded in A . In this case, a honest device A can correctly retrieve the device's PUF secret P_{2B} of B , i.e., $\tilde{P}_{2B} = P_{2B}$. Therefore, for the honest A and B , we have $A \models A \xrightarrow{P_{2B}} B$ and $B \models A \xleftarrow{P_{2B}} B$.

Mutual authentication can be established if only the authorized prover can send out the correct message digests of m_A and m_B (in Fig. 4), that match the ones calculated by their corresponding verifier. In other words, m_A and

m_B should only be made available to the honest IoT peer nodes, A and B . Therefore, the protocol's expected goal is: m_A and m_B are good shared keys between A and B , i.e., $A \models A \xleftrightarrow{m_A} B$, $B \models A \xleftrightarrow{m_A} B$, $A \models A \xleftrightarrow{m_B} B$ and $B \models A \xleftrightarrow{m_B} B$.

According to the idealization rules of the MB logic, the protocol is firstly idealized as follows:

- $Msg_1: A \rightarrow B : ID_A, T_1$
- $Msg_2: B \rightarrow A : ID_A, ENC(m_A \mathcal{R}T_1, P_{1A})$
- $Msg_4: B \rightarrow A : ID_B, T_2$
- $Msg_5: A \rightarrow B : ID_B, ENC(m_B \mathcal{R}T_2, P_{2B})$

The security analysis using the MB logic is shown in Figs. 5(c)-(f). To prove the correctness of $A \models A \xleftrightarrow{m_A} B$, the good key rule (6) can be applied first, which leads to two pre-conditions, $A \models \{A, B\}^{c\triangleleft} \parallel m_A$ and $A \models \#(m_A)$. Next, the fresh rule (5) is applied to prove $A \models \#(m_A)$. Its correctness can be ensured if A believes the freshness of T_1 and has received m_A together with it. The correctness of $A \models \{A, B\}^{c\triangleleft} \parallel m_A$ requires the proof of A trusts B on the condition that m_A is only available to A and B according to the super-principal rule (4). To prove $A \models B \models \{A, B\}^{c\triangleleft} \parallel m_A$, the derived rule (8) is applied to obtain the three assumptions that: 1) $A \models B \models A \xleftrightarrow{P_{1A}} B$; 2) $A \models B \models \{B\}^{C\triangleleft} \parallel m_A$; and 3) $A \models B \xrightarrow{P_{1A}} m_A$. Assumptions 1) and 3) can be further proved with the nonce-verification rule (3) and the authentication rule (1). If the leaves of the tree (Fig. 5(c)), i.e., the initial beliefs, are reasonable, the fact that $A \models A \xleftrightarrow{m_A} B$ can be established. Similarly, the good-key rule and the confidentiality rule can be applied to obtain the initial beliefs for $B \models A \xleftrightarrow{m_A} B$ to be correct. For the two statements to be true, the initial beliefs derived are listed below:

- 1) $A \models A \xleftrightarrow{P_{1A}} B$ and $B \models A \xleftrightarrow{P_{1A}} B$
- 2) $A \models \#(T_1)$ and $B \models \#(m_A)$
- 3) $A \models sup(B)$
- 4) $B \models \{B\}^{C\triangleleft} \parallel m_A$
- 5) $A \models B \models \{B\}^{C\triangleleft} \parallel m_A$
- 6) $A \triangleleft m_A \mathcal{R}T_1$
- 7) $A \xrightarrow{P_{1A}} m_A$
- 8) $B \xrightarrow{P_{1A}} m_A$

Since B is the super-principal for its hashed response P_{1B} and its generated n_A , B is also the super-principal for m_A as $m_A = P_{1B} \oplus n_A$. Besides, T_1 and m_A are freshly generated each time by A and B . Therefore, the initial beliefs 1) to 5) are well satisfied. The remaining beliefs 6) to 8) are also reasonable as indicated by Msg_2 . As shown in Figs. 5(e) and (f), similar analysis can be conducted to prove the authentication of B to A . The resulting initial assumptions and communication events are listed below:

- 1) $A \models A \xleftrightarrow{P_{2B}} B$ and $B \models A \xleftrightarrow{P_{2B}} B$
- 2) $B \models \#(T_2)$ and $A \models \#(m_B)$
- 3) $B \models sup(A)$
- 4) $A \models \{A\}^{C\triangleleft} \parallel m_B$
- 5) $B \models A \models \{A\}^{C\triangleleft} \parallel m_B$
- 6) $B \triangleleft m_B \mathcal{R}T_2$
- 7) $B \xrightarrow{P_{2B}} m_B$
- 8) $A \xrightarrow{P_{2B}} m_B$

By similar arguments and logical theory, all the initial beliefs are reasonable. Therefore, m_A and m_B are fresh in each authentication process and are only available to the honest principals, A and B . Hence, according to the MB logic, mutual authentication between A and B is secure.

4.2 ProVerif Analysis

ProVerif [15] uses the symbolic, Dolev-Yao model [27] of cryptography for analysis. To be more specific, it treats the cryptographic primitives as black boxes, and the messages are viewed as terms on these primitives. The attacker is able to compute the messages but the computation is restricted to the use of only these primitives. Besides, it can intercept, modify, delete and inject messages sent on the network. ProVerif is sound in providing correspondence, reachability and observational equivalence proofs [28]. The proposed protocol introduced in Sec. 3 is translated into ProVerif scripts and arbitrarily many number of sessions and message space are simulated between protocol entities.

4.2.1 Mutual Authentication and Various Attacks

One objective of the proposed protocol is to ensure that the mutual authentication between two IoT peer nodes is valid and secure. The provenance proof of the mutual authentication also indicates the resistance of the protocol against replay and MITM attacks. To test this security property, the following events are declared:

- 1) **event** beginAparam(hostA, hostB)
- 2) **event** endAparam(hostA, hostB)
- 3) **event** beginBparam(hostB, hostA)
- 4) **event** endBparam(hostB, hostA).
- 5) **event** beginAfull(hostA, hostB, keyA, keyB).
- 6) **event** endAfull(hostA, hostB, keyA, keyB).
- 7) **event** beginBfull(hostB, hostA, keyA, keyB).
- 8) **event** endBfull(hostB, hostA, keyA, keyB).

Two different levels of authentication are used. The first four events prove the agreement on the host names only. “**event** beginAparam(hostA, hostB)” means hostB has commenced a run of the protocol with hostA and “**event** endAparam(hostA, hostB)” means hostA believes she has successfully completed the protocol with hostB, and vice versa for “**event** beginBparam(hostB, hostA)” and “**event** endBparam(hostB, hostA)”. The events that end with “full” are used for proving the agreement on all parameters of the protocol. For example, “**event** beginAfull(hostA, hostB, keyA, keyB)” denotes the intention of hostB to launch the protocol with hostA with the shared secret keys “keyA” and “keyB”, and “**event** endAfull(hostA, hostB, keyA, keyB)” means hostA believes she has successfully completed the protocol with hostB with the declared shared secret keys.

If the mutual authentication is established, the following correspondence assertions should hold:

- 1) $\text{inj-event}(\text{endAparam}(\text{hostA}, \text{hostB}))$
 $\Rightarrow \text{inj-event}(\text{beginAparam}(\text{hostA}, \text{hostB}))$
 which means if hostA reaches the end of the protocol and she believes she has completed the protocol with hostB, then hostB should have started a session with hostA. The relationship is injective. Similar implication holds for the following assertions.

- 2) `inj-event(endBparam(hostB,hostA))`
 $\Rightarrow$ `inj-event(beginBparam(hostB,hostA))`
- 3) `inj-event(endAfull(hostA,hostB,keyA,keyB))`
 $\Rightarrow$ `inj-event(beginAfull(hostA,hostB,keyA,keyB))`
- 4) `inj-event(endBfull(hostB,hostA,keyA,keyB))`
 $\Rightarrow$ `inj-event(beginBfull(hostB,hostA,keyA,keyB))`

4.2.2 Reachability and Secrecy

The other objective of the proposed protocol is to evaluate the reachability and secrecy of the shared secrets between the two IoT peer nodes. Reachability evaluation is a basic capability of ProVerif, which tests whether the term under test is reachable to an attacker. In the proposed protocol, the real secrets are the PUF responses of the two IoT devices, i.e., R_A and R_B , to a selected challenge $C_{A,B}$. As the session keys established are the message digests of the PUF responses, if the session keys (P_{2A} or P_{2B}) are kept secret, the underlying PUF responses (R_A and R_B) will remain secret. Therefore, to test the reachability and secrecy of the PUF's CRP in the protocol, we only need to confirm the secrecy of the session keys. In our experiments, the following queries are included to test this property:

query attacker(messageA); attacker(messageB).

where “messageA” (“messageB”) is a free name sent by device B (A) in encrypted form with the encryption key being P_{2A} (P_{2B}) over a public channel after the mutual authentication.

4.2.3 Observational Equivalence

In addition to the above correspondence and reachability proofs, four typical classes of observational equivalence (OE) are also evaluated using ProVerif:

- 1) Strong secrecy:
 This query evaluates if an attacker is able to distinguish when the secrets change. By denoting
noninterf messageA; messageB
 the secrecy of the transmitted “messageA”, “messageB” encrypted by the established session key P_{2A} or P_{2B} can be proved.
- 2) Off-line guessing attacks:
 If the secrets are weak with low entropy, it may be successfully guessed by the attackers without further interaction with the protocol. The absence of off-line guessing attacks against “messageA” and “messageB” can be evaluated by the query:
weaksecret messageA; messageB
- 3) OE between processes that differ only by terms:
 This query tests the equivalence between two processes that have the same structure but different terms, which can be encoded by two single “biprocesses”:
choice[ENC(messageA, P_{2A}), ENC(messageA, randomA)]
choice[ENC(messageB, P_{2B}), ENC(messageB, randomB)]

where the construct “**choice**[term1,term2]” is used to represent the two processes with different terms while *randomA* and *randomB* are freshly generated random values.

- 4) Real-or-random secrecy:

This query evaluates whether the secrets are indistinguishable from the fresh random values. For example,

choice[P_{2A} , randomA]
choice[P_{2B} , randomB]

As shown in Fig. 6, the proposed protocol has successfully achieved mutual authentication (correspondence assertion) and proved the secrecy of the shared keys (reachability) as well as the abovementioned four classes of observational equivalence.

Verification summary:

- (a) • Query **not** attacker(messageA[]) is **true**.
- (b) • Query **not** attacker(messageB[]) is **true**.
- (c) • Non-interference messageA is **true**.
- (d) • Non-interference messageB is **true**.
- (e) • Weak secret messageA is **true**.
- (f) • Weak secret messageB is **true**.
- (g) • Query `inj-event(endBparam(x,y)) ==> inj-event(beginBparam(x,y))` is **true**.
- (h) • Query `inj-event(endAparam(x,y)) ==> inj-event(beginAparam(x,y))` is **true**.
- (i) • Query `inj-event(endBfull(x,y,p1,p2)) ==> inj-event(beginBfull(x,y,p1,p2))` is **true**.
- (j) • Query `inj-event(endAfull(x,y,p1,p2)) ==> inj-event(beginAfull(x,y,p1,p2))` is **true**.
- (k) • Observational equivalence is **true**.
- (l) • Observational equivalence is **true**.

Fig. 6. ProVerif outputs. (a-b): Reachability proof; (c-d): Strong secrecy proof; (e-f): The absence of off-line guessing attacks proof; (g-j): Mutual authentication proof; (k-l): OE between processes that differ only by terms and real-or-random secrecy proof.

5 PROTOTYPE AND COMPARISON

5.1 Hardware Implementation

Fig. 7 shows the prototype implementation of our proposed system. Two Avnet Ultra96-V2 boards are used as the IoT endpoints. Ultra96-V2 is an ARM-based, Xilinx Zynq UltraScale+TM MPSoC ZU3EG A484 development board. It supports PYNQ for Xilinx FPGA device, which means that Python language and libraries are provided for the application development to benefit from both the FPGA programmable logic and ARM microprocessor. The IoT endpoints are assumed to be in the same local area network (LAN). The LAN is created by a router but the router does not participate in the proposed scheme. A personal computer (PC) is used as the local server. The involvement of the local server is only in the enrolment and update phase as described in Sec. 3.

Any PUF with good uniqueness and randomness to minimize the probability of response collision or correlation that may be exploited by the attackers can be embedded into the IoT devices. The PUF can be flexibly selected to meet the device resource or any specific application requirements. A highly reliable PUF will relax the error correction requirement. Though PUF with near perfect reliability has been proposed in the literature [29], without loss of generality, we assume that the PUFs embedded in the devices have high but not perfect reliability. Therefore, ECC is required as the PUF responses are used for key generation in the proposed scheme. In our experiment, the reliable and modelling resistant Arbiter PUF from [30] is chosen for the implementation on the FPGA. The PUF overlay is then loaded into the

Fig. 7. Experimental set up and device A and B's output in the mutual authentication and key exchange phase.

TABLE 3
Comparison with Existing PUF-based Protocols without CRP Storage

Protocols	Computational Complexity		NVM Secret Free
	Single Node	Third Party*	
JIoT2017 [19]	$1N_H + 5N_{UMAC} + 2N_{PUF} + 3N_{Enc}$	$2N_H + 4N_{UMAC} + 4N_{Enc}$ (Server)	Yes
TDSC2018 [13]	$9N_H + 1N_{PUF} + 1N_{ECC} + 3N_{PA} + 2N_{PM} + 1N_{BP}$	$24N_H + 10N_{PA} + 4N_{PM} + 2N_{BP}$ (Verifier), -(SAP)	No
Elsevier2019 [18]	$4N_{PUF}$	-(Authentication service)	Yes
JSEN2021 [20]	$6N_H + 1N_{PUF} + 1N_{ECC} + 3N_{PA} + 7N_{PM}$	-	Yes
This Work	$4N_H + 1N_{PUF} + 1N_{ECC} + 2N_{Enc}$	-	Yes

*: In this column, “-(third party name)” means the third party doesn’t have to perform computation but serves as an authentication helper data provider; ‘-’ means no third party is needed.

ARM core for system design. The remaining cryptographic modules such as ECC and hash are directly imported from Python libraries. For demo purpose, the proposed protocol is designed on top of the network socket. The outputs of devices A and B in the authentication process are indicated in Fig. 7. It shows that the proposed mutual authentication and key exchange can be successfully conducted. The one-round transmission time, i.e., from the time the device A prepares the encrypted data (the puzzle) for transmission to the time A receives the encrypted data (the proof) from the device B, is only 27.8 ms. This latency is considered low for the device and communication link we used for this demonstration. As only public information, i.e., device identity, challenge, ECC helper data and authentication mask, are stored in the device, the storage and security requirements in the device side are also low. As in the experiment, one such record is only 78 bytes if the device identity is presented by its IP address and a 128-bit PUF and SHA256 are used.

5.2 Comparison With Existing Works

There are only limited existing works [13], [18], [19], [20] that are able to achieve PUF-based device to device authentication without the need to store the CRPs in the verifier’s side. In this section, only the related protocols in the existing works are compared, i.e., protocols in Fig. 3 of [13], [19] and [20], the BC-PHEMAP protocol in [18], and our proposed mutual authentication and key-exchange protocol presented in Fig. 4. The computational complexity both on the side of a single device node and that of a third party (if any) are listed and compared. Another important factor for protocol comparison is whether a locally stored device key is required (NVM secret free). Let N_H , N_{UMAC} ,

N_{PUF} , N_{ECC} , N_{Enc} , N_{PA} , N_{PM} and N_{BP} denote the numbers of rounds of hash function, message authentication code based on universal hashing (UMAC), PUF, error correction code for PUF, encryption and decryption, point addition over elliptic curve, point multiplication over elliptic curve and bilinear pairing, respectively. Since the proposed protocol does not dictate the type of cryptographic modules such as PUF and hash as long as they meet the required functionality with acceptable implementation cost, Table 3 only lists the names of the cryptographic modules for a fair comparison. Similarly, for an implementation platform independent comparison of computational complexity, the number of rounds for each required operation is listed and compared. Trivial operations like concatenation or bitwise exclusive OR are omitted without impacting the relative accuracy of the comparison.

As shown in Table 3, the scheme [13] is the only one that requires a locally stored key and the three schemes [13], [18], [19] all require a third party to complete the mutual authentication between devices. The schemes [13] and [20] have the highest computational complexity among all as they both require public cryptography over elliptic curve for the protocol execution. The scheme [13] requires one bilinear pairing operation and two point multiplications to be performed in each device side while the work [20] requires seven rounds of point multiplications at each device side. A point multiplication over elliptic curve *secp256r1* consumes around 112.34 ms on TI’s CC2538 SoC (SHA256 only consumes around 0.061 ms in the same platform) [20]. As for bilinear pairing, it is widely regarded as an expensive operation for terminal devices [31]. The scheme of [18] is lightweight but its practicality is severely constrained by

the PUF reliability problem. Besides, as analyzed in Sec. 2.2, it is also vulnerable to modelling attacks. As UMAC has similar computational complexity as hash operation [19], the computational complexity of the scheme of [19] can be approximated by $6N_H + 2N_{PUF} + 3N_{Enc}$. To deal with the PUF reliability problem of this work, $2N_{ECC}$ has to be added. Therefore, the overall complexity of [19] is estimated to be higher than our proposed scheme in addition to the need of a trust server. Besides the high performance, privacy and security achievable with typical device-side components, our proposed protocol outperforms those existing schemes in terms of achieving lost-cost direct P2P connection without the need for a secret key to be stored locally in the device.

6 CONCLUSION

This paper presents a PUF-based protocol for direct mutual authentication, automatic key-exchange and direct data transmission between IoT end devices. The proposed protocol overcomes the PUF's bottleneck in providing direct mutual authentication between resource-constrained devices without going through a proxy server. The requirement to store and safekeep a database of all provers' CRPs in the verifier's local memory is not only difficult to be satisfied by the resource-limited IoT devices, but the locally stored secret is also vulnerable to hardware attacks due to the accessibility of IoT endpoint devices. This security problem is solved by creating and storing the authentication mask data that do not need to be kept private in the device side. A new and important side benefit of the proposed protocol is that secure key-exchange between the two endpoints is directly established upon successful mutual authentication with neither additional flight message transfer nor complex public-key algorithm. Formal MB logic analysis and ProVerif simulation have been performed to prove the security soundness of the proposed protocol. The hardware cost and computational complexity are reasonably low in comparison with the existing PUF-based CRP-storage-free authentication protocols.

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