Secure Authentication Schemes for Internet of Things (IoT)

by

Moneer Ramadan Fakroon
B.Sc., Faculty of Engineering/Misurata University, Libya, 2009
M.Sc., Nottingham Trent University, UK, 2012
M.Eng., Victoria University, Canada, 2018

A Dissertation Submitted in Partial Fulfillment of the Requirements for
The Degree of
DOCTOR OF PHILOSOPHY
in the Department of Electrical and Computer Engineering

Secure Authentication Schemes for Internet of Things (IoT)

by

Moneer Ramadan Fakroon
B.Sc., Faculty of Engineering/Misurata University, Libya, 2009
M.Sc., Nottingham Trent University, UK, 2012
M.Eng., Victoria University, Canada, 2018

Supervisory Committee

Dr. Fayez Gebali, Supervisor
(Department of Electrical and Computer Engineering, University of Victoria)

Dr. T. Ilamparithi, Departmental Member
(Department of Electrical and Computer Engineering, University of Victoria)

Dr. Alex Thomo, Outside Member
(Department of Computer Science, University of Victoria)

Supervisory Committee

Dr. Fayez Gebali, Supervisor
(Department of Electrical and Computer Engineering, University of Victoria)

Dr. T. Ilamparithi, Departmental Member
(Department of Electrical and Computer Engineering, University of Victoria)

Dr. Alex Thomo, Outside Member
(Department of Computer Science, University of Victoria)

Abstract

Smart home technology is an emerging application of Internet-of-Things (IoT) where the user can remotely control home devices. Since the user/home communication channel is insecure, an efficient and anonymous authentication scheme is required to provide secure communications in smart home environment. In this work, we propose a new scheme for user authentication that combines physical context awareness and transaction history. The new scheme offers two advantages: it does not maintain a verification table and avoids clock synchronization problem. Communication overhead and computational cost of the proposed scheme are analyzed and compared with other related schemes. The security of the scheme is evaluated using three different methods: (1) formal analysis using the Burrows-Abadi-Needham logic (BAN); (2) informal analysis; (3) model check using the automated validation of internet security protocols and applications (AVISPA) tool. Also, we aim to propose a new anonymous device to device mutual authentication and key exchange scheme. such scheme enables IoT devices to authenticate in the network and agree on a shared secret session key when communicating with each other via a trusted intermediary (home gateway).

Contents

List of Tables

List of Figures

List of Acronyms

AES	Advanced Encryption Standard
AVISPA	Automated Validation of Internet Security Protocols and Applications
BAN	Burrows–Abadi–Needham
CLAtSe	Constraint-Logic-based Attack Searcher
ECC	Elliptic Curve Cryptography
HLPSL	High-Level Protocol Specification Language
ID	Identification
IF	Intermediate Format
IoT	Internet of Things
OFMC	On-the-fly Model-Checker
SATMC	SAT-based Model-Checker
SPAN	Security Protocol Animator
TA4SP	Tree Automata based on Automatic Approximations for the Analysis of Security Protocols
XOR	Exclusive OR

Chapter 1

Introduction

1.1 Context

The term Internet of Things (IoT) was first coined by Kevin Ashton in 1999 in the context of supply chain management [1]. The most recent IoT platforms were designed based on a diverse mixture of readapting existing components, solutions, protocols, and platforms for different purposes in terms of their development and enhancement.

IoT devices are often resource-constrained and deployed in unmonitored, physically unsecured environments. However, although there is an urgent need to secure IoT infrastructures, this necessity is confronted with the aforementioned resource limitations of the infrastructure underlying platforms and devices.

One of the essential aspects of securing an IoT infrastructure is the device identity and the mechanisms to authenticate it. Authentication is one of the Achilles' heels of the current IoT infrastructure.

As a matter of fact, many IoT devices have weak passwords or are still using manufacturer-issued default passwords, which make them vulnerable to botnets (e.g., the Mirai IoT botnet) [2] and exploit kits specially designed to target IoT networks. At the same time, hackers can connect rogue devices to IoT networks using fake or multiple identities without being caught.

The enactment of the above threats is made possible because the landscape of IoT authentication is still in its infancy [3]. Furthermore, existing authentication mechanisms involve heavy computations that cannot be afforded by IoT devices, which, as mentioned earlier, are resource-constrained. Additionally, these authentication mechanisms also require a degree of user intervention in terms of configuration

and provisioning. Furthermore, many IoT devices have limited access, thus requiring the initial configuration to be protected from tampering, theft and other forms of compromise throughout the device's usable life, which, in many cases, could be years.

1.2 Research Problem

Despite the growing interest in IoT products and services and the advancements in its underlying technology, IoT devices and networks are exposed to a wide variety of security threats, some of which are well-known and part of the existing attack arsenal against conventional systems, while others involve novel attack vectors that are specific to the IoT technology and remain unknown until they are detected in the network [4], [5], [6] and [7].

One of the principal aspects in making an IoT infrastructure secure is the underlying IoT node authentication mechanism. The resource-constrained IoT nodes cannot afford the current authentication mechanisms due to the complex computations involved in these mechanisms [8, 9]. Moreover, the existing authentication mechanisms involve a high level of user intervention in configuring and controlling the devices.

Unlike conventional network devices, IoT nodes, which are usually deployed in unmonitored and unsecured environments, have limited access; hence, their initial configurations need to be protected against any kinds of external or insider threats or compromises during the lifetime of the IoT node. Additionally, due to the fact that most IoT devices are weak and resource constrained, the cryptographic techniques used can easily be exploited and broken. Hence, compromising one node could lead to the compromise of the entire IoT network.

Moreover, authentication necessitates identification through a unique identifier. As time goes by, attackers can trace transactions linked to the same identity, thus leading to privacy breach.

In an IoT domain such as smart home, transaction's traceability may result in tracing the lifestyle of the household or deducing from the data, sensitive information, such as health and credit history, living arrangements, and so on [10]. Hence, anonymity, unlinkability, and untraceability [11, 12, 13] are important key properties when designing and operating authentication mechanisms for IoT networks, as these prevent an adversary from obtaining the real identity of an IoT end device and from linking any given session to any other session of the same device.

Consequently, there is a necessity to introduce new mechanisms to authenticate

and control IoT nodes in a secure way that must be compatible with the environmental and engineering limitations underlying the IoT ecosystem. In this work, we present different protocols to authenticate IoT nodes while addressing security and privacy, and performance considerations.

The Internet of Things (IoT) defines an ecosystem where each thing can be any physical or virtual object, identified and reached by other objects and showing smart capabilities. Such smart things are characterized by embedded electronic components that allow them to sense, compute, communicate and integrate seamlessly with the rest of the network. It has been forecast, based on Moore's law, that by 2025 the number of IoT devices will exceed 7 trillion, distributed with an average of 1000 devices per person.

IoT devices are often resource-constrained, and deployed in unmonitored, physically unsecured environments. As such there is an urgent need to secure IoT infrastructure.

One of the fundamental elements in securing an IoT infrastructure is around device identity and mechanisms to authenticate it. However, existing authentication mechanisms involve heavy computations which cannot be afforded by IoT devices, which as mentioned earlier are resource-constrained. Many IoT devices do not have the required compute power, memory or storage to support the current authentication protocols, which rely on computationally intensive cryptographic algorithms, e.g., AES and RSA [14] and [15]. Additionally, these authentication mechanisms also require a degree of user-intervention in terms of configuration and provisioning. However, many IoT devices will have limited access, thus requiring initial configuration to be protected from tampering, theft and other forms of compromise throughout its usable life, which in many cases could be years.

Recently, large swathe of the Internet was brought down in a distributed denial of service (DDoS) attack carried out using the Mirai IoT botnet. Mirai propagates by brute-forcing IoT device passwords via Telnet in a way that is much faster and less resource-intensive than traditional botnet.

Hence, relying on only on password-based solutions is not a viable option, as passwords can easily be broken, and many IoT devices do not provide an interface through which password authentication can take place.

1.3 Approach

To address the aforementioned security challenges, we propose a new secure mutual authentication and key exchange scheme for the IoT based on transient or dynamic identities. The dynamic identity of IoT nodes (DIdoT) is a new concept for uniquely identifying IoT nodes.

The DIdoT is constructed from fixed and variable components, and evolving time-dependent component. The fixed component is created from fixed parameters of the IoT node, which is the node ID. The variable component is created from a random number generator.

The time-dependent component is created from the time stamp. These different components are hashed together using SHA-3 as a hashing algorithm, which provides a tunable parameter allowing a tradeoff between security and performance. The real identity is kept secret and never transmitted by the IoT node. This guarantees uniqueness of identities of the IoT nodes and mitigates the possibilities of identities theft attacks such as impersonation and sybil attacks. Another new concept is temporal keys (TKs) that change every session. The TKs are constructed from fixed and variable components. The fixed component is created from a fixed parameter of the IoT node, which is the node ID. The variable component is created from a random number generator. These two different components are hashed together using SHA-3, and as aforementioned, the hashing algorithm provides a tradeoff between security and performance. This continuously variable nature of the identity significantly limits the impact of brute-force attacks by limiting the session key lifetime.

According to a survey carried out by CA Technologies on the state of insider threat in 2018 [16], 90% of surveyed organizations felt that they were vulnerable to insider attacks and 53% of organizations pointed out that they have been the target of insider attacks during the year.

Although most organizations focus on how to defend against external attacks, they sometimes put considerably less efforts into defending against internal attackers or rather ignore them. As the IoT devices are ubiquitous and unattended, internal attackers will play a big role in cyber security threats and may cause serious issues.

Moreover, due to the fact that most IoT devices are weak and resource-constrained, the cryptography techniques can easily be exploited and broken. Hence, compromising one node could make it easy to take control of the other IoT devices. By securing IoT identities, we can maintain the CIA triad: confidentiality, integrity, and availabil-

ity. If an attacker succeeds in impersonating an identity on an IoT node, all security measures, such as authentication and access protection, make no sense.

1.4 Contributions

In this thesis, we make two key contributions as follows:

1. Propose a new scheme for user authentication that combines physical context awareness and transaction history.

2. Propose a secure telehealth system using multifactor authentication for the mobile devices as well as the IoT edge devices in the system

1.4.1 List of publications

1. M. Fakroon, M. Alshahrani, F. Gebali, and I. Traor‘e, “Secure remote anonymous user authentication scheme for smart home environment,” Internet Things, vol. 9, pp. 100–158, 2020.

2. M. Fakroon, F. Gebali, and M. Mamun, “Multifactor authentication scheme using physically unclonable functions,” Internet of Things, p. 100343, 2020.

1.5 Thesis Outline

The remainder of this thesis is organized as follows.

Chapter 2 provides an overview of the literature underlying this research. It provides a quick introduction to the Internet of Things and authentication. Also, this chapter provides an outline of the related security methods and tools used in this research.

Chapter 3 summarizes and discusses related work on authentication.

Chapter 4 describes our first proposed authentication scheme and introduces the enforcement of the security policy. The proposed scheme achieves different security properties, anonymity, unlinkability, and conditional traceability.

Chapter 5 presents the second proposed authentication scheme. The scheme achieves different security properties, anonymity, unlinkability, and conditional traceability, in addition to the important dual properties of confidentiality and integrity.

Chapter 6 concludes the thesis by discussing the contributions of the research and outlining future work.

Chapter 2

Related works

In this section, we summarize and discuss related work on user authentication scheme for smart home environment.

Jeong et al. [17] proposed a user authentication scheme based on one-time password (OTP) protocol. This scheme is lightweight because it uses one-way hash functions. However, the mutual authentication between Gateway node (GWN) and the smart device is not provided. Moreover, the anonymity and traceability properties are not achieved as the real identity of the user is sent in plain-text. In addition, the scheme is not immune from stolen smart card and privileged–insider attack.

Roman et al. [18] attempted to solve IoT security via different IoT topologies: centralized architectures [19] and distributed architectures. Again, these solutions does not consider the available resources in IoT devices and only emphasize high level structures of these topologies.

Other research concentrates on the protected communication between IoT devices. For instance, Mahalle et al. [20] proposed an Identity Authentication and Capability based Access Control (IACAC) model to secure communication between IoT devices and protect from replay, man-in-the-middle and denial of service (DoS) attacks.

Vaidya et al. [21] proposed one-time password authentication scheme for home network environment. This scheme is also lightweight as it uses only hash-chaining methods and hashed one-time password. Kim et al. [22] studied Vaidya et al.'s scheme and indicated that it does not provide user anonymity and forward secrecy. Furthermore, it is vulnerable to password guessing attack. An enhanced authentication scheme is proposed subsequently where they improved the weakness observed in Vaidya et al.'s scheme [21]. However, Kim et al.'s scheme also suffered from guessing attack, user impersonation attack and privileged-insider attack. Moreover, the

anonymity and traceability properties were not achieved.

Santoso et al. [23] proposed a user authentication scheme for a smart home system based on elliptic curve cryptography (ECC). Similar to the schemes in [17, 21, 22], the anonymity and traceability properties were not provided. In addition, the scheme is not immune against privileged-insider attack and stolen smart card attack.

Kumar et al. [24] proposed a lightweight and secure session key establishment scheme for smart home environments. Using a short authentication token, a session key was established between GWN and smart device.

Wazid et al. [25] proposed a new secure remote user authentication scheme for a smart home environment. The scheme only utilizes the one way hash function and XOR operation as result it is efficient for resource-constrained smart devices. However, this scheme uses a verification table saved in the GWN's database which if it was stolen by the attacker, then the result is disastrous. In addition, the proposed scheme suffered from synchronization attack as it uses time stamp to resist replay attack.

Shuai et al. [26] proposed a remote authentication scheme for smart home environment using ECC. The scheme did not require to store the verification table for authentication purposes. However, the scheme suffers from unsatisfactory performance in terms of computational and communication costs.

Chen et al. [27, 28] proposed a new scheme for patient's privacy based on the cloud computing. Mobile device characteristics were used to allow people to use medical resources on the cloud environment. The scheme did not support patient anonymity or message authentication.

Chiou et al. [29] improved on the scheme proposed by Chen et al. [27] to reduce computation costs while achieving patient anonymity and unlinkability, and message authentication.

Mohit et al. [30] proposed a mutual authentication protocol for cloud computing based telehealth system. However Li et al. [31] found design flaws in the proposed protocol in that it did not provide security against health report revelation, inspection report forgery and patient anonymity and unlinkability.

Yu and Li [32] proposed an anonymous authentication key agreement scheme for multi-sensor home-based IoT. The proposed scheme used lightweight authentication and key agreement technology using pairing-based cryptography. A lightweight scheme was used due to the limited communication and processing capabilities of the edge devices.

The authors in [33] focused on reviewing data security using blockchain in the IoT for telehealth. These authors summarized possible IoT attacks in general as physical attacks, network attacks, software attacks and encryption attacks. The authors argue that telehealth is at the top of digital technologies that are at risk from cyber attacks. The authors stated that medical data is attacked where it is stored or when it is being transferred from one location to another.

Islam et al. [34] provided a survey of IoT for telehealth including proposed architectures for efficient telehealth delivery. Telehealth implies delivery of telehealth to stay-at-home patients through the internet cloud and remotely-located IoT networks.

2.1 Discussion

It appears from the above summary that most of the works on authentication protocols are dependent on symmetric and asymmetric algorithms, and it is known that asymmetric encryption requires much more computation than what the constrained resource devices in IoT can afford. However, a number of research studies have introduced the potential of using lightweight cryptographic functions such as hash function and bitwise XOR, but they did not consider strong mutual authentication; thus an efficient mutual authentication framework remains a challenge for the IoT ecosystem [35], [36] and [37].

Chapter 3

Background

In this chapter, we provide background information on the Internet of Things and authentication. Furthermore, we give an overview of the validation and evaluation methods and tools used in our work.

3.1 Internet of Things and Authentication

The Internet of Things (IoT) is one of the most recent emerging and advanced computing paradigms set forth in the 21st century, which connects both living and non-living things with non-living things into ecosystems. The IoT refers to everyday objects that can sense the environment around them and communicate that data to other objects and services via the Internet without any intervention from human or living bodies.

The IoT integrates several existing technologies, such as wireless sensor networks (WSN), which appeared since the 1980s. WSN technology is an essential component of IoT because it is composed of a collection of sensor nodes connected wirelessly to one another, which provide digital interfaces to the real-world things [38]. However, WSN is different from IoT in a number of respects. One of the important differences is that WSN is comprised of a large number of connected sensors' nodes that are capable of performing sensing and data collection while IoT system consists of a large number of interconnected objects, things, sensors, devices, etc., which are able to provide value-added services such as location and analytic via utilizing intelligent data processing and management for several applications. Another important difference is that in the IoT infrastructure, it is required to provide the nodes with Internet connectivity, whereas, Internet connectivity is not required in WSN.

Furthermore, many IoT devices do not have the required compute power, memory, or storage to support the current authentication protocols, which rely on computationally intensive cryptographic algorithms, e.g., AES and RSA [39].

Authentication requires identification by means of a unique identifier, and over time transactions associated with the same identity can be traceable, leading to privacy breach. In an IoT environment such as smart home, transactions traceability can be used to track the lifestyle of the household or infer from the data, critical information such as health and credit history, living arrangements and patterns, and so on [40].

Anonymity and unlinkability are privacy-preserving mechanisms, which make user transactions traceability much harder. Although a number of authentication schemes have been proposed for IoT, to our knowledge, none of these contributions has considered full anonymity of the IoT sensor nodes during the authentication or access control processes.

3.2 Burrows–Abadi–Needham Logic

Burrows et al. [41] introduced the Burrows–Abadi–Needham (BAN) logic, which is used to describe and analyze the authentication protocols. The BAN logic has widely been used for the formal verification of security protocols and to provide the proof of correctness of any authentication protocol [42]. Hence, we capitalize on the widely-accepted BAN logic to prove that our authentication scheme provides secure mutual authentication between an IoT node N and the controller CRN. In this subsection, we present a summarized introduction about the essential symbols and rules of BAN logic.

3.2.1 A brief introduction of important symbols and rules of BAN

The most important symbols and notations adapted from [41] which are given in Table 4.2.

Table 3.1: Notations in BAN logic.

Notation	Descriptions
P and Q	Principals
$P \mid \equiv$ X	Principal P believes the statement X
$P \triangleleft$ X	Principal P sees the statement X
$P \mid \Rightarrow$ X	Principal P has jurisdiction over the statement X
$P \mid \sim$ X	Principal P once said statement X
(X, Y)	The statement X or Y is one part of message (X, Y)
$< X >_Y$	The statement X is encrypted with the key K
$(X)_K$	The statement X is hashed with the key K
$P \overset{K}{\longleftrightarrow} Q$	K is a secret parameter shared (or to be shared) between P and Q
$P \overset{K}{=\!\!=} Q$	X is a secret known only to P and Q, and possibly to parties trusted by them.
# (X)	The message X is *fresh*.

3.2.2 A brief introduction of BAN logic's rules

The following commonly used BAN logic rules are utilized to prove that the authentication scheme ensures secure mutual authentication and key agreement:

- Message-meaning rule:
  If P believes that the key K is shared with Q and P sees X encrypted under K, then P believes that Q once said X.

$$\frac{P| \equiv Q \overset{K}{\leftrightarrow} P, P \triangleleft \langle X \rangle_K}{P| \equiv Q| \sim X}$$

- Nonce verification rule:
  If P believes X is fresh and P believes Q once said X, then P believes Q believes

X.

$$\frac{P| \equiv \#(X), P| \equiv Q| \sim X}{P| \equiv Q| \equiv X}$$

- Jurisdiction rule:
  If P believes Q has jurisdiction over X and P believes Q believes X, then P believes X.

$$\frac{P| \equiv Q| \Longrightarrow X, P| \equiv Q| \equiv X}{P| \equiv X}$$

- Freshness conjuncatenation rule:
  If one part of a statement is fresh, then the entire statement must also be fresh; so if P believes X is fresh, then P believes X and Y are fresh.

$$\frac{P| \equiv \#(X)}{P| \equiv \#(X, Y)}$$

- Belief rule:
  If P believes X and Y, then P believes X .

$$\frac{P| \equiv (X, Y)}{P| \equiv X}$$

- Session keys rule:

$$\frac{P| \equiv \#(X), P| \equiv Q| \equiv X}{P| \equiv P \overset{K}{\leftrightarrow} Q}$$

3.3 Attacker Model

A better understanding of threats helps us make better decisions about where to deploy defensive techniques. Dolev–Yao's threat model [13] is employed to anticipate any security issues in our IoT network model. The attacker model is based on the following two assumptions:

- Cryptography is secure:

1. The attacker is not able to decrypt a message without the key.
2. The attacker is not able to compute HMAC without the key.
3. The attacker is not able to guess an encryption key or a nonce.

- The attacker has a complete control over the system, so it has the ability to do the following:

1. The attacker is able to initiate any number of parallel protocol sessions.
2. The attacker is aware of all the public data of the protocol.
3. The attacker benefits from all the privileges/keys of bad agents.
4. The attacker is able to read, store, and block every message in transit.
5. The attacker is able to create and transmit messages.
6. The attacker is able to construct and deconstruct messages.
7. The attacker is able to encrypt/decrypt if the encryption/decryption key is known.

The Dolev-Yao threat model aids in evaluating the security features of the proposed scheme. Hence, the security analysis and simulation of our scheme are provided using this model.

3.4 AVISPA Tool

Armando et al. [43] introduced Automated Validation of Internet Security Protocols and Applications (AVISPA), which is a toolkit used to validate and assess the Internet Security Protocols and Applications.

AVISPA is a widely used platform in the research community for security protocol validation, and to demonstrate proof-of-concept, the authors have expressed and evaluated the specifications of several industrial-scale security protocols currently being drafted or standardized [44].

AVISPA is a role-oriented language where each agent plays a distinct role during the execution of the given protocol. The security protocols can be defined and specified under the AVISPA tool using High-Level Protocol Specification Language (HLPSL). HLPSL's semantics rest on Lamport's Temporal Logic of Actions (TLA).

The main goal of HLPSL is to provide a means for verifying security properties such as data secrecy and authentication in message exchanges between agents. HLPSL provides a separate section to define the security properties, named the goal section. Thus, the security protocol is determined, whether SAFE or not based on predefined goals.

HLPSL specifications are automatically translated into a lower language named the Intermediate Format (IF) using the HLPSL2IF translator. The main goal of these translations and designing the IF language is to offer and serve an adequate input to the various back-ends of the AVISPA tool set.

AVISPA has the following four back-end tools:

- OFMC Model Checker: The On-the-Fly Model-Checker (OFMC) incorporates several symbolic techniques and algebraic properties to explore the state space in a demand-driven way.
- CL-AtSe Model Checker: The Constraint-Logic-based Attack Searcher (CL-AtSe) translates any security protocol specification written as a transition relation in IF language into a set of constraints that are effectively used to discover attacks if any on the protocol.
- SATMC Model Checker: SAT-based Model checker (SATMC) constructs a propositional formula based on Transitional state obtained from the IF specification. The propositional formula represents any violation of the security properties, which can be translated into an attack.
- TA4SP Model Checker: The Tree Automata based on Automatic Approximations for the Analysis of Security Protocols (TA4SP) identifies the vulnerability of a protocol or predicts the protocol correctness by accurate estimation of the intruder's capabilities.

3.5 Summary

This chapter provided a brief overview of the concepts, paradigms, and tools used in our work. The next chapter focuses on the main theme of this thesis by surveying and discussing related work.

Chapter 4

Secure remote anonymous user authentication scheme for smart home environment

This chapter introduces secure remote anonymous user authentication scheme for smart home environment.

4.1 The proposed scheme

In this section, we discuss our proposed secure remote anonymous user authentication scheme. The proposed scheme uses context-awareness and transaction history to achieve the desirable security features. A typical high-level architecture of smart home environment is illustrated in Fig. 4.1 adapted from [24, 25, 26].

There are four types of participants: User devices, Home devices (smart devices), gateway and registration authority. Every smart device, and GWN is securely registered offline at the registration authority (RA). At that point the user who needs to access the smart device requires to register at the registration authority by offering his/her necessary information.

Each user has a mobile device (MD_i) capable of reading the credentials supplied by that user, such as identity, password and biometrics (fingerprint scanning, etc.).

The gateway is responsible for managing the communication between the home

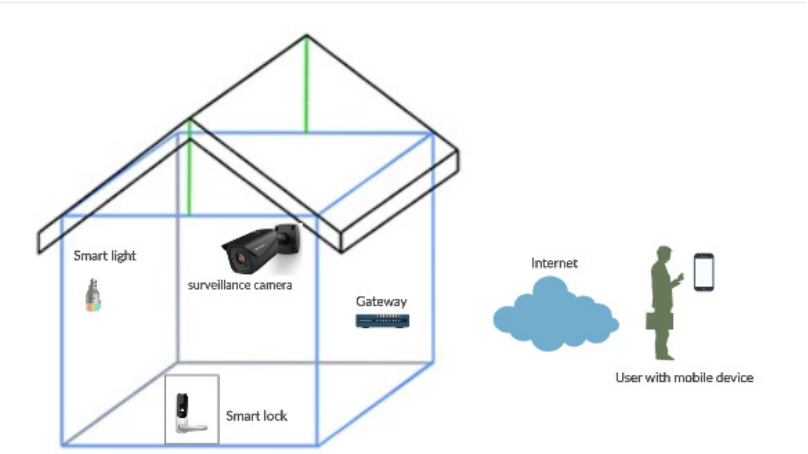


Figure 4.1: high-level architecture of smart home environment

devices and user devices. The authentication request of the authorized user is sent to the GWN and then the GWN sends the request to target smart device. The smart device sends corresponding reply to the GWN and then the GWN forwards the response to the user. Our scheme has five phases:

1. Pre-deployment phase
2. Registration phase
3. Login phase
4. Authentication phase
5. Password update phase

For convenience, the notations mentioned in the proposed scheme presented in the Table 4.1.

4.1.1 Pre-deployment phase

The pre-deployment phase takes place at the manufacturer's site before the devices are deployed. The mobile devices will be loaded with unique symmetric key K_{ur} shared between the registration authority and each mobile device. The smart devices also will be loaded with unique symmetric key K_{sr} shared between the registration authority and each smart device. Lastly, the gateway will be loaded with unique symmetric key K_{gr} shared between the registration authority and gateway.

Table 4.1: Notations used in our protocol.

Notation	**Descriptions**
U_i	Mobile User
ID_{Ui}	Identity of user
PW_i	Password of users
TID_{Ui}	Temporary identity of user
MD_i	Mobile device of i^{th} user
GWN	Gateway node
GID	Unique identity of GWN
SD_j	Smart device in the home
SID_j	Unique identity of SD_j
RA	Registration authority
K_{ur}	Symmetric key shared between the registration authority and each mobile device
L_P, L_C	The previous and current location, respectively
X_n	The history of all user locations
$HMAC$	keyed-hash message authentication code
N_1, N_2, N_3	Current nonces generated by U_i, GWN and SD_j, respectively
SK	Session key
$M_1 \| \| M_2$	Concatenate operation
$(X)\_K$	Message X encrypted with K
$h(\cdot)$	One-way hash function
$\oplus$	XOR operation

4.1.2 Registration phase

Each smart device in the smart home and the gateway have to be register with the RA. Moreover, each user needs to access a smart devices SD_j has to register with the RA. The registration phase consists of two parts.

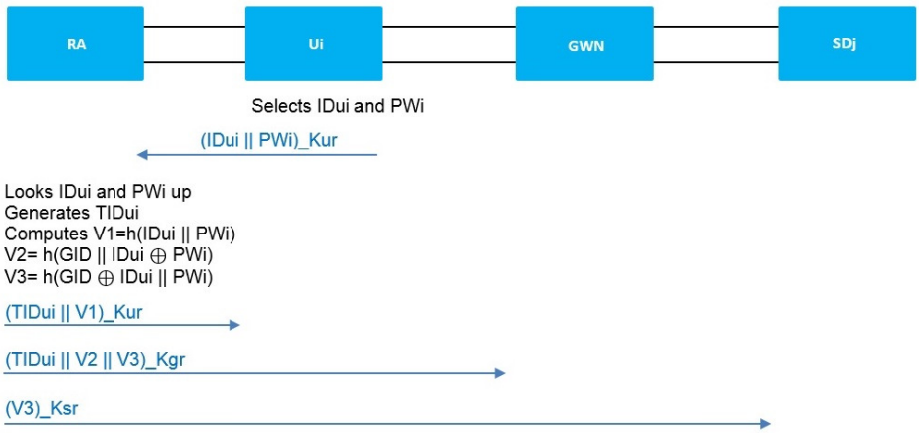


Figure 4.2: Registration phase of the proposed scheme

Smart device and gateway registration step:

This step is done offline. Assuming in the smart home environment, there are j^{th} smart devices (SD_j) and one gateway. The RA selects unique identity for the gateway GID and each smart device SID_j.

User registration step:

Assume that there are i^{th} users U_i. Each user selects the identity ID_{Ui} and a generates password PW_i, the user then needs to supply his/her identity and password to the MD_i, which then encrypts the ID_{Ui} and PW_i using the symmetric key K_{ur} and send them to RA.

$$U_i \rightarrow RA : (ID_{Ui}||PW_i)\_K_{RA} \tag{4.1}$$

Upon receiving the ID_{Ui} and PW_i, RA will look them up in its database. If they exist, this indicates that the user is trying to update his/her credentials, the RA will then ask the user to re-submit the identity and password again.

The identity and password update phase are explained in Section 4.1.5. Otherwise, the RA generates a temporary identity for the user TID_{Ui} and computes the following

parameters:

$$V_1 = h(ID_{Ui}||PW_i) \tag{4.2}$$

$$V_2 = h(GID||ID_{Ui} \oplus PW_i) \tag{4.3}$$

$$V_3 = h(GID \oplus ID_{Ui}||PW_i) \tag{4.4}$$

RA sends back TID_{Ui} and V_1 to the user, TID_{Ui} and V_3 to the smart device and *TID*, V_2 and V_3 to the gateway as shown in Fig. 4.2.

When MD_i receives the TID_{Ui} and V_1, it will generate variable *Counter* and set it to 0. Finally, the user, gateway and smart device store the received parameters in their databases.

4.1.3 Login phase

The user inputs his/her identity ID_{Ui} and password PW_i into the mobile device, which compute V_1^*, and check if $V_1^* \neq V_1$ then the mobile device terminates the login request, increments the counter and check if it reaches predetermined value for instance 3, this mean the mobile device is breached, then the mobile device terminates the login request immediately until the user re-registers again. Otherwise, the user is authenticated and can access the application on his/her mobile device.

4.1.4 Authentication phase

Referring to Fig. 4.3, the mobile device generates a nonce N_1, then computes the dynamic identity.

$$DID_{Ui} = TID_{Ui} \oplus N_1 \tag{4.5}$$

The DID_{Ui} will be unique in each session. Hence, the anonymity and untraceability proprieties are achieved. Next, the user chooses target smart device, defined by its identity SID_j.

The mobile device extracts its current location L_C and performs the following iterative hashing operation preformed at session n

$$X_n = h(X_{n-1}||L_C), \quad n > 0 \tag{4.6}$$

$$X_0 = 0 \tag{4.7}$$

where X_n represents the hash of cumulative locations or the hashed history of all user

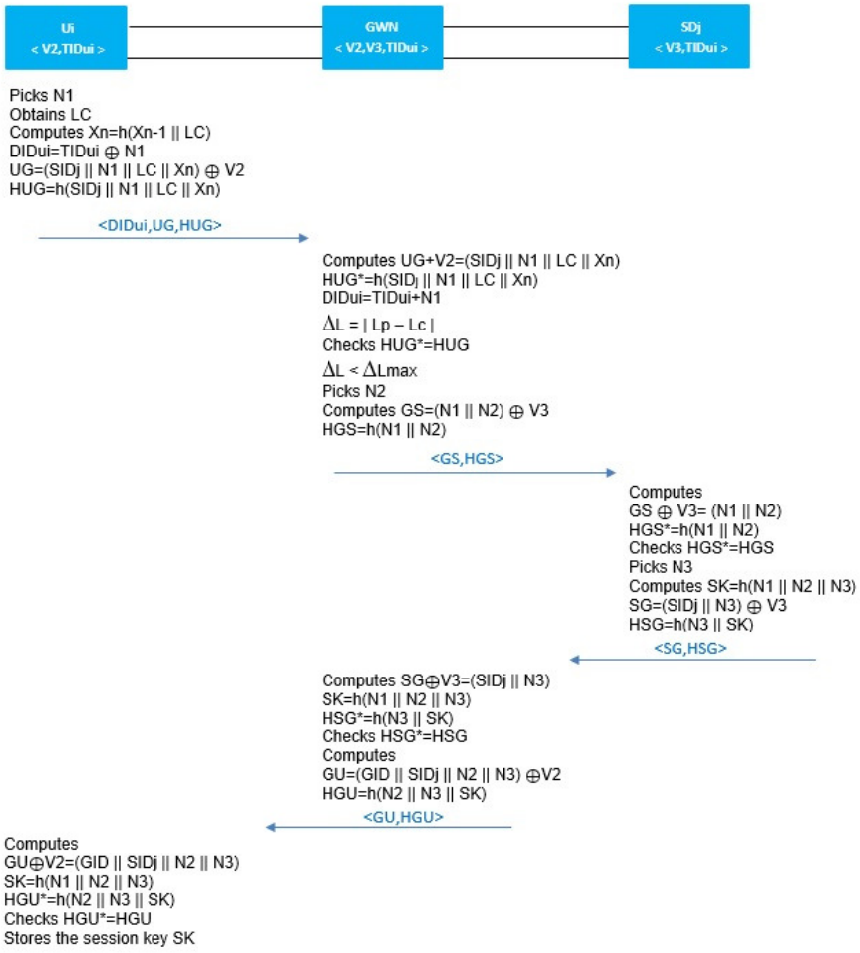


Figure 4.3: Authentication phase of the proposed scheme

locations at session n. Next, the mobile device computes V_2 using Eq. (4.3). Using V_2, the MD_i computes UG.

$$UG = (SID_j||N_1||L_C||X_n) \oplus V_2 \tag{4.8}$$

Next, the MD_i computes HUG:

$$HUG = h(SID_j||N_1||L_C||X_n) \tag{4.9}$$

The mobile sends the following message to the gateway through the public channel:

$$U_i \rightarrow GWN : (DID_{Ui}||UG||HUG) \tag{4.10}$$

Upon receiving the message, the gateway will compute
$(SID_j||N_1||L_C||X_n)$ using the stored value V_2:

$$(SID_j||N_1||L_C||X_n) = UG \oplus V_2 \tag{4.11}$$

GWN now has the values of SID_j, N_1, L_C and X_n. Using those values and from Eq. (4.9) the GWN computes HUG^* and check if $HUG^* = HUG$, then the integrity is verified. Otherwise, the GWN will terminate the session with the user because the message is modified before it reaches to GWN.

GWN then checks the freshness of received nonce N_1. This will prevent the replay attack.

Using N_1, GWN computes TID_{Ui}:

$$TID_{Ui} = DID_{Ui} \oplus N_1 \tag{4.12}$$

GWN checks TID_{Ui} and compares it with the stored value in its database. If TID_{Ui} does not match the stored value, GWN terminates the session with the user.

GWN then estimates the maximum radius of motion for the user given its current location L_c and using the linear motion equation to calculate the highest displacement for user in location L_p change to location L_c, where L_p and L_c are the previous and current location of the user, respectively.

$$\Delta L_{max} = V\Delta T \tag{4.13}$$

where ΔT represents the time needed by the user to move from location L_p to location L_c and V represents the maximum velocity that the user could have. For this work, we assume $V = 489.241$ km/h which represents the highest speed for Bugatti Chiron Super Sport recorded in 2019 [45].

Assuming the user at location A accessed a smart device and after 10 min, the user is trying to access a smart device at location B, L_p and L_c represents the the previous location and current location, respectively.

The distance between location A and location B is about 93 km, using the linear motion equation we get:

$$\Delta L_{max} = 447.19km/h \times 10min = 74.233km \tag{4.14}$$

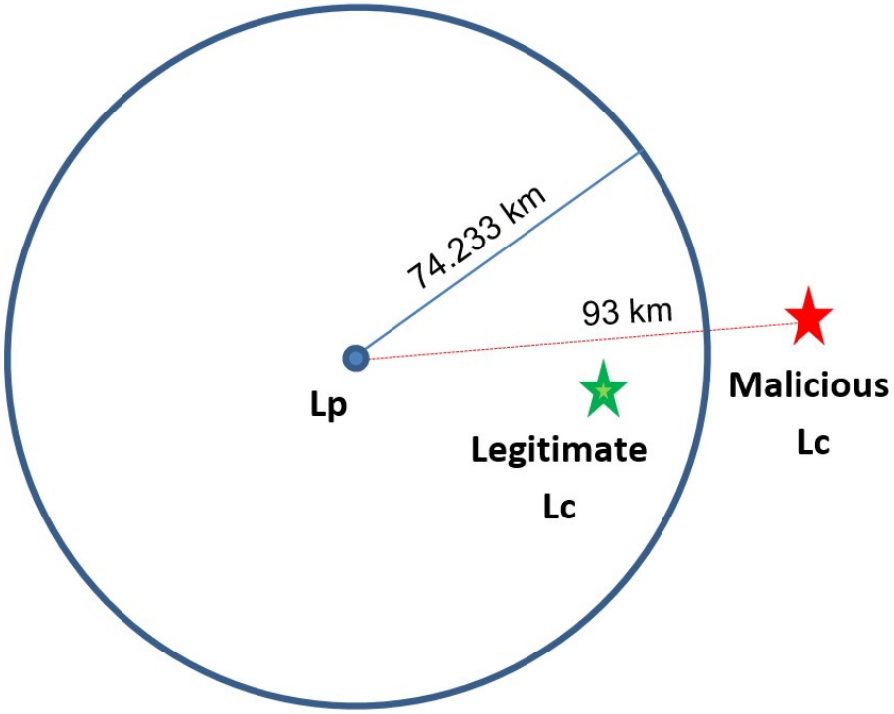


Figure 4.4: Authentication based on location

Fig. 4.4, we consider the previous location at the center. The maximum radius will be ΔL_{max}, whereas the next authentication attempt is at 93 km from the previous location. This is going to be flagged as malicious access because the user cannot be 93 km away from the previous location in 10 min. However, if current location is less than maximum radius, the authentication attempt will be legitimate. Increasing the value of V reduces the false alarm rate. If the gateway checks that the location is within the expected range, it still needs to verify the consistency of the cumulative hash history of all previous locations. This can be done by computing X_n^* from Eq. (4.6) and comparing it to the received X_n. If the two values match, this confirms that the user has consistent locations with GWN and the user is authenticated by GWN.

Next, the gateway starts to prepare the message that will be sent to the smart device. It will first generate a nonce N_2 and forms the GS and HGS:

$$GS = (N_1||N_2) \oplus V_3 \tag{4.15}$$

$$HGS = h(N_1||N_2) \tag{4.16}$$

Finally, the gateway sends the message to the smart device SD_j:

$$GWN \rightarrow SD_j : (GS||HGS) \tag{4.17}$$

Once the smart device SD_j receives the message, it computes the following:

$$(N_1||N_2) = GS \oplus V_3 \tag{4.18}$$

First, SD_j verifies the GID and TID_{Ui}. Next, SD_j checks the freshness of N_1 and N_2. Next, to verify the integrity of the message, SD_j computes HGS using Eq. (4.16) and compare it with the received HGS, if it does not matches, the smart device terminates the session with the gateway because the smart device might communicates with rogue device as gateway. Otherwise, the smart device generates a nonce N_3 and computes the shared key as follows:

$$SK = h(N_1||N_2||N_3) \tag{4.19}$$

The smart device starts to prepare the reply to the gateway. First, it will compute SG and HSG:

$$SG = (SID_j||N_3) \oplus V_3 \tag{4.20}$$

$$HSG = h(N_3||SK) \tag{4.21}$$

Lastly, the smart device sends the following message to the gateway:

$$SID_j \rightarrow GWN : (SG||HSG) \tag{4.22}$$

Upon receiving the message, the gateway will extract N_3:

$$(SID_j||N_3) = SG \oplus V_3 \tag{4.23}$$

The gateway now has the value of N_3 and can calculate SK using Eq. (4.19). Then it will verify the integrity using Eq. (4.21). Finally, the gateway forwards N_2 and N_3 to the user:

$$GU = (GID||SID_j||N_2||N_3) \oplus V_2 \tag{4.24}$$

Next, the GWN computes HGU:

$$HGU = h(N_2||N_3||SK) \tag{4.25}$$

The GWN sends the following message to the user:

$$GWN \rightarrow U_i : (GU||HGU) \tag{4.26}$$

Upon receiving the message, the user will extract N_2 and N_3:

$$(N_2||N_3) = GU \oplus V_2 \tag{4.27}$$

Using N_2 and N_3 the mobile device will compute the session key using Eq. 4.19. Finally, the mobile device verifies the integrity by calculate HGU from Eq. (4.25) and compare it with the received HGU.

If for any reason the user failed to submit a correct location (ex. the user travels by airplane and he/she is a legitimate user), we add a challenge for instance the gateway sends a one of previous nonce (assume N_5) as follows:

$$c = N_5 \oplus V_2 \tag{4.28}$$

$$HMAC = h(c, N_5) \tag{4.29}$$

$$GWN \rightarrow U_i : (c, HMAC) \tag{4.30}$$

Upon receiving the challenge message, the mobile device computes the nonce:

$$N_5 = c \oplus V_2 \tag{4.31}$$

Next, the mobile device computes the $HMAC$ and verifies the integrity, if it matches the received $HMAC$. Then mobile device checks its database for the value of X_5 that meet N_5 and then sends back the response as follows:

$$R = X_5 \oplus V_2 \tag{4.32}$$

$$HMAC = h(R, N_5) \tag{4.33}$$

Upon receiving the response, the gateway will verify the $HMAC$ and the value of X_5 and based on that whether the user is authenticated by the gateway or not.

4.1.5 Password update phase

The proposed scheme offers a password update facility through which a permissible user U_i can update his/her password at any time after user registration without involving the RA. The User needs to provide his/her identity and old password into mobile device. The mobile device calculates V_1 from Eq. (4.2) and check if $V_1^* = V_1$. If it is not, the mobile device refuses the request to change the password. Otherwise, the mobile device believes that U_i is a legitimate user and enable him/her to change the password. The mobile device asks the user to re-submit his/her identity and new password then mobile will calculate the new V_1 and store it in the mobile device. Next, the mobile device computes the new V_2 and V_3, and send the new V_2 and V_3 to GWN and V_3 to SD_j after being encrypted with SK.

4.2 Security analysis of the proposed scheme

In this section, we use three different approaches to validate the security of our proposed protocol: informal security analysis, formal validation using BAN logic, model checking and simulation using AVISPA tool.

4.2.1 Formal proof based on BAN logic

In this Subsection, we introduce a formal analysis for the proposed scheme using widely accepted model called BAN logic, this model has been used for a formal verification of security protocols which introduced in 1989 by Burrows et al. [41]. We begin our analysis by introducing the most important symbols and notations adapted from [25] which are given in Table 4.2.

In addition, the following BAN logic basic rules are used to prove that our authentication protocol provides secure mutual authentication and key agreement as follows:

- Message-meaning rule:
  If P believes that the key K is shared with Q and P sees X encrypted under K, then P believes that Q once said X.

$$\frac{P| \equiv Q \overset{K}{\leftrightarrow} P, P \triangleleft \langle X \rangle_K}{P| \equiv Q| \sim X}$$

Table 4.2: Notations in BAN logic.

Notation	**Descriptions**
P and Q	Principals
$P \mid \equiv$ X	Principal P believes the statement X
$P \triangleleft$ X	Principal P sees the statement X
$P \mid \Rightarrow$ X	Principal P has jurisdiction over the statement X
$P \mid \sim$ X	Principal P once said statement X
(X, Y)	The statement X or Y is one part of message (X, Y)
$< X >_Y$	The statement X is encrypted with the key K
$(X)_K$	The statement X is hashed with the key K
$P \overset{K}{\longleftrightarrow} Q$	K is a secret parameter shared (or to be shared) between P and Q
$P \overset{K}{=\!=} Q$	X is a secret known only to P and Q, and possibly to parties trusted by them.
# (X)	The message X is *fresh*.

- Nonce verification rule:
  If P believes X is fresh and P believes Q once said X, then P believes Q believes X.

$$\frac{P| \equiv \#(X), P| \equiv Q| \sim X}{P| \equiv Q| \equiv X}$$

- Jurisdiction rule:
  If P believes Q has jurisdiction over X and P believes Q believes X, then P

believes X.

$$\frac{P| \equiv Q| \Longrightarrow X, P| \equiv Q| \equiv X}{P| \equiv X}$$

- Freshness conjuncatenation rule:
  If one part of a statement is fresh, then the entire statement must also be fresh; so if P believes X is fresh, then P believes X and Y are fresh.

$$\frac{P| \equiv \#(X)}{P| \equiv \#(X, Y)}$$

- Belief rule:
  If P believes X and Y, then P believes X .

$$\frac{P| \equiv (X, Y)}{P| \equiv X}$$

- Session keys rule:

$$\frac{P| \equiv \#(X), P| \equiv Q| \equiv X}{P| \equiv P \overset{K}{\leftrightarrow} Q}$$

The proposed scheme must achieve the following goals:

- Goal 1

$$GWN| \equiv U_i| \equiv U_i \overset{SK}{\leftrightarrow} GWN$$

- Goal 2:

$$GWN| \equiv U_i \overset{SK}{\leftrightarrow} GWN$$

- Goal 3:

$$GWN| \equiv SD_j| \equiv SD_j \overset{SK}{\leftrightarrow} GWN$$

- Goal 4:

$$GWN| \equiv SD_j \overset{SK}{\leftrightarrow} GWN$$

- Goal 5:

$$SD_j| \equiv GWN| \equiv GWN \overset{SK}{\leftrightarrow} SD_j$$

- Goal 6:

$$SD_j| \equiv GWN \overset{SK}{\leftrightarrow} SD_j$$

- Goal 7:

$$U_i| \equiv GWN| \equiv U_i \overset{SK}{\leftrightarrow} GWN$$

- Goal 8:

$$U_i| \equiv U_i \overset{SK}{\leftrightarrow} GWN$$

- Goal 9:

$$U_i| \equiv SD_j| \equiv U_i \overset{SK}{\leftrightarrow} SD_j$$

- Goal 10:

$$SD_j| \equiv U_i| \equiv U_i \overset{SK}{\leftrightarrow} SD_j$$

- Goal 11:

$$U_i| \equiv U_i \overset{SK}{\leftrightarrow} SD_j$$

- Goal 12:

$$SD_j| \equiv U_i \overset{SK}{\leftrightarrow} SD_j$$

The fundamental assumptions of the authentication protocol are as follows:

- A1:

$$GWN| \equiv \#(N_1)$$

- A2:

$$GWN| \equiv \#(N_3)$$

- A3:

$$SD_j| \equiv \#(N_2)$$

- A4:

$$U_i| \equiv U_i \overset{V_2}{\leftrightarrow} GWN$$

- A5:

$$GWN| \equiv U_i \overset{V_2}{\leftrightarrow} GWN$$

- A6:

$$SD_j| \equiv SD_j \overset{V_3}{\leftrightarrow} GWN$$

- A7:

$$GWN| \equiv SD_j \overset{V_3}{\leftrightarrow} GWN$$

- A8:

$$U_i| \equiv SD_j| \Rightarrow (N_3, SID_j, SK)$$

- A9:

$$U_i| \equiv GWN| \Rightarrow (N_2, V_2, SK)$$

- A10:

$$GWN| \equiv U_i| \Rightarrow (N_1, TID_{Ui}, V_2, SK)$$

- A11:

$$GWN| \equiv SD_j| \Rightarrow (N_3, SID_j, V_3, SK)$$

- A12:

$$SD_j| \equiv U_i| \Rightarrow (N_1, TID_{Ui}, V_2, SK)$$

- A13:

$$SD_j| \equiv GWN| \Rightarrow (N_2, V_3, SK)$$

Messages transferred in the authentication protocol:

- Msg 1:

$$U_i \rightarrow GWN : (TID_{Ui}||UG||HUG)_{U_i \overset{V2}{\leftrightarrow} GWN}$$

- Msg 2:

$$GWN \rightarrow SD_j : (GID||GS||HGS)_{GWN \overset{V3}{\leftrightarrow} SD_j}$$

- Msg 3:

$$SID_j \rightarrow GWN : (SG||HSG)_{SD_j \overset{V3}{\leftrightarrow} GWN}$$

- Msg 4:

$$GWN \rightarrow U_i : (GU||HGU)_{GWN \overset{V2}{\leftrightarrow} U_i}$$

Analysis of our authentication scheme:

- S1: According to Msg 1, we get:

$$GWN \triangleleft (TID_{Ui}, UG, HUG)_{U_i \overset{V2}{\leftrightarrow} GWN}$$

- S2: Based on Assumption A5, S1 and message-meaning rule, we have:

$$\frac{GWN| \equiv U_i \overset{V2}{\leftrightarrow} GWN, GWN \triangleleft (TID_{Ui}, UG, HUG)_{U_i \overset{V2}{\leftrightarrow} GWN}}{GWN| \equiv U_i| \sim (TID_{Ui}, UG, HUG)_{U_i \overset{V2}{\leftrightarrow} GWN}}$$

- S3: From A1 and freshness-conjuncatenation rule, we get:

$$GWN\,| \equiv \#\,(TID_{Ui}, UG, HUG)_{U_i \overset{V2}{\leftrightarrow} GWN}$$

- S4: From S3, S2 and nonce-verification rule, we get:

$$\frac{GWN| \equiv \#(TID_{Ui}, UG, HUG)_{U_i \overset{V2}{\leftrightarrow} GWN}, GWN| \equiv U_i| \sim (TID_{Ui}, UG, HUG)_{U_i \overset{V2}{\leftrightarrow} GWN}}{GWN| \equiv U_i| \equiv (TID_{Ui}, UG, HUG)_{U_i \overset{V2}{\leftrightarrow} GWN}}$$

- S5: According to the Msg 2, we get:

$$SD_j \ \triangleleft \ (GID, GS, HGS)_{GWN \overset{V3}{\leftrightarrow} SD_j}$$

- S6: From A6, S5 and message-meaning rule, we have:

$$\frac{SD_j| \equiv (SD_j \overset{V3}{\leftrightarrow} GWN), SD_j \triangleleft (GID, GS, HGS)_{GWN \overset{V3}{\leftrightarrow} SD_j}}{SD_j| \equiv GWN| \sim (GID, GS, HGS)_{GWN \overset{V3}{\leftrightarrow} SD_j}}$$

- S7: From A3 and freshness-conjuncatenation rule, we get:

$$SD_j\,| \equiv \#\,(GID, GS, HGS)_{GWN \overset{V3}{\leftrightarrow} SD_j}$$

- S8: From S6, S7 and nonce-verification rule, we get:

$$\frac{SD_j\,| \equiv \#\,(GID, GS, HGS)_{GWN \overset{V3}{\leftrightarrow} SD_j}, SD_j| \equiv GWN| \sim (GID, GS, HGS)_{GWN \overset{V3}{\leftrightarrow} SD_j}}{SD_j| \equiv GWN| \equiv (GID, GS, HGS)_{GWN \overset{V3}{\leftrightarrow} SD_j}}$$

- S9: According to the Msg3, we get:

$$GWN \triangleleft (SG||HSG)_{SD_j \overset{V3}{\leftrightarrow} GWN}$$

- S10: From A7, S9 and message-meaning rule, we have:

$$\frac{GWN| \equiv (SD_j \overset{V_3}{\leftrightarrow} GWN), GWN \triangleleft (SG||HSG)_{SD_j \overset{V_3}{\leftrightarrow} GWN}}{GWN| \equiv SD_j| \sim (SG||HSG)_{SD_j \overset{V_3}{\leftrightarrow} GWN}}$$

- S11: From A2 and freshness-conjuncatenation rule, we get:

$$GWN| \equiv \#(SG, HSG)_{SD_j \overset{V_3}{\leftrightarrow} GWN}$$

- S12: From S10, S11 and nonce-verification rule, we get:

$$\frac{GWN| \equiv \#(SG, HSG)_{SD_j \overset{V_3}{\leftrightarrow} GWN}, GWN| \equiv SD_j| \sim (SG, HSG)_{SD_j \overset{V_3}{\leftrightarrow} GWN}}{GWN| \equiv SD_j| \equiv (SG, HSG)_{SD_j \overset{V_3}{\leftrightarrow} GWN}}$$

- S13: According to the Msg4, we get:

$$U_i \triangleleft (GU||HGU)_{GWN \overset{V_2}{\leftrightarrow} U_i}$$

- S14: From A4, S13 and message-meaning rule, we have:

$$\frac{U_i| \equiv U_i \overset{V_2}{\leftrightarrow} GWN, U_i \triangleleft (GU||HGU)_{GWN \overset{V_2}{\leftrightarrow} U_i}}{U_i| \equiv GWN| \sim (GU||HGU)_{GWN \overset{V_2}{\leftrightarrow} U_i}}$$

- S15: From A1, A2, A3 and freshness-conjuncatenation rule, we get:

$$U_i| \equiv \#(GU, HGU)_{GWN \overset{V_2}{\leftrightarrow} U_i}$$

- S16: From S14, S15 and nonce-verification rule, we get:

$$\frac{U_i| \equiv \#(GU, HGU)_{GWN \overset{V_2}{\leftrightarrow} U_i}, U_i| \equiv GWN| \sim (GU, HGU)_{GWN \overset{V_3}{\leftrightarrow} U_i}}{U_i| \equiv GWN| \equiv (GU, HGU)_{GWN \overset{V_2}{\leftrightarrow} U_i}}$$

- S17: From A10, S4 and jurisdiction rule, we get:

$$\frac{GWN| \equiv U_i| \Rightarrow (N_1, TID_{Ui}, V_2, SK), GWN| \equiv U_i| \equiv (TID_{Ui}, UG, HUG)_{U_i \overset{V_2}{\leftrightarrow} GWN}}{GWN| \equiv (TID_{Ui}, UG, HUG)_{U_i \overset{V_2}{\leftrightarrow} GWN}}$$

- S18: From S3, S4 and session keys rule, we get:

$$\frac{GWN| \equiv \#(TID_{Ui}, UG, HUG)_{U_i \overset{V_2}{\leftrightarrow} GWN}, GWN| \equiv U_i| \equiv (TID_{Ui}, UG, HUG)_{U_i \overset{V_2}{\leftrightarrow} GWN}}{GWN| \equiv U_i| \equiv U_i \overset{SK}{\leftrightarrow} GWN}$$

(Goal 1)

- S19: From S18, A10 and jurisdiction rule, we get:

$$\frac{GWN| \equiv U_i| \Rightarrow (N_1, TID_{Ui}, V_2, SK), GWN| \equiv U_i| \equiv U_i \overset{SK}{\leftrightarrow} GWN}{GWN| \equiv U_i \overset{SK}{\leftrightarrow} GWN}$$

(Goal 2)

- S20: From A11, S12 and jurisdiction rule, we get:

$$\frac{GWN| \equiv SD_j| \Rightarrow (N_3, SID_j, V_3, SK), GWN| \equiv SD_j| \equiv (SG, HSG)_{SD_j \overset{V_3}{\leftrightarrow} GWN}}{GWN| \equiv (SG, HSG)_{SD_j \overset{V_3}{\leftrightarrow} GWN}}$$

- S21: From S11, S12 and session keys rule, we get:

$$\frac{GWN| \equiv \#(SG, HSG)_{SD_j \overset{V_3}{\leftrightarrow} GWN}, GWN| \equiv SD_j| \equiv (SG, HSG)_{SD_j \overset{V_3}{\leftrightarrow} GWN}}{GWN| \equiv SD_j| \equiv SD_j \overset{SK}{\leftrightarrow} GWN}$$

(Goal 3)

- S22: From A11, S21 and jurisdiction rule, we get:

$$\frac{GWN| \equiv SD_j| \Rightarrow (N_3, SID_j, V_3, GWN| \equiv SD_j| \equiv SD_j \overset{SK}{\leftrightarrow} GWN}{GWN| \equiv SD_j \overset{SK}{\leftrightarrow} GWN}$$

(Goal 4)

- S23: From A13, S8 and jurisdiction rule, we get:

$$\frac{SD_j| \equiv GWN| \Rightarrow (N_2, V_3, SK), SD_j| \equiv GWN| \equiv (GID, GS, HGS)_{GWN \overset{V_3}{\leftrightarrow} SD_j}}{SD_j| \equiv (GID, GS, HGS)_{GWN \overset{V_3}{\leftrightarrow} SD_j}}$$

- S24: From S7, S8 and session keys rule, we get:

$$\frac{SD_j \mid \equiv \#\,(GID, GS, HGS)_{GWN \overset{V_3}{\leftrightarrow} SD_j}, SD_j| \equiv GWN| \equiv (GID, GS, HGS)_{GWN \overset{V_3}{\leftrightarrow} SD_j}}{SD_j| \equiv GWN| \equiv SD_j \overset{SK}{\leftrightarrow} GWN}$$

(Goal 5)

- S25: From A13, S24 and jurisdiction rule, we get:

$$\frac{SD_j| \equiv GWN| \Rightarrow (N_2, V_3, SK), SD_j| \equiv GWN| \equiv GWN \overset{SK}{\leftrightarrow} SD_j}{SD_j| \equiv GWN \overset{SK}{\leftrightarrow} SD_j}$$

(Goal 6)

- S26: From A9, S16 and jurisdiction rule, we get:

$$\frac{U_i| \equiv GWN| \Rightarrow (N_2, V_2, SK), U_i| \equiv GWN| \equiv (GU, HGU)_{GWN \overset{V_2}{\leftrightarrow} U_i}}{U_i| \equiv (GU, HGU)_{GWN \overset{V_2}{\leftrightarrow} U_i}}$$

- S27: From S15, S16 and session keys rule, we get:

$$\frac{U_i \mid \equiv \#\,(GU, HGU)_{GWN \overset{V_2}{\leftrightarrow} U_i}, U_i| \equiv GWN| \equiv (GU, HGU)_{GWN \overset{V_2}{\leftrightarrow} U_i}}{U_i| \equiv GWN| \equiv U_i \overset{SK}{\leftrightarrow} GWN}$$

(Goal 7)

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
role role_Ui(Ui,RA,GWN,SD:agent,Kur:symmetric_key,H:hash_func,SND,RCV:channel(dy))
played_by Ui
def=
        local State:nat,GID,IDUi,PWi,IDsd,N1,N2,N3,Lc,X1,TID:text,UG,GU,M1,M4:message,HUG,HGU:hash(message),V1:hash
(text.text),V2:hash(text.message),X2:hash(text.message),SK:hash(text.text.text)
        init State := 0
        transition
                0. State=0 /\ RCV(start) =|> State':=2 /\ SND({IDUi.PWi}_Kur) /\ secret(IDUi,idui,{RA,Ui,GWN,SD}) /\ secret
(PWi,pwi,{RA,Ui,GWN,SD})
                2. State=2 /\ RCV({V1'.TID'}_Kur) =|> State':=4 /\ N1':=new() /\ Lc':=new() /\ X1':=new() /\ X2':=H(Lc.X1) /\
V2':=H(GID.xor(IDUi.PWi)) /\ M1':=(IDsd.N1.Lc.X2) /\ UG':=xor(M1,V2) /\ HUG':=H(M1) /\ SND(H(TID).UG.HUG) /\ secret(N1,sec_N1,
{Ui,GWN,SD}) /\ witness(Ui,GWN,ui_gwn_N1,N1) /\ secret(Lc,sec_Lc,{Ui,GWN}) /\ secret(X2,sec_X2,{Ui,GWN})
                4. State=4 /\ RCV(GU'.HGU') =|> State':=6 /\ M4':=xor(GU,V2) /\ SK':=H(N1.N2.N3) /\ HGU':=H(N2.N3.SK)
end role
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Figure 4.5: The role played by the user U_i

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
role role_RA(RA,Ui,GWN,SD:agent,Kur,Kgr,Ksr:symmetric_key,H:hash_func,SND,RCV:channel(dy))
played_by RA
def=
        local State:nat,IDUi,GID,PWi,TID:text,V1:hash(text.text),V2:hash(text.message),V3:hash(message)
        init State := 1
        transition
                1. State=1 /\ RCV({IDUi'.PWi'}_Kur)  =|>  State':=3 /\ TID':=new() /\ V1':=H(IDUi.PWi) /\ V2':=H(GID.xor
(IDUi.PWi)) /\ V3':=H(xor(GID.(IDUi.PWi)))
                /\ SND({V1.TID'}_Kur) /\ secret(V1,sec_v1,{RA,Ui,GWN,SD}) /\ SND({V2.V3}_Kgr) /\ secret(V2,sec_v2,{RA,Ui}) /\
SND({V3}_Ksr) /\ secret(V3,sec_v3,{RA,Ui,GWN,SD})
end role
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Figure 4.6: The role played by the registration authority RA

- S28: From A9, S27 and jurisdiction rule, we get:

$$\frac{U_i| \equiv GWN| \Rightarrow (N_2, V_2, SK), U_i| \equiv GWN| \equiv U_i \overset{SK}{\leftrightarrow} GWN}{U_i| \equiv U_i \overset{SK}{\leftrightarrow} GWN}$$

(Goal 8)

- S29: From S27 and S21, we get:

$$\frac{U_i| \equiv GWN| \equiv U_i \overset{SK}{\leftrightarrow} GWN, GWN| \equiv SD_j| \equiv SD_j \overset{SK}{\leftrightarrow} GWN}{U_i| \equiv SD_j| \equiv U_i \overset{SK}{\leftrightarrow} SD_j}$$

(Goal 9)

- S30: From S24 and S18, we get:

$$\frac{SD_j| \equiv GWN| \equiv SD_j \overset{SK}{\leftrightarrow} GWN, GWN| \equiv U_i| \equiv U_i \overset{SK}{\leftrightarrow} GWN}{SD_j| \equiv U_i| \equiv SD_j \overset{SK}{\leftrightarrow} U_i}$$

(Goal 10)

- S31: From A8, S29 and jurisdiction rule, we get:

$$\frac{U_i| \equiv SD_j| \Rightarrow (N_3, SID_j, SK), U_i| \equiv SD_j| \equiv U_i \overset{SK}{\leftrightarrow} SD_j}{U_i| \equiv U_i \overset{SK}{\leftrightarrow} SD_j}$$

(Goal 11)

- S32: From A12, S30 and jurisdiction rule, we get:

$$\frac{SD_j| \equiv U_i| \Rightarrow (N_1, TID_{Ui}, V_2, SK), SD_j| \equiv U_i| \equiv SD_j \overset{SK}{\leftrightarrow} U_i}{SD_j| \equiv U_i \overset{SK}{\leftrightarrow} SD_j}$$

(Goal 12)

To validate a protocol using BAN logic we established the participants and their beliefs at the beginning of the protocol. Also we expressed those beliefs using BAN specific notation (see table 4.2 for BAN notation). Each of the messages exchanged during the run of a protocol is then idealized (this is called the idealization process), i.e., each message is represented by a logical formula using BAN symbols and notation. These formulae are accompanied by a set of assertions, also represented in BAN notation. The assertions express conclusions reached after sending the message. Hence, the above BAN logic analysis formally proves that the proposed scheme successfully achieves mutual authentication, and the session key SK is mutually established between the U_i and the SD_j through the GWN.

4.2.2 Simulation based on AVISPA tool

AVISPA, introduced by Armando et al. [43] is a toolkit based on the Dolev – Yao threat model [46]. In this model, the adversary has the ability to change, forward and modify messages. This toolkit is utilized to formally assess and validate Internet security protocols. AVISPA is a widely recognized tool used to evaluate the specifications of several industrial-scale security protocols [44]. Avispa uses a high level

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
role role_GWN(Ui,RA,GWN,SD:agent,Kgr:symmetric_key,H:hash_func,SND,RCV:channel(dy))
played_by GWN
def=
	local State:nat,TID,IDsd,Lc,GID,N1,N2,N3,X1:text,V2:hash(text.message),V3:hash
(message),UG,GS,SG,GU,M1,M2,M3,M4:message,HUG,HGS,HSG,HGU:hash(message),X2:hash(text.message),SK:hash(text.text.text)
	init State := 30
	transition
		30. State=30 /\ RCV({V2'.V3'}_Kgr) =|> State':=32
		32. State=32 /\ RCV(H(TID').UG'.HUG') =|> State':=34  /\ M1':=xor(UG,V2) /\ HUG':=H(M1) /\ X2':=H(Lc.X1) /\
N2':=new() /\ M2':=(TID.GID.N1.N2) /\ GS':=xor(M2,V3) /\ HGS':=H(M2) /\ SND(GS.HGS) /\ secret(N2,sec_N2,{Ui,GWN,SD}) /\ request
(GWN,Ui,ui_gwn_N1,N1) /\ witness(GWN,SD,gwn_sd_N2,N2)
		34. State=34 /\ RCV(SG'.HSG') =|> State':=36 /\ M3':=xor(SG,V3) /\ SK':=H(N1.N2.N3) /\ HSG':=H(N3.SK) /\ request
(GWN,SD,sd_gwn_N3,N3)/\ M4':=(GID.TID.N2.N3) /\ GU':=xor(M4,V2) /\ HGU':=(N2.N3.SK) /\ SND(GU.HGU)
end role
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Figure 4.7: The role played by the gateway GWN

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
role role_SD(Ui,RA,GWN,SD:agent,Ksr:symmetric_key,H:hash_func,SND,RCV:channel(dy))
played_by SD
def=
	local State:nat,TID,GID,IDsd,N1,N2,N3:text,V3:hash(message),GS,SG,M2,M3:message,HGS,HSG:hash(message),SK:hash
(text.text.text)
	init State := 60
	transition
		60. State=60 /\ RCV({V3'}_Ksr) =|> State':=62
		62. State=62 /\ RCV(GS'.HGS') =|> State':=64 /\ M2':=xor(GS,V3) /\ HGS':=H(M2) /\ N3':=new() /\ SK':=H
(N1.N2.N3) /\ M3':=TID.GID.IDsd.N3 /\ SG':=xor(M3,V3) /\ HSG':=H(N3.SK) /\ SND(SG.HSG) /\ secret(N3,sec_N3,{Ui,GWN,SD}) /\
request(SD,GWN,gwn_sd_N2,N2) /\ witness(SD,GWN,sd_gwn_N3,N3)

end role
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Figure 4.8: The role played by the smart device SD

protocol specification language (HLPSL) to describe and define the security protocols. Protocol specifications in HLPSL are break down into roles. Some roles are used to define the actions of one single agent in a protocol run. Every agent plays a unique role during the execution of a given protocol. The main objective of HLPSL is to check security properties such as the message authentication, agent authentication and secrecy. The security protocol is checked indicating whether or not it is secure on the basis of the predefined goals. AVISPA includes four built-in model checkers, defined as follows:

Preliminaries

1. On-the-fly model checker (OFMC): uses lazy data types as an easy way to create an effective on-the-fly model for security protocols with infinite state spaces [47].

2. Constraint-logic-based attack searcher (CL-AtSe): The input of (CL-AtSe) is protocol defined as a set of rewriting rules (IF format) into In a set of constraints that help to detect the attacks on the security protocol [48].

3. SAT-based model checker (SATMC): produces a propositional formula based on a transitional state obtained from the IF specification. The propositional

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
role session(RA,Ui,GWN,SD:agent,IDUi,PWi:text,Kur,Kgr,Ksr:symmetric_key,H:hash_func)
def=
	local SND4,RCV4,SND3,RCV3,SND2,RCV2,SND1,RCV1:channel(dy)
	composition
		role_RA(RA,Ui,GWN,SD,Kur,Kgr,Ksr,H,SND1,RCV1) /\ role_Ui(Ui,RA,GWN,SD,Kur,H,SND2,RCV2) /\ role_GWN
(RA,Ui,GWN,SD,Kgr,H,SND3,RCV3) /\ role_SD(RA,Ui,GWN,SD,Ksr,H,SND4,RCV4)
end role
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
role environment()
def=
	const ra,ui,gwn,sd:agent,kur,kgr,ksr:symmetric_key,h:hash_func,iDUi,pWi:text,
idui,pwi,sec_v1,sec_v2,sec_v3,sec_N1,sec_N2,sec_N3,sec_Lc,sec_X2,ui_gwn_N1,gwn_sd_N2,sd_gwn_N3:protocol_id

	intruder_knowledge = {ra,ui,gwn,sd}
	composition
		session(ra,ui,gwn,sd,iDUi,pWi,kur,kgr,ksr,h)
end role
goal
	secrecy_of idui,pwi,sec_v1,sec_v2,sec_v3,sec_N1,sec_N2,sec_N3,sec_Lc,sec_X2
	authentication_on ui_gwn_N1,gwn_sd_N2,sd_gwn_N3
end goal

environment()
```

Figure 4.9: Role session and environment

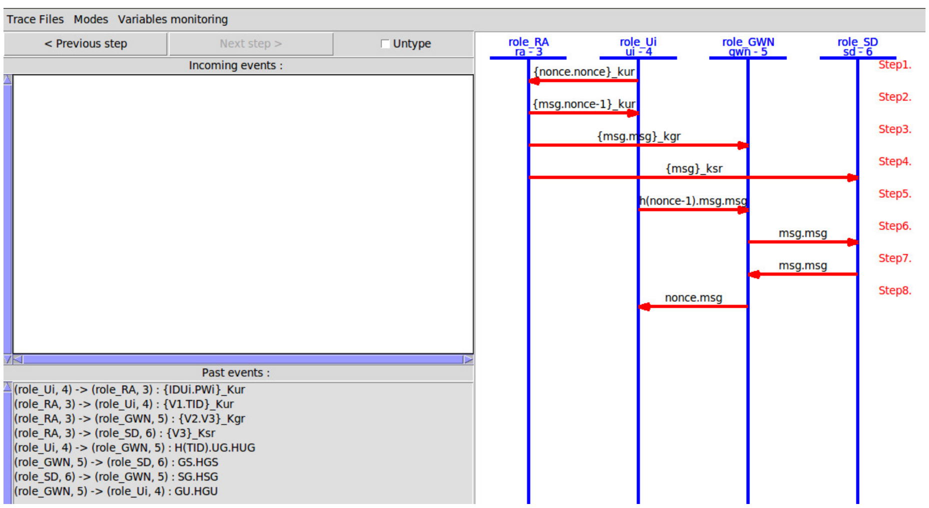


Figure 4.10: Result based on model checker OFMC

formula defines any breach of the security properties that can be turned into an attack [49].

4. Tree automata-based on automatic approximations for the analysis of security protocols (TA4SP) model checker:It shows the vulnerability of the protocol and predicts the correctness of the protocol by accurately estimating the capabilities of the attacker.

Simulation details

We start writing the HLPSL script for our scheme by setting the simulation security goals. Our main objective is to ensure the secrecy of a number of values such as V_1, V_2, V_3, N_1, N_2, N_3. In addition, we define the six roles as follows: role(1) is role RA which is played by the registration authority, role(2) is role U_i which is played by the user, role (3) is role GWN which is played by the gateway, role(4) is role SD which is played by the smart device, role(5) is role session which combine the basic roles (RA, U_i, GWN and SD), role(6) is role environment which combines several sessions and contains global variables, functions and define the simulation security goals of the protocol.

```
% OFMC
% Version of 2006/02/13
SUMMARY
  SAFE
DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
PROTOCOL
  /home/span/span/testsuite/results/proto10.if
GOAL
  as_specified
BACKEND
  OFMC
COMMENTS
STATISTICS
  parseTime: 0.00s
  searchTime: 0.23s
  visitedNodes: 112 nodes
  depth: 9 plies
```

Figure 4.11: Result based on model checker OFMC

Fig 4.5 shows the specification for role U_i which is played by the user. In this role, the U_i recognizes all the agents (U_i, RA, GWN, SD), the symmetric key K_{ur} which is shared between the user and the RA, the hash function H(.) and send/receive channels (SND, RSV). The (dy) notation shows that the channels follow the Dolev–Yao model. U_i receives a start message (RCV(start)) as a signal to start the run of the protocol at the first state (state 0), the user generate the identity ID_{Ui} and password PW_i, then user sends ID_{Ui} and PW_i after being encrypted with K_{ur} to the registration authority in order to register. At state 2, the U_i receives TID_{Ui} and V_1 encrypted with K_{ur} coming from the RA. At state 4, the U_i generates a fresh value as a nonce N_1. Next, the U_i generates a fresh value L_C which represent the location of U_i as if the U_i obtain it from the GPS. Next, the U_i generates the X_1 which has all the location's history of the U_i, this value is shared with GWN. Next, U_i computes X_2, V_2, UG and HUG. Next, U_i sends (TID_{Ui}, UG, HUG) to GWN. at the next transition, the U_i receives

the message (GU, HGU) coming from the *GWN*. Next, the U_i computes *SK* using N_1, N_2 and N_3. Finally, U_i computes *HUG* and compare it with the received *HUG*.

Fig. 4.6 illustrates the specification for role *RA* which is played by the registration authority. In this role, the *RA* recognizes all the agents (U_i, *RA*, *GWN*, *SD*), the symmetric keys K_{ur}, K_{gr} and K_{sr} which are shared between the registration authority and User, gateway and smart device, respectively. In addition, *RA* knows the hash function H(.) and send/receive channels (SND, RSV). The (dy) notation shows that the channels follow the Dolev–Yao model. The reset part of the specification describes the different states of the protocol execution by *RA*.

Fig. 4.7 shows the specification for role *GWN* which is played by the gateway. In this role, the *GWN* knows all the agents (U_i, *RA*, *GWN*, *SD*), the symmetric key K_{gr} which is shared between the gateway and the *RA*, the hash function H(.) and send/receive channels (SND, RSV). The (dy) notation shows that the channels follow the Dolev–Yao model.

Fig. 4.9 shows the specification of the session and environment role. In the session role, all roles (role *RA*, role U_i, role *GWN*, role *SD*) combine together. In the environment role, one or more sessions are initiated. We defined the constants as (ra,ui,gwn,sd) represents the agents (*RA*,U_i, *GWN*, *SD*), respectively. (kur,kgr,ksr) represents the symmetric keys shared between *RA* and user, *RA* and gateway, *RA* and smart device, respectively. h represents the hash function H. In the intruder knowledge part, the relevant parameters that the intruder suppose to knows are defined. We assume that the intruder knows all the agents (*RA*,U_i, *GWN*, *SD*). The simulation goals are defined under goal keyword. We interested to check the secrecy of the following parameters: ID_{Ui}, PW_i, V_1, V_2, V_3, N_1, N_2, N_3.

Simulation results

In this section, we present the simulation results of our proposed scheme. The results are based on AVISPA back-end model checker OFMC. The Security Protocol Animator (SPAN) is used to interactively create a message sequence chart (MSC) of the HLPSL specification protocol previously described. Furthermore, SPAN automatically generates attacks using the Dolev-Yao intruder model.

Fig. 4.10 shows the protocol execution using SPAN software [43], where the all agents exchange the messages in registration and authentication phase.

Fig. 4.11 illustrates the report of model checker OFMC which clearly states that

the proposed scheme is safe. hence, all the security goals are meet.

4.2.3 Informal security analysis

In this section, the security of the protocol is discussed against various well-known attacks. We explain how our protocol successfully resists these attacks.

4.2.4 Replay attack

The random number method is adopted to resist replay attack, so replay attack can be prevented by using the nonces which change in every session.

4.2.5 Eavesdropping attack

In our protocol the attacker can easily intercept the message in transit between U_i, GWN, and SD as the messages are all sent in plain-text. However, adversary cannot obtain any confidential information from any messages because the secret information are protected using secret parameters shared between the communicating parties securely (Eg, V_1 and V_2), and shielded using one-way hash function and XOR bitwise operator. Therefore, the attacker will be unable to unfold the transmitted parameters, and thus cannot obtain any useful information.

4.2.6 Smart-phone device loss attack

In the proposed scheme, the smart-phone of the user stores the secret parameters $V_1 = h(ID_{Ui}||PW_i)$. Suppose that an adversary A steals the smart-phone and extracts the stored secret value V_1, A cannot obtain the identity and password because V_1 is a hash value derived by application of a one-way hashing function. Hence, the proposed protocol is secure even if the smart-phone is lost or stolen.

4.2.7 Impersonation attack

Suppose if an adversary A tries to impersonate the user, A cannot succeed because does not know the user's identity ID_{Ui} and password PW_i as discussed in resisting smart-phone device loss attack. Thus, the proposed protocol is secure from user impersonation attack.

4.2.8 Man-in-the-middle attack

As discussed in BAN logic section 4.2.1, our proposed protocol provides mutual authentication. Additionally, the transmitted messages are protected by the secret values V_1, V_2, V_3 and nonces, and no one would be able to forge legal authentication messages without knowledge of these secret values. Therefore, the proposed protocol can stop the Man-in-the-Middle attack.

4.2.9 Forward/backward secrecy

The session key SK is constructed using three different random numbers, namely N_1, N_2 and N_3 which are randomly generated in each session by U_i, GWN and SD_j, respectively. Therefore, if the SK is compromised by an adversary A, it cannot compromise the confidentiality information of past or future communication sessions. Therefore, forward/backward secrecy is achieved in the proposed scheme.

4.2.10 User credentials attack

When U_i registers at RA as a legitimate user in the proposed protocol, U_i sends the registration message
$(ID_{Ui}||PW_i)\_K_{RA}$ to RA. Next, RA computes V_1 from Eq. (4.2) and sends V_1 to U_i. U_i will never store its identity and password credentials, and instead it will store the hash value V_1. An insider attacker targeting user credentials cannot obtain user identity ID_{Ui} and password PW_i from V_1 as V_1 is protected by the one-way hash function. Thus, the proposed protocol can resist the user credentials attack.

4.2.11 Session key Guessing Attack

The session key SK is created by all communication participants, namely U_i, GWN and SD_j randomly chosen nonces. Therefore, SK depends on randomness of the Input values N_1, N_2 and N_3 and the one-way hash functions, which make it nearly impossible for an adversary to extract it from the protocol. The probability of an adversary to guess the correct SK key is so negligible, given that N_1, N_2 and N_3 are randomly chosen in every session.

4.2.12 User anonymity and untraceability

User anonymity and untracebility are two crucial security properties in authentication. Anonymity ensures the real identity of the mobile device is kept secure and the mobile device remain unidentifiable among the other set of devices. Thus, the attacker cannot identify the identities of the devices. Untraceability, on the other hand, ensures the different sessions established by a particular mobile device cannot be traced, so that an attacker cannot relate any sessions to the correct mobile device. We achieved these two key security properties by using the dynamic identity of the mobile user, where we use different ID in every session.

4.2.13 Location-based authentication

The physical context awareness (location) that is used in our protocol involves verifying whether the previous location of mobile device is proximate to the current location. The location of the mobile device is checked using the linear motion equation to calculate the highest displacement for user in location L_P change to location L_C as explained in Section 4.1.

4.2.14 User authentication based on transaction history information

Each mobile device and the gateway maintain a synchronized database of cumulative hashes generated from the previous session based on the location as discussed in Section 4.1. Therefore, when the transaction from the mobile device is not approved (as discussed in Subsection 4.1.4, the gateway will challenge the knowledge of the mobile device about the previous locations stored from the previous session. The gateway will select one of previous nonce to represent one of the previous session, and challenge the mobile device to send back the correct corresponding location X_n. The gateway will approve the mobile device if it succeeds in sending the correct X_n; otherwise the mobile device's transaction is rejecting and flagged as malicious.

4.3 Performance comparison

In this Section, we evaluate the performance of our proposed scheme in terms of storage cost, communication overhead, and computation costs. We also compare our performance with other related works.

4.3.1 Storage cost

We analyze storage cost (in bits) for the three participants user U_i, gateway GWN, and smart device SD_j.

U_i is required to store GID, SID, TID_{Ui}, X_n and V_1. We use SHA-1 as an example of hash function, and the output of SHA-1 is 160 bits. By applying SHA-1, we obtain X_n=160 bits [50]. While TID_{Ui}=GID =SID=128 bits. Thus, the total storage required by U_i is 160 + (3 × 128)+ 160 = 704 bits.

GWN is required to store GID, SID, TID_{Ui}, X_n, V_2, and V_3. By applying these settings, we obtain X_n = 160 bits. The TID_{Ui}=GID=SID=128 bits, and V_2=512 and V_3=256 bits. Therefore, the total storage required by GWN is 160 + (3 × 128) + (512) + (256) = 1056 bits.

SD is required to store SID and V_3. SID=128 bits, V_3=256 bits. Hence, the total storage required by U_i is 128+256 =384 bits.

4.3.2 Communication overheads

Table 4.3: The communication overheads of our scheme.

Transmitted messages	**Communication cost in bits**
$U_i \rightarrow GWN$	800
$GWN \rightarrow SD$	416
$SD \rightarrow GWN$	416
$GWN \rightarrow U_i$	672

In this Subsection, we discuss the communication cost based on transmitted messages in both directions between these three participants. The communication costs of our scheme are shown in Table 4.3.

To make a reasonable comparison, we assume that the length of the transmitted messages' parameters TID_{Ui}, UG, HUG, GS, HGS, SG, HSG, GU, HGU are 128 bits, 512 bits, 160 bits, 256 bits, 160 bits, 256 bits, 160 bits, 512 bits, 160 bits, respectively.

In our proposed scheme, the transmitted messages $U_i \rightarrow GWN : (TID_{Ui}, UG, HUG)$, $GWN \rightarrow SD : (GS, HGS)$, $SD \rightarrow GWN : (SG, HSG)$ and $GWN \rightarrow U_i : (GU, HGU)$ require (128 + 512 + 160) = 800 bits, (256 +160) = 416 bits, (256 +160) = 416 bits, (512 +160) = 672 bits, respectively.

Three existing relevant schemes, namely Wazid et al. [25], Shuai et al. [26]. Kumar et al. [24]. In terms of number of exchanged messages and total number of bits for a successful mutual authentication during authentication and key agreement phase. Considering our proposed scheme, the total communication cost turns out to be 4 messages in terms of number of exchanged messages, and to be (800+416+416+672) = 2304 bits in terms of total number of bits.

Table 4.4 shows a comparison of communication cost between the proposed scheme and other relevant schemes in terms of number of exchanged messages and total number of bits for a successful mutual authentication. our scheme requires 4 messages and 2304 bits total number of bits for a successful mutual authentication. The comparison, in general, shows that our scheme is comparatively more cost-efficient than the other related works in terms of number of exchanged messages and total number of bits , and just a little less cost efficient than that of Kumar et al.'s scheme [24] because our scheme adds additional functionality and security features are not provided by Kumar et al.'s scheme [24] such as mutual authentication between user and smart device, mutual authentication between user and gateway, password guessing attack, password change attack, stolen smart phone/smart card attack and password change phase, physical context awareness (i.e., location awareness), and transaction history authentication.

Therefore, the communication cost analysis shows that our proposed scheme is effective and feasible for smart homes.

4.3.3 Computational cost

In this Subsection, we conduct the computation cost analysis of our proposed protocol. In order to ensure a precise computation cost of our protocol, the experimental data reported in [51] [52] are applied. They defined the terms T_{exp}, T_h, and T_E/T_D as the

Table 4.4: Comparison of communication cost between the proposed scheme and other most related schemes.

Authentication scheme	**Number of exchanged messages**	**Total number of bits**
Wazid et al. [25]	4	3232
Shuai et al. [26]	4	2944
Kumar et al. [24]	3	1696
Santoso et al. [23]	3	4416
Kim et al. [22]	2	4352
Proposed scheme	4	2304

computational time for modular exponentiation operation, hash function h(.), and symmetric encryption/decryption, respectively.

Table 4.5 shows the time needed for executing those operations. However, the bitwise XOR operation execution time is negligible. Our protocol performs 10 hash invocations and 8 XOR operations, which yields a total computation cost ($10 \times T_h$). Hence, the computation cost of our proposed protocol is (10×0.32 ms)= 3.2 ms.

Table 4.5: Crypto-operations and the computational times needed

Crypto-operations	**Computational time**
Modular exponentiation operation (T_{exp})	19.2 ms
Hash function (T_h)	0.32 ms
Symmetric encryption or decryption (T_E/T_D)	5.6 ms

Table 5.4 shows a comparison of computation cost between the proposed scheme and other most related schemes in ms. Table 5.5 provides security and functionality features compared to other existing related schemes.

In summary, our scheme achieves significantly better performance, security and functionality features as compared to those of other existing schemes.

Table 4.6: Comparison of computation cost between the proposed scheme and other most related schemes in ms.

Authentication scheme	**Total cost**	**Rough estimation**
Wazid et al. [25]	$4T_E/T_D + T_{fe} + 22T_h$	46.54 ms
Shuai et al. [26]	$3T_{exp} + 16T_h$	162.72 ms
Kumar et al. [24]	$2T_E/T_D + T_{mac} + T_{hmac} + 2T_h$	12.48 ms
Santoso et al. [23]	$3T_{exp} + 2T_h$	58.24 ms
Kim et al. [22]	$3T_E/T_D + 30T_h$	26.40 ms
Proposed scheme	$10T_h$	3.2 ms

Table 4.7: Security and functionality features comparison.

Functionality features	**Wazid et al.**	**Shuai et al.**	**Kumar et al.**	**Santoso et al.**	**Kim et al.**	**Proposed scheme**
Mutual authentication	Yes	Yes	No	No	No	Yes
Session key agreement	Yes	Yes	Yes	Yes	Yes	Yes
User anonymity	Yes	Yes	No	No	No	Yes
Untraceability	Yes	Yes	No	No	No	Yes
Forward security	No	Yes	Yes	No	No	Yes
Avoid clock synchronization problem	No	Yes	No	No	No	Yes
No verification table	No	Yes	Yes	No	No	Yes
Password guessing attack	Yes	Yes	No	No	No	Yes
Mobile device loss attack	Yes	Yes	No	No	No	Yes
Privileged insider attack	Yes	Yes	Yes	Yes	No	Yes
Impersonation attack	Yes	Yes	No	No	No	Yes
Replay attack	Yes	Yes	Yes	Yes	Yes	Yes
Man-in-the-middle attack	Yes	Yes	Yes	No	No	Yes
Password change phase	Yes	Yes	No	No	Yes	Yes
Formal proof (BAN logic)	Yes	Yes	No	No	No	Yes
Formal verification (AVISPA)	Yes	No	Yes	No	No	Yes
Authentication based on contextual factors	No	No	No	No	No	Yes
Authentication based on transaction history	No	No	No	No	No	Yes

4.4 Conclusion

Security and privacy issues are significant obstacles that impedes the large-scale applications of smart home. In previous research, there are almost no robust authentication schemes suitable for smart home ecosystem. As a step in the right direction, we proposed a lightweight and secure two-factor anonymous authentication scheme. The proposed scheme grants a legal user mutually authenticate with the smart device through *GWN*. By the end of successful mutual authentication, a symmetric session key *SK* for future secure communications is established between the user and the smart device. The security of the proposed scheme is formally proved using widely-accepted the BAN logic. Moreover, the informal security verification demonstrate that the proposed scheme resists most common attacks. Finally, the formal security is evaluated using the AVISPA tool and the results indicate that our scheme is safe. The following are our plans for future work:
We will use OMNet++ to implement the proposed scheme which is used to simulate computer networks protocols.

Chapter 5

Multifactor authentication scheme using physically unclonable functions

This chapter introduces a secure telehealth system using multifactor authentication for the mobile devices as well as the IoT edge devices in the system. These two types of devices constitute the weakest link in telehealth systems. The mobile devices and edge devices are typically unsecured and contain vulnerable processors. The mobile devices use the healthcare professional's biometric and endowing the edge device with biometrics is accomplished by using physically unclonable functions (PUFs). The embedded PUF acts as a means of enabling mutual authentication and key exchange.

5.1 Notation & Terms Used

Table 5.1 summarizes the notations used in this work.

5.2 Preliminaries

In this section we describe the models and assumptions related to the agents or entities interacting with the IoT telehealth system. The main actors in this system include the threat/adversary, the edge devices and the users.

Table 5.1: Notations Used in the Proposed Protocol

Symbol	**Description**
E	Edge device: sensor or actuator
G	Gateway
S	Server
M	Mobile device: cell phone, tablet, etc.
Healthcare Professional	Person giving healthcare services such as a doctor or a nurse using a mobile device M
ID_s	Identity of server S
ID_g	Identity of gateway G
ID_m	Identity of mobile device M
B_m	Biometric of mobile device user
ID_d	Identity of edge device D
DB_d	CRP Dataset associate with built-in PUF of edge device D
K	Session secret key
K_s	Symmetric key of server S
K_g	Symmetric key of gateway G
K_m	Symmetric key of mobile device M
K_d	Symmetric key of edge device D
N	Nonce
x	PUF-based secret key
$x == y$	Check equality of x and y
$E_s(K, m)$	Symmetric encryption of message m with secret key K
$E_p(K, m)$	Public key encryption of message m with public key K
$D_s(K, m)$	Symmetric decryption of message m with secret key K
$D_p(K, m)$	Public key decryption of message m with secret key K
$h(m)$	Collision-resistant one-way hash function of message M
$h(K, m)$	Collision-resistant one-way cryptographic hash of message M using secret key K
Request(ID_s,ID_d, m)	Request to communication between source ID_s and destination ID_d and an encrypted message
$A \rightarrow B : m$	A sends a message to B through a communication channel
$m_1 \| \| M_2$	Concatenating two messages m_1 and m_2
$m_1 \oplus m_2$	Bitwise XOR operation between m_1 and m_2

5.2.1 Silicon Physically Unclonable Function (PUF)

The use of physically unclonable functions (PUF) for mutual authentication in IoT devices has been the recognized solution to endowing IoT devices with a unique identity, akin to a fingerprint or retina image for humans. A PUF serves to authenticate a device and also provides a measure of tamper resistance

Delvaux et al. [53, 54] reviewed designs of strong and weak PUFs and how they can be used in entity authentication. The authors provided a review of the two types of PUF circuits and their statistical properties. Delvaux also provided an excellent survey of PUF-based key generation. Discussion was provided on how the helper data algorithm can be used to extract a stable secret key from the noisy PUF response (see Chapter 4 in [54]).

Dodis et al. [55, 56] provided efficient secure techniques for using biometrics to provide secure device authentication and converting the noisy biometric data into stable cryptographic keys. They indicated that any biometric signal inherently has low entropy and is also noisy. On the other hand, any useful cryptographic key must have high entropy and be stable and noise free. For this end, the technique they introduced depends on a fuzzy extractor or helper data algorithm. Figure 5.3 in the sequel shows the main building blocks of the secure sketch or fuzzy extractor. Figure 5.4 in the sequel shows only the secure key generation part of the fuzzy extractor.

Ravikanth [57, 58] discussed the concept of one-way functions in general and distinguished between the similarities between algorithmic one-way functions (e.g RSA and Rabin functions) versus physical one-way functions (e.g. PUFs) which depend on physical phenomena for their operation. He discussed the operation of optical one-way functions and reported the like and unlike binomial distribution of the resulting optical responses to ensure the uniqueness of the optical fingerprint of the devices.

Gassend et al. [59] discussed the more common silicon physical random functions, which are now commonly known as physically unclonable functions (PUF). They studied different types of delay-based PUF such as self-oscillating circuits exhibiting monotonic and non-monotonic delays. They also discussed generating redundant information to be added to the challenge-response pairs (CRP) as a means of error correction to remove the noise from the responses and implemented the designs on FPGA hardware.

Suh et al. [60] discussed two different types of delay-based silicon PUFs: ring oscillator PUF and arbiter PUF. Techniques to generate sufficiently large number of CRP

by increasing the options for configuring or selecting the circuit delays. A low-cost authentication scheme is proposed that does not use resource-hungry cryptographic techniques. Error detection and correction techniques using BCH coding/decoding are used for reliable cryptographic key generation based on the CRP used. The authenticator generates the redundant information and sends it in the clear to the device to be authenticated to remove the random process variations.

Guajardo et al. [61] proposed PUF SRAM structures suitable for today's FPGA technology. The statistical properties of the SRAM were investigated. The fuzzy extractor or helper data algorithm was used to extract one or more secure keys. The authenticator generates the helper data W based on the golden PUF response that does not include thermal noise and sends this to the device. Referring to Fig. 5.3 and Fig. 5.4 in the sequel, the device to be authenticated receives the helper data r and uses it, together with the noise PUF response (w'), to generate a stable and secure session secret key.

Maes et al. [62, 63, 64] reviewed electronic and non-electronic PUF types and discussed the Hamming inter-distance and intra-distance as a means of ensuring unique device ID and to be able to distinguish between the different devices. Seven different types of PUFs were reviewed. PUF-based key generation properties were identified and the secure sketch, strong and fuzzy extractor technique proposed by Dodis et al. [55, 56] were discussed.

Herder et al. [65] described using PUF for a low-cost authentication and key generation applications. The thesis defined two primary PUF types: "strong PUFs" and "weak PUFs".

Operation of the PUF relies on a challenge-response pair (CRP) where the server issues a challenge and the IoT device, or client, provides a response that is unique to the device. The problem with PUF response is it is noisy but has low entropy. Therefore techniques have been developed to recover a reliable and stable response from the noisy responses using fuzzy extractor or secure sketch [66, 67, 56, 55]. The advantage of the fuzzy extractor serves also to generate a secret key with high entropy from the low-entropy noisy responses. Silicon Physically unclonable functions (PUF) are circuits that make use of inevitable random process variations (RPV) and thermal nose present in integrated-circuits (IC). A PUF operates on a challenge-response pair (CRP) where each challenge or input to the PUF generates a response that is unique to each manufactured IC and can not be repeated by an attacker or even the IC manufacturer. The function produced by the PUF should be easy to evaluate but

hard to model or characterize by the designer, manufacturer or even the adversary. Examples of PUFs include [60] arbiter PUFs, ring oscillator PUFs and SRAM PUFs [68].

A black-box model of a silicon PUF is represented as

$$R[1:M] = \text{PUF}(C[1:N])$$

where $C[1:N]$ is the N-bit challenge, $R[1:M]$ is the M-bit response, and $PUF(\cdot)$ is the one-way unique function characterizing the PUF given the physical parameters of a particular IC.

The simple CRP set is not practical for authentication for the following reasons:

1. The responses are noisy since they are subject to processing variations and environmental factors such as temperature, supply voltage variations and ground bounce [69].

2. A CRP can only be used once to prevent replay attack. Hence, a finite number of authentication operations are feasible after which the device is withdrawn from service.

3. There is nonzero probabilities of false rejection and false acceptance.

4. Publicly exchanging the CRP on an open and un-secure channel and to an un-secure edge device significantly reduces the unpredicatability of the remaining CRPs. An attacker using machine learning algorithms can quickly train for responding to a new challenge [70, 54, 71].

PUF-Based Secret Key Generation and Storage

Countering random manufacturing variations, ambient effects, aging, and thermal noise is feasible using helper data algorithm [72, 66, 61] or fuzzy extractors [55, 56, 63]. These approaches allow a PUF to resist forgery and duplication while generating device-unique keys that are not visible when the device is powered off. Avoiding use of nonvolatile memory to store secret keys prevents theft of the cryptographic keys.

However, associating a challenge response pair for each device is possible only after the device is manufactured since no accurate model is possible to describe the PUF of a given IC. Authenticating a PUF-based device and establishing a secret key are done by the manufacturer for each device fabricated. This is because the fingerprint

of each device must be obtained by explicitly examining each device. Another reason is that it is impossible to create an equivalent model for the PUF associated with a specific device. The procedure for generating and regenerating the session key are described in Sections 5.2.7.

PUF-Based Device Enrlolment

Enrolment of a PUF-based device is done by the manufacturer where each device is assigned a unique ID and a set of challenge-response pairs (CRP) and a secret key associated with each CRP. In addition, the manufacturer generates publicly available helper data for each CRP so that the device can use the noisy response together with the helper data to can generate the same secret key to be used to help authenticate the device, prove freshness of the session and encrypt/decrypt data [73, 54].

5.2.2 Threat Model

The adversary launches targeted attacks through either the edge device or the mobile device or by intercepting the communication across the cloud. The weak link in the IoT telehealth is the edge devices since they usually have limited compute resources and seldom undergo a software/firmware updates. The Dolev-Yao model for the adversary is assumed. In addition, the adversary can

1. Infer the device ID through brute force or guessing based on knowledge of the device brand and ID sequence assignment.

2. Gain physical access to the edge devices in the field and extract stored information.

3. Launch various attacks to steal the device secret keys through reading the flash or solid-state drive (SSD) content through fault injection, memory permanence or cold boot attacks for example.

4. Launch a passive attack using side-channel analysis on the edge devices.

5. Change the flash or SSD content to run malicious software.

5.2.3 Network Model

There communication network comprising the IoT-based healthcare system has the following main entities

1. Internet *cloud* which could rely on 5G and Wi-Fi 6 technologies for increased throughput and reduced latency.

2. Secure *Server* S connecting the mobile devices to the internet. The server could be considered a hardware root-of-trust (HRoT) since it contains tamper-proof security processors and implements layered security protocols.

3. Gateway G connecting the edge devices to the internet. The gateway could be considered a hardware root-of-trust (HRoT) since there is one gateway in each remote location so it would not impose too much expense on the system deployment in relation to the security benefits dividents. G contains tamper-proof security processors and implements layered security protocols also.

4. *Mobile* devices M which are used by the healthcare professionals to access telehealth system through the server. The mobile devices are located where healthcare professionals practice their profession at clinics, hospitals, research centres, etc). The mobile devices could be connected to the server through secure virtual private networks (VPN) to reduce the number of possible attacks.

5. IoT edge *devices* D which are located at the local IoT network, which are typically located at the patient's home, or remote healthcare centre, and are connected through a local-area network. These devices typically have limited compute capabilities and small memory footprint. However, it is now not too expensive to include PUF circuitry to help authenticate these devices and securely generate secret keys.

Some authors added an extra entity to the above components— mainly "patients without sensors". We do not include such patients as a member of the IoT system since interaction between those patients and healthcare professionals is done using separate channels such as email, phone, virtual meetings, etc. The IoT system is in charge of the hardware, sensors, and actuators in the patients' home or the body area network, if it exists.

5.2.4 Client Model

Figure 5.1 shows the client-side architecture of the IoT for the telehealth system under consideration. The client-side IoT system represents the infrastructure at the

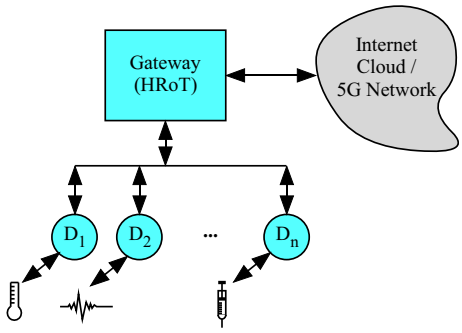


Figure 5.1: Basic structure for the client-side IoT for telehealth system.

patient's home or the remote health care delivery site. The system consists of a gateway that provides access to the Internet through its communication layers. In addition the gateway maintains the local IoT security by serving as a local hardware-based root-of-trust (HRoT). This is not a severe requirement since price of a trusted platform module (TPM), or crypto processor, is getting lower and lower and the benefits it provides far exceeds the cost [74]. In addition to the gateway, the client-side IoT contains n edge devices ($E_1,\ E_2,\ \cdots,\ E_n$) that serve as sensors and/or actuators such as insulin pump, pacemaker, etc. In that sense, the gateway is the first line of defence against local attacks emanating from malicious or compromised devices. It also protects the system from remote attacks arriving through the Internet cloud. Authentication of the devices is the responsibility of the gateway. The gateway requires assistance naturally from a registration authority (RA) as well as the telehealth server discussed in the paragraph below.

5.2.5 Server Model

Figure 5.2 shows the server-side architecture of the telehealth system under consideration.

The server is located at the telehealth system infrastructure at the hospital or an equivalent infrastructure. It is supported by information technology (IT) personnel and security experts to maintain layered security measures. The computing resources of the server can be assumed limitless. Security is maintained at the application level

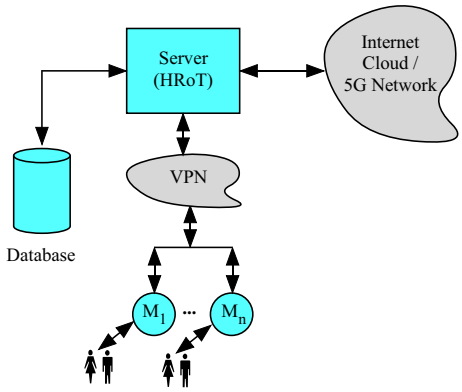


Figure 5.2: Basic structure for the server-side IoT for telehealth system.

down to the hardware level. A hardware root-of-trust (HRoT) must be present in order to secure the cryptographic keys and cryptographic primitives and protocols.

5.2.6 Mobile Device Model

Figure 5.2 shows the mobile devices of the IoT telehealth system which helps access by the healthcare professionals. In addition, the mobile device could be replaced with an app that runs at the remote telehealth authority and connects to a certain IoT to poll the data of all edge devices and check the status of the actuators. This app could be used later on using machine learning (ML) techniques to infer the behaviour of the IoT and its connected devices.

The mobile devices are vulnerable to several types of attacks such as phishing, theft, reverse engineering, etc.

5.2.7 Edge Device Model

The IoT edge device used for remote telehealth is an embedded system where secret keys used for cryptographic primitives are PUF-based as was discussed in Section 5.2.1. Using a PUF ensures each device has a unique ID and a session secret key that is generated by the hardware and not stored in vulnerable nonvolatile memory [60, 63, 64, 59, 75].

Authentication of a device is essentially based on a challenge-response pair (CRP). The server issues a challenge c and generates the expected response w. The client is the edge device that receives c and generates a noisy response w'. Dodis et al. and others [55, 76, 77, 54] provided a description of how the noisy data of a PUF can be used to generate a consistent session key to be used for authentication and secure message exchange.

Fuzzy Extractor

Figue 5.3 shows the basic structure of the fuzzy extractor technique for extracting helper data from the PUF response at the server (left) and client or IoT device (right) [54]. The server selects a challenge c and uses the dataset supplied by the manufacturer to extract the expected response w. The server also performs forward error correction coding (FEC) on the response to produce helper data r, session key K and a hash value h. The hash value will serve establish mutual authentication

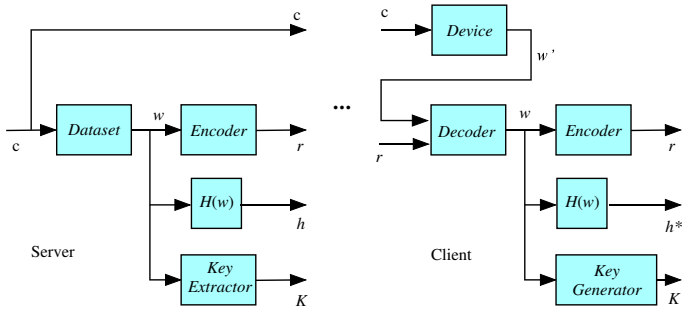


Figure 5.3: Basic structure of the fuzzy extractor at the server and client.

between the server (gateway in our case) and the client (IoT edge device in our case).

Figure 5.4 illustrates the key extraction process using the fuzzy extractor, also known as secure sketch.

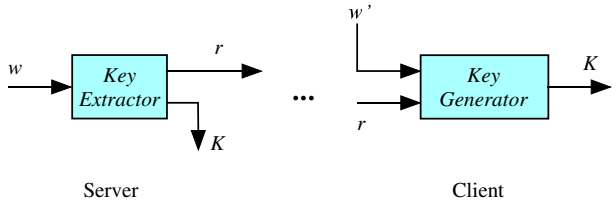


Figure 5.4: Basic structure of the fuzzy extractor at the server and client.

At the server side, the key extractor block uses the low-entropy response w to generate a stable high-entropy key using any technique such as hashing for example as shown in Fig. 5.3.

The client receives the challenge c and helper data r and in response produces the actual noisy response w' and with the help of r it decodes w' to produce a copy of the error-free response w. The client then hashes this value and sends h^* to the server to establish mutual authentication. Having regenerated the error-free response w, the server generates the secret key using the Key Generation block as shown in Fig. 5.3.

It should be noted that the secret key changes each time a new challenge c is issued. In this thesis we will use this feature to generate a nonce which could be N_d or a hashed value of N_d to increase its entropy. This will serve to construct a secret key shared among the four entities of our system: mobile device (M) , server (S), gateway (G) and IoT edge device (D).

Key extraction using the fuzzy extractor process can be expressed by the equation

$$(K_{dg},\ N_d) = \text{key\_regen}(c,\ r) \tag{5.1}$$

where K_{dg} is the secret key and N_d is the secret random number.

Some implementations were done in FPGA platforms [78, 63] and some were implemented on microcontrollers [79]. Gao et al. [76] proposed an SRAM-based PUF key generator on a microcontroller using radio frequency (RF) energy harvesting.

5.2.8 Gateway Model

The gateway is located at the IoT home location or it could be located at a medical clinic at a geographically remote area. The compute resources at the gateway must be able to implement layered security starting from the applications all the way down to the hardware processors. A hardware root-of-trust (HRoT) could be implemented in order to secure the cryptographic keys and cryptographic primitives and protocols. The concomitant cost is justified by resulting enhanced security features.

A random number (nonce) N_d is generated at the gateway and applied to a cryptographic hash function to generate the secret key K_{dg} with a predetermined number of bits and high entropy. This serves two purposes, N_d serves to query the presence and freshness of the connection with the IoT device and K_{dg} serves to generate a one-time password (OTP) for use in cryptographic operations for the current session. The key generation using the fuzzy extractor process can be expressed by the equation

$$(K_{dg},\ r) = \text{key\_gen}(ID_d,\ c,\ N_d) \tag{5.2}$$

where K_{dg} is the secret key and r is the helper data. The authentication process starts by the gateway to generate the quantities N_d, K_{dg} and r.

The authenticating device also queries the dataset associated with the device using its identity ID_d and a selected challenge c to obtain a response w. N_d is then encoded using a linear block code such as BCH and the resulting redundant bit are XORed with the PUF response to generate the helper data r. The helper data is public and is transmitted, along with c, to the IoT edge device at the start of a session.

At the start of a session, the gateway computes a nonce N_d and chooses a challenge c to generate a one-time password/secret key K_{dg} according to Eq. (5.2). The gateway sends the chosen challenge and helper data to the edge device

$$G \rightarrow E : M = (c,\ r, N_d) \tag{5.3}$$

The edge device is capable of generating its own copy of K_{dg} through the publicly received quantities c and r. At this stage, both the gateway and edge device know K_{dg} and N_d based on Eq. (5.1).

5.3 The Proposed Scheme

The gateway manages all communications between the edge devices and the server. Similarly, the server manages all communications with the gateway as well as with the mobile devices. The proposed protocol is divided into several phases.

1. Predeployment
2. Registration
3. Login
4. Authentication
5. Password update

5.3.1 Predeployment Phase

Server

As was mentioned in Sec. 5.2.5, the server establishes secure communication with the RA through a symmetric secret key K_{sr}. The server is also assigned a unique identity ID_s. The server can be considered a HRoT and implements several layers of security protocols. The server communicates with the RA to obtain credentials for the gateways, mobile devices and edge devices comprising the main components of the telehealth system in question.

Gateway

The manufacturer assigns to the gateway a symmetric secret key K_{gs} for communication with the server and also assigns a unique identity ID_g.

Mobile Device

The mobile device is considered here as the access device used by the healthcare professional to communicate with the IoT edge devices through the server and gateway. The manufacturer assigns to each mobile device a symmetric secret key K_{ms} for communication with the server and also assigns a unique identity ID_m. A password PW_m and a biometric B_m will be supplied by the user.

Edge Device

The manufacturer assigns a unique ID during manufacture (ID_d) and after the device is fabricated, the manufacturer generates the device CRP Dataset which must be kept secret to be shared later by an authenticating entity. The fabricator also includes in the CRP dataset the helper data as per Section 5.2.7.

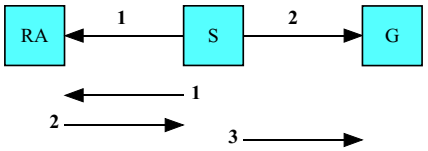
5.3.2 Registration phase

The main parties involved in the operation of the telehealth system are the registration authority (RA), the server and the device fabricator (fab house) responsible for manufacturing the gateway, mobile devices, and edge devices. The server and the fab house establish secure communication with the RA through public key infrastructure (PKI).

The administrator for the telehealth system establishes associations between

1. The server and the gateway
2. The server and the mobile devices connected to it
3. The gateway and the edge devices connected to it

Figure 5.5 shows the registration phase implemented by the manufacturer (fab house) for the the gateway, mobile devices and edge devices, as will be explained below.



1: ID_g, ID_m, ID_d

2: K_{gs}, ID_g, TID_g, K_{ms}, ID_m, TID_m, K_{dg}, ID_d, TID_d, G, H, (n,k,d), CRP_d

3: K_{gs}, ID_g, TID_g, K_{dg}, ID_d, TID_d, G, H, (n,k,d), CRP_d

Figure 5.5: Registration phase for the the gateway, mobile devices and edge devices using the server.

The following transactions take place.

Transaction #1: the server contacts the RA requesting data associated with the gateway, mobile devices and edge devices.

Transaction #2: the RA sends the server all the data associated with the gateway, mobile devices and edge devices.

Transaction #3: the server sends the gateway all the data associated with the edge devices connected to it. Note that in our protocol the gateway only communicates with the edge devices and server. The gateway, mobile devices, or edge devices are not llowed to directly contact the RA or the mobile devices directly to reduce the chance of attacks.

Registration of Gateway

Registration of the gateway is initiated by the server through communicating with the RA to obtain the gateway secret key K_{gs}. Communication starts with a challenge message from S and a response from RA.

$$S : m_{g1} = E\left(K_{sr},\ (ID_s||ID_g||N_{s1})\right) \tag{5.4}$$

$$S \rightarrow RA : \text{Request}(ID_s, ID_{ra}, m_{g1}) \tag{5.5}$$

$$RA : V_g = h(ID_s||ID_g||K_{gs}||N_{s1}) \tag{5.6}$$

$$RA \rightarrow S : E\left(K_{sr}, (K_{gs}||ID_g||V_g||N_{s1})\right) \tag{5.7}$$

$$S : m_{g2} = E(K_{gs},\ (ID_g||V_g||N_{s2})) \tag{5.8}$$

$$S \rightarrow G : \text{Request}(ID_s,\ ID_g,\ m_{g2}) \tag{5.9}$$

$$G \rightarrow S : E(K_{gs},\ N_{s2}) \tag{5.10}$$

where N_{s1} and N_{s2} are nonces to ensure message freshness and the hash V_g will be used later in the authentication phase between S and G.

Operation in Eq. (5.4): server prepares a challenge for RA as an encrypted message that includes a nonce N_{s1}.

Operation in Eq. (5.5): server sends a request to communicate with RA.

Operation in Eq. (5.6): RA prepares the has V_g to be used later for authentication between S and G.

Operation in Eq. (5.7): RA responds by sending back the nonce as a proof of existence and freshness.

Operation in Eq. (5.8): server prepares a challenge for G as an encrypted message that includes the nonce N_{s2}.

Operation in Eq. (5.9): server sendsa request to communicate with G.

Operation in Eq. (5.10): gateway responds to the challenge by sending back the encrypted nonce N_{s2}.

Registration of the Mobile Device

Registration of the mobile device M is initiated by the mobile device through communicating with S that in turn communicates with the RA to obtain the mobile device identity ID_m. The server also informs RA of the password selected by the user PW_m.

$$M : m_{m1} = E(K_{ms},\ (ID_m||N_m)) \tag{5.11}$$
$$M \rightarrow S : \text{Request}(\text{ID}_m,\ ID_s,\ m_{m1}) \tag{5.12}$$
$$S : m_{m2} = E(K_{sr},\ (ID_s||ID_m||N_{s1})) \tag{5.13}$$
$$S \rightarrow RA : \text{Request}(ID_s,\ ID_{ra},\ m_2) \tag{5.14}$$
$$RA : V_m = h(ID_m||PW_m) \tag{5.15}$$
$$RA \rightarrow S : E(K_{sr}, (ID_m||V_m||N_{s1})) \tag{5.16}$$
$$S \rightarrow M : E(K_{ms},\ (ID_m||V_m||N_{s2})||m_{m1}) \tag{5.17}$$
$$M \rightarrow S : E(K_{ms},\ N_{s2}) \tag{5.18}$$

where the hash V_m will be used later in the authentication phase between S and M. The steps in Eq. (5.11)–Eq. (5.18) have the same meaning as was explained for steps Eq. (5.4)–Eq. (5.10)

Registration of the Edge Device

The network administrator informs the server of all the entities forming the telehealth system including server, mobile devices, gateway, and all the edge devices connected to the gateway. As a result, registration of the edge devices is initiated by the server through communicating with the RA to obtain each edge device secret key K_{dg} and CRP_d Dataset, corresponding to the built-in PUF, as well as fuzzy extractor data such as BCH code with parameters (n, k, d) as well the generator matrix ($\mathbf{G}$) and parity check matrix ($\mathbf{H}$). The server also communicates these information to the

gateway.

$$
\begin{aligned}
S &: m_1 = E(K_{sr},\ (ID_s||ID_g||ID_d||N_{s1})) && (5.19)\\
S \rightarrow RA &: \text{Request}(ID_s,\ ID_{ra},\ m_1) && (5.20)\\
RA &: V_d = h(ID_d||K_{dg}||N_{s1}) && (5.21)\\
RA &: m_2 = TID_d||\mathbf{G}||\mathbf{H}||CRP_d||(n,k,d)||\\
&\qquad V_d||N_{s1} && (5.22)\\
RA \rightarrow S &: E(K_{sr}, m_2) && (5.23)\\
S &: m_3 = E(K_{gs},\ (ID_d||V_d||N_{s2})) && (5.24)\\
S \rightarrow G &: \text{Request}(ID_s,\ ID_g,\ m_3) && (5.25)\\
G \rightarrow S &: E(K_{gs},\ N_{s2}) && (5.26)\\
G &: m_4 = E(K_{dg},\ (ID_d||V_d||N_g)) && (5.27)\\
G \rightarrow E &: \text{Request}(ID_g,\ ID_d,\ m_4) && (5.28)\\
D \rightarrow G &: E(K_{dg},\ N_g) && (5.29)
\end{aligned}
$$

where the hash V_d and TID_d will to be used for the duration of the session during communication between the gateway and the edge device. The steps in Eq. (5.19)–Eq. (**??**) have the same meaning as was explained for steps Eq. (5.4)–Eq. (5.10)

5.3.3 Login Phase

The healthcare professional logs in to the telehealth system through the mobile device using three-factor authentication by what he/she has (mobile device), what he/she knows (password), and what he/she is (biometric). The mobile device also computes V'_m and sends it to the server.

$$
\begin{aligned}
M &: V'_m = h(ID_m||PW_m) && (5.30)\\
S &: V_m \ == \ V'_m && (5.31)
\end{aligned}
$$

Login is successful when V_m matches V'_m. If first login in is not successful, another login is established by asking for other personal information such as a security question or reaching out to the system administrator. A limited number of login attempts is allowed and if this number is exceeded, the device terminates the login request immediately until the user re-registers again.

5.3.4 Authentication Phase

Mutual authentication is required between the communicating entities. We consider here the case when a healthcare professional desires to communicate with an edge device. In that case four entities are involved: mobile device M, server S, gateway G and finally the edge device D. Figure 5.6 shows the authentication phase between the four communicating entities. Authentication proceeds as three stages:

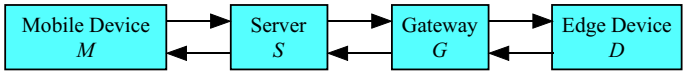


Figure 5.6: Authentication phase of the proposed scheme.

1. Mobile device–server stage
2. Server–gateway stage
3. Gateway–edge device stage

Mobile Device–Server Stage

The mobile device chooses a nonce N_1 and obtains its current location L_m and calculates a dynamic identity

$$DID_m = ID_m \oplus N_1 \tag{5.32}$$

The dynamic identity depends on the nonce N_1 and becomes unique to each session to preserve anonymity and untraceability.

The mobile device employs hash chains to calculate the quantities:

$$MS = (DID_m||N_1||L_m) \oplus V_m \tag{5.33}$$

$$H_{ms} = h(DID_m||N_1||L_m) \tag{5.34}$$

where V_m was obtained from RA in Eq. (5.15).

The mobile device sends the following message to the server

$$M \rightarrow S : (MS, H_{ms}) \tag{5.35}$$

This assures the server of the freshness and presence of the mobile device.

The server receives the message in Eq. (5.35), and computes MS using the stored value V_m

$$DID_m||N_1||L_m = MS \oplus V_m \tag{5.36}$$

The server checks the freshness of received nonce N_1 to prevent replay attack and computes ID_m^* and H_{ms}^*

$$\begin{aligned} ID_m^* &= DID_m \oplus N_1 && (5.37)\\ H_{ms}^* &= h(DID_m||N_1||L_m) && (5.38) \end{aligned}$$

The mobile device is authenticated when the following equalities are statisfied:

$$\begin{aligned} ID_m^* &== ID_m \\ H_{ms}^* &= H_{ms} \\ L_m^* &\leq L_{m-1} + \Delta \end{aligned}$$

where Δ is the maximum change allowed in the location between two sessions. This verifies the integrity of the message, otherwise the server will terminate the session with the mobile device.

Server–Gateway Stage

The server prepares a message to send to the gateway. It starts by generating a nonce N_2 and computes a server dynamic identity DID_s:

$$DID_s = ID_s \oplus N_2 \tag{5.39}$$

The server then computes:

$$\begin{aligned} SG &= (DID_s||N_1||N_2) \oplus V_g && (5.40)\\ H_{sg} &= h(DID_s||N_1||N_2) && (5.41) \end{aligned}$$

The server sends the following message to the gateway

$$S \rightarrow G : (SG, H_{sg}) \tag{5.42}$$

The gateway receives the message in Eq. (5.42) from the server, and computes

SG using the stored value V_g

$$DID_s||N_1||N_2 = SG \oplus V_g \tag{5.43}$$

The gateway computes ID_s^* and H_{sg}^*

$$ID_s^* = DID_s \oplus N_2 \tag{5.44}$$
$$H_{sg}^* = h(DID_s||N_1||N_2) \tag{5.45}$$

The gateway compares H_{sg}^* with the received value H_{sg}. This verifies the integrity of the message, otherwise the gateway will terminate the session with the server.

Gateway–Edge Device Stage

The gateway prepares a message to send to the edge device. It starts by preparing a nonce N_3 and computes

$$GE = (N_1||N_2||N_3) \oplus V_d \tag{5.46}$$
$$H_{ge} = h(N_1||N_2||N_3) \tag{5.47}$$

The gateway sends the following message to the edge device

$$G \rightarrow E : (GE, H_{ge}) \tag{5.48}$$

The edge device receives the message in Eq. (5.48) from the gateway, and computes GD using the stored value V_d

$$N_1||N_2||N_3 = GD \oplus V_d \tag{5.49}$$

The edge device computes H_{ge}^*

$$H_{ge}^* = h(N_1||N_2||N_3) \tag{5.50}$$

The edge device compares H_{ge}^* with the received value H_{ge}. This verifies the integrity of the message, otherwise the edge device will terminate the session with the gateway.

The Reverse Path

The edge device generates a nonce N_4 and computes its dynamic identity DID_d and the session key SK

$$DID_d = ID_d \oplus N_4 \tag{5.51}$$
$$SK = h(N_1||N_2||N_3||N_4) \tag{5.52}$$

The edge device collects the identities of all the edge devices it sees around it through its Bluetooth or Zigbee connection:

$$\mathbb{D}_d = \{ID_{di}|i \in \mathbb{D}\} \tag{5.53}$$

where $\mathbb{D}_d$ is the set of identities of all edge devices seen by the particular edge device being authenticated and $\mathbb{E}$ is the set of all edge devices in the IoT network.

The edge device prepares a reply to the gateway by computing the following quantities

$$DG = (DID_d||\mathbb{D}_d||N_4) \oplus V_d \tag{5.54}$$
$$H_{gd} = h(N_4||SK) \tag{5.55}$$

The edge device sends the following message to the gateway

$$D \rightarrow G : (DG, H_{dg}) \tag{5.56}$$

When the gateway receives the message from the edge device, it will extract N_4 and $\mathbb{D}_d$:

$$(DID_d||\mathbb{D}_d||N_4) = DG \oplus V_g \tag{5.57}$$

The gateway then computes the device identity

$$ID_d = DID_d \oplus N_4 \tag{5.58}$$

The edge device is authenticated when the following are satisfied

$$\begin{aligned} ID_d^* &== ID_d \\ \mathbb{D}_d &\neq \phi \\ \mathbb{D}_d &\subset \mathbb{D} \\ H_{gd}^* &== H_{gd} \end{aligned}$$

Having the value N_4, the gateway verifies message integrity using Eq. (5.55) and ensures the validity of the above equations.

The gateway now has the value N_4 and can independently calculate its dynamic identity and the session key SK using Eq. (5.52).

$$DID_g = ID_g \oplus N_3 \tag{5.59}$$

The gateway embeds the values N_3 and N_4 in the following quantity

$$GS = (DID_g||N_3||N_4) \oplus V_g \tag{5.60}$$

The gateway also computes H_{gs}

$$H_{gs} = h(N_3||N_4||SK) \tag{5.61}$$

The gateway now sends the following message to the server

$$G \rightarrow S : (GS||H_{gs}) \tag{5.62}$$

When the server receives the message from the gateway, it will extract N_3 and N_4

$$(DID_g||N_3||N_4) = GS \oplus V_g \tag{5.63}$$

Using N_3 and N_4, the server will independently calculate the gateway dynamic identity DID_g^* using Eq. (5.59) and the session key SK using Eq. (5.52).

The server verifies the integrity of the message by calculating H_{gs}^* form Eq. (5.61) and compare it with the received H_{gs}.

The server now has the values N_2, N_3 and N_4. The server now embeds the values

N_2, N_3 and N_4 in the following quantity

$$SM = (N_2||N_3||N_4) \oplus V_m \tag{5.64}$$

The server also computes H_{sm}

$$H_{sm} = h(N_2||N_3||N_4) \tag{5.65}$$

The server now sends the following message to the mobile device

$$S \rightarrow M : (SM||H_{sm}) \tag{5.66}$$

When the mobile device receives the message from the server, it will extract N_2, N_3 and N_4

$$(N_2||N_3||N_4) = SM \oplus V_m \tag{5.67}$$

Using N_2, N_3 and N_4, the mobile device will independently calculate the session key SK using Eq. (5.52).

The mobile device verifies the integrity of the message by calculating H^*_{sm} form Eq. (5.65) and compare it with the received H_{sm}.

5.3.5 Pasword Update Phase

The password update phase applies to the user of the mobile device. The user can update the password after registration without involving the RA. In order to do that, the user supplies ID_m and the old password. The mobile device calculates V^*_m according to Eq. (5.15) and compare this with V_m that was defined during the registration phase. If the two values match, then the password update process can proceed further. The mobile device calculates a new V_m based on the new password and send this to the server.

5.4 Security Analysis of the Proposed Scheme

To analyze the security of our proposed scheme, we use BAN logic [80] and formal model checking and simulations using AVISPA tool [81] and informal security analysis.

5.4.1 Formal Proof Based on BAN Logic

In this subsection, we introduce a formal analysis for the proposed scheme using widely accepted model called BAN logic, this model has been used for a formal verification of security protocols which introduced in 1989 by Burrows et al. [80]. We begin our analysis by introducing the most important symbols and notations adapted from [82] which are given in Table 5.2.

Table 5.2: Notations in BAN logic.

Notation	**Descriptions**
P and Q	Principals
$P\mid\equiv X$	Principal P believes the statement X
$P \triangleleft X$	Principal P sees the statement X
$P\mid\Rightarrow X$	Principal P has jurisdiction over the statement X
$P\mid\sim X$	Principal P once said statement X
(X, Y)	The statement X or Y is one part of message $(X,\ Y)$
$< X >_Y$	The statement X is encrypted with the key K
$(X)_K$	The statement X is hashed with the key K
$P \overset{K}{\longleftrightarrow} Q$	K is a secret parameter shared (or to be shared) between P and Q
$P \overset{K}{=\!=} Q$	X is a secret known only to P and Q, and possibly to parties trusted by them.
$\#(X)$	The message X is *fresh*.

In addition, the following BAN logic basic rules are used to prove that our authentication protocol provides secure mutual authentication and key agreement as follows:

- Message-meaning rule:
  If P believes that the key K is shared with Q and P sees X encrypted under K, then P believes that Q once said X.

$$\frac{P\mid\equiv Q \overset{K}{\leftrightarrow} P, P \triangleleft \langle X\rangle_K}{P\mid\equiv Q\mid\sim X}$$

- Nonce verification rule:
  If P believes X is fresh and P believes Q once said X, then P believes Q believes

X.

$$\frac{P| \equiv \#(X), P| \equiv Q| \sim X}{P| \equiv Q| \equiv X}$$

- Jurisdiction rule:
  If P believes Q has jurisdiction over X and P believes Q believes X, then P believes X.
  $$\frac{P| \equiv Q| \Longrightarrow X, P| \equiv Q| \equiv X}{P| \equiv X}$$

- Freshness conjuncatenation rule:
  If one part of a statement is fresh, then the entire statement must also be fresh; so if P believes X is fresh, then P believes X and Y are fresh.

  $$\frac{P| \equiv \#(X)}{P| \equiv \#(X, Y)}$$

- Belief rule: If P believes X and Y, then P believes X.

  $$\frac{P| \equiv (X, Y)}{P| \equiv X}$$

- Session keys rule:
  $$\frac{P| \equiv \#(X), P| \equiv Q| \equiv X}{P| \equiv P \overset{K}{\leftrightarrow} Q}$$

The proposed scheme must achieve the following goals:

- Goal 1
  $$S| \equiv M| \equiv M \overset{SK}{\leftrightarrow} S$$

- Goal 2:
  $$S| \equiv M \overset{SK}{\leftrightarrow} S$$

- Goal 3:
  $$G| \equiv S| \equiv S \overset{SK}{\leftrightarrow} G$$

- Goal 4:
  $$G| \equiv S \overset{SK}{\leftrightarrow} G$$

- Goal 5:
$$D| \equiv G| \equiv G \overset{SK}{\leftrightarrow} D$$
- Goal 6:
$$D| \equiv G \overset{SK}{\leftrightarrow} D$$
- Goal 7:
$$G| \equiv D| \equiv G \overset{SK}{\leftrightarrow} D$$
- Goal 8:
$$G| \equiv G \overset{SK}{\leftrightarrow} D$$
- Goal 9:
$$S| \equiv G| \equiv S \overset{SK}{\leftrightarrow} G$$
- Goal 10:
$$S| \equiv S \overset{SK}{\leftrightarrow} G$$
- Goal 11:
$$M| \equiv S| \equiv M \overset{SK}{\leftrightarrow} S$$
- Goal 12:
$$M| \equiv M \overset{SK}{\leftrightarrow} S$$
- Goal 13:
$$M| \equiv G| \equiv M \overset{SK}{\leftrightarrow} G$$
- Goal 14:
$$G| \equiv M| \equiv M \overset{SK}{\leftrightarrow} G$$
- Goal 15:
$$S| \equiv D| \equiv S \overset{SK}{\leftrightarrow} D$$
- Goal 16:
$$D| \equiv S| \equiv S \overset{SK}{\leftrightarrow} D$$

The fundamental assumptions of the authentication protocol are as follows:

- A1:
$$M| \equiv \#(N_2)$$
- A2:
$$M| \equiv \#(N_3)$$
- A3:
$$M| \equiv \#(N_4)$$
- A4:
$$S| \equiv \#(N_1)$$
- A5:
$$S| \equiv \#(N_3)$$
- A6:
$$S| \equiv \#(N_4)$$
- A7:
$$G| \equiv \#(N_2)$$
- A8:
$$G| \equiv \#(N_4)$$
- A9:
$$D| \equiv \#(N_1)$$
- A10:
$$D| \equiv \#(N_2)$$
- A11:
$$D| \equiv \#(N_3)$$
- A12:
$$S| \equiv M \overset{V_m}{\leftrightarrow} S$$
- A13:
$$G| \equiv S \overset{V_g}{\leftrightarrow} G$$

- A14:

$$D| \equiv G \overset{V_d}{\leftrightarrow} D$$

- A15:

$$G| \equiv D \overset{V_d}{\leftrightarrow} G$$

- A16:

$$M| \equiv S \overset{V_m}{\leftrightarrow} M$$

- A17:

$$S| \equiv G \overset{V_g}{\leftrightarrow} S$$

- A18:

$$G| \equiv D| \Rightarrow (N_4, ID_d, V_d, SK)$$

- A19:

$$S| \equiv G| \Rightarrow (N_3, N_4, ID_g, V_g, SK)$$

- A20:

$$M| \equiv S| \Rightarrow (N_2, N_3, N_4, V_m, SK)$$

- A21:

$$D| \equiv G| \Rightarrow (N_1, N_2, N_3, V_d, SK)$$

- A22:

$$S| \equiv M| \Rightarrow (N_1, ID_m, V_m, L_m, SK)$$

- A23:

$$G| \equiv S| \Rightarrow (N_1, N_2, ID_s, V_g, SK)$$

Messages transferred in the authentication protocol:

- Msg 1:

$$M \rightarrow S : (MS, H_{ms})_{M \overset{V_m}{\leftrightarrow} S}$$

- Msg 2:

$$S \rightarrow G : (SG, H_{sg})_{S \overset{V_g}{\leftrightarrow} G}$$

- Msg 3:

$$G \rightarrow D : (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}$$

- Msg 4:

$$D \rightarrow G : (DG, H_{dg})_{D \overset{V_d}{\leftrightarrow} G}$$

- Msg 5:

$$G \rightarrow S : (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}$$

- Msg 6:

$$S \rightarrow M : (SM, H_{SM})_{S \overset{V_m}{\leftrightarrow} M}$$

Analysis of our authentication scheme:

- S1: According to Msg 1, we get:

$$S \ \triangleleft \ (MS, H_{ms})_{M \overset{V_m}{\leftrightarrow} S}$$

- S2: Based on Assumption A12, S1 and message-meaning rule, we have:

$$\frac{S| \equiv M \overset{V_m}{\leftrightarrow} S, S \ \triangleleft \ (MS, H_{ms})_{M \overset{V_m}{\leftrightarrow} S}}{S| \equiv M| \sim (MS, H_{ms})_{M \overset{V_m}{\leftrightarrow} S}}$$

- S3: From A4 and freshness-conjuncatenation rule, we get:

$$S \mid \equiv \# \ (MS, H_{ms})_{M \overset{V_m}{\leftrightarrow} S}$$

- S4: From S3, S2 and nonce-verification rule, we get:

$$\frac{S \mid \equiv \# \ (MS, H_{ms})_{M \overset{V_m}{\leftrightarrow} S}, S| \equiv M| \sim (MS, H_{ms})}{S| \equiv M| \equiv (MS, H_{ms})_{M \overset{V_m}{\leftrightarrow} S}}$$

- S5: According to the Msg 2, we get:

$$G \triangleleft (SG, H_{sg})_{S \overset{V_g}{\leftrightarrow} G}$$

- S6: From A13, S5 and message-meaning rule, we have:

$$\frac{G| \equiv S \overset{V_g}{\leftrightarrow} G, G \triangleleft (SG, H_{sg})_{S \overset{V_g}{\leftrightarrow} G}}{G| \equiv S| \sim (SG, H_{sg})_{S \overset{V_g}{\leftrightarrow} G}}$$

- S7: From A7 and freshness-conjuncatenation rule, we get:

$$G \mid \equiv \# (SG, H_{sg})_{S \overset{V_g}{\leftrightarrow} G}$$

- S8: From S7, S6 and nonce-verification rule, we get:

$$\frac{G \mid \equiv \# (SG, H_{sg})_{S \overset{V_g}{\leftrightarrow} G}, G| \equiv S| \sim (SG, H_{sg})_{S \overset{V_g}{\leftrightarrow} G}}{G| \equiv S| \equiv (SG, H_{sg})_{S \overset{V_g}{\leftrightarrow} G}}$$

- S9: According to the Msg 3, we get:

$$D \triangleleft (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}$$

- S10: From A14, S9 and message-meaning rule, we have:

$$\frac{D| \equiv (G \overset{V_d}{\leftrightarrow} D), D \triangleleft (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}}{D| \equiv G| \sim (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}}$$

- S11: From A11 and freshness-conjuncatenation rule, we get:

$$D \mid \equiv \# (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}$$

- S12: From S11, S10 and nonce-verification rule, we get:

$$\frac{D \mid \equiv \# (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}, D| \equiv G| \sim (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}}{D| \equiv G| \equiv (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}}$$

- S13: According to the Msg 4, we get:

$$G \triangleleft (DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}$$

- S14: From A15, S13 and message-meaning rule, we have:

$$\frac{G| \equiv D \overset{V_d}{\leftrightarrow} G, G \triangleleft (DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}}{G| \equiv D| \sim (DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}}$$

- S15: From A8 and freshness-conjuncatenation rule, we get:

$$G \mid \equiv \# (DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}$$

- S16: From S15, S14 and nonce-verification rule, we get:

$$\frac{G \mid \equiv \# (DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}, G| \equiv D| \sim (DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}}{G| \equiv D| \equiv (DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}}$$

- S17: According to the Msg 5, we get:

$$S \triangleleft (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}$$

- S18: From A17, S17 and message-meaning rule, we have:

$$\frac{S| \equiv G \overset{V_g}{\leftrightarrow} S, S \triangleleft (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}}{S| \equiv G| \sim (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}}$$

- S19: From A5, A6 and freshness-conjuncatenation rule, we get:

$$S \mid \equiv \# (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}$$

- S20: From S19, S18 and nonce-verification rule, we get:

$$\frac{S \mid \equiv \# (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}, S| \equiv G| \sim (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}}{S| \equiv G| \equiv (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}}$$

- S21: According to the Msg 6, we get:

$$M \triangleleft (SM, H_{SM})_{S^{\overset{V_m}{\leftrightarrow}} M}$$

- S22: From A16, S21 and message-meaning rule, we have:

$$\frac{M| \equiv S \overset{V_m}{\leftrightarrow} M, M \triangleleft (SM, H_{SM})_{S^{\overset{V_m}{\leftrightarrow}} M}}{M| \equiv S| \sim (SM, H_{SM})_{S^{\overset{V_m}{\leftrightarrow}} M}}$$

- S23: From A1, A2, A3 and freshness-conjuncatenation rule, we get:

$$M \mid \equiv \# (SM, H_{SM})_{S^{\overset{V_m}{\leftrightarrow}} M}$$

- S24: From S23, S22 and nonce-verification rule, we get:

$$\frac{M \mid \equiv \# (SM, H_{SM})_{S^{\overset{V_m}{\leftrightarrow}} M}, M| \equiv S| \sim (SM, H_{SM})_{S^{\overset{V_m}{\leftrightarrow}} M}}{M| \equiv S| \equiv (SM, H_{SM})_{S^{\overset{V_m}{\leftrightarrow}} M}}$$

- S25: From A22, S4 and jurisdiction rule, we get:

$$\frac{S| \equiv M| \Rightarrow (N_1, ID_m, V_m, L_m, SK), S| \equiv M| \equiv (MS, H_{ms})_{M^{\overset{V_m}{\leftrightarrow}} S}}{S| \equiv (MS, H_{ms})_{M^{\overset{V_m}{\leftrightarrow}} S}}$$

- S26: From S3, S4 and session keys rule, we get:

$$\frac{S \mid \equiv \# (MS, H_{ms})_{M^{\overset{V_m}{\leftrightarrow}} S}, S| \equiv M| \equiv (MS, H_{ms})_{M^{\overset{V_m}{\leftrightarrow}} S}}{S| \equiv M| \equiv M \overset{SK}{\leftrightarrow} S}$$

  (Goal 1)

- S27: From A22, S26 and jurisdiction rule, we get:

$$\frac{S| \equiv M| \Rightarrow (N_1, ID_m, V_m, L_m, SK), S| \equiv M| \equiv M \overset{SK}{\leftrightarrow} S}{S| \equiv M \overset{SK}{\leftrightarrow} S}$$

  (Goal 2)

- S28: From A23, S8 and jurisdiction rule, we get:

$$\frac{G| \equiv S| \Rightarrow (N_1, N_2, ID_s, V_g, SK), G| \equiv S| \equiv (SG, H_{sg})_{S^{\overset{V_g}{\leftrightarrow}} G}}{G| \equiv (SG, H_{sg})_{S^{\overset{V_g}{\leftrightarrow}} G}}$$

- S29: From S7, S8 and session keys rule, we get:

$$\frac{G \mid \equiv \#\ (SG, H_{sg})_{S \overset{V_g}{\leftrightarrow} G}, G| \equiv S| \equiv (SG, H_{sg})_{S \overset{V_g}{\leftrightarrow} G}}{G| \equiv S| \equiv S \overset{SK}{\leftrightarrow} G}$$

(Goal 3)

- S30: From A23, S29 and jurisdiction rule, we get:

$$\frac{G| \equiv S| \Rightarrow (N_1, N_2, ID_s, V_g, SK), G| \equiv S| \equiv S \overset{SK}{\leftrightarrow} G}{G| \equiv S \overset{SK}{\leftrightarrow} G}$$

(Goal 4)

- S31: From A21, S12 and jurisdiction rule, we get:

$$\frac{D| \equiv G| \Rightarrow (N_1, N_2, N_3, V_d, SK), D| \equiv G| \equiv (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}}{D| \equiv (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}}$$

- S32: From S11, S12 and session keys rule, we get:

$$\frac{D \mid \equiv \#\ (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}, D| \equiv G| \equiv (GD, H_{gd})_{G \overset{V_d}{\leftrightarrow} D}}{D| \equiv G| \equiv G \overset{SK}{\leftrightarrow} D}$$

(Goal 5)

- S33: From A21, S32 and jurisdiction rule, we get:

$$\frac{D| \equiv G| \Rightarrow (N_1, N_2, N_3, V_d, SK), D| \equiv G| \equiv G \overset{SK}{\leftrightarrow} D}{D| \equiv G \overset{SK}{\leftrightarrow} D}$$

(Goal 6)

- S34: From A18, S16 and jurisdiction rule, we get:

$$\frac{G| \equiv D| \Rightarrow (N_4, ID_d, V_d, SK), G| \equiv D| \equiv (DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}}{G| \equiv (DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}}$$

- S35: From S15, S16 and session keys rule, we get:

$$\frac{G \mid \equiv \#\,(DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}, G| \equiv D| \equiv (DG, H_{dg})_{G \overset{V_d}{\leftrightarrow} D}}{G| \equiv D| \equiv G \overset{SK}{\leftrightarrow} D}$$

(Goal 7)

- S36: From A18, S35 and jurisdiction rule, we get:

$$\frac{G| \equiv D| \Rightarrow (N_4, ID_d, V_d, SK), G| \equiv D| \equiv G \overset{SK}{\leftrightarrow} D}{G| \equiv G \overset{SK}{\leftrightarrow} D}$$

(Goal 8)

- S37: From A19, S20 and jurisdiction rule, we get:

$$\frac{S| \equiv G| \Rightarrow (N_3, N_4, ID_g, V_g, SK), S| \equiv G| \equiv (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}}{S| \equiv (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}}$$

- S38: From S19 and S20, we get:

$$\frac{S \mid \equiv \#\,(GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}, S| \equiv G| \equiv (GS, H_{GS})_{S \overset{V_g}{\leftrightarrow} G}}{S| \equiv G| \equiv S \overset{SK}{\leftrightarrow} G}$$

(Goal 9)

- S39: From A19, S38 and jurisdiction rule, we get:

$$\frac{S| \equiv G| \Rightarrow (N_3, N_4, ID_g, V_g, SK), S| \equiv G| \equiv S \overset{SK}{\leftrightarrow} G}{S| \equiv S \overset{SK}{\leftrightarrow} G}$$

(Goal 10)

- S40: From A20, S24 and jurisdiction rule, we get:

$$\frac{M| \equiv S| \Rightarrow (N_2, N_3, N_4, V_m, SK), M| \equiv S| \equiv (SM, H_{SM})_{M \overset{V_m}{\leftrightarrow} S}}{M| \equiv (SM, H_{SM})_{M \overset{V_m}{\leftrightarrow} S}}$$

- S41: From S23, S24 and session keys rule, we get:

$$\frac{M \mid \equiv \#\,(SM, H_{SM})_{S \overset{V_m}{\leftrightarrow} M}, M| \equiv S| \equiv (SM, H_{SM})_{S \overset{V_m}{\leftrightarrow} M}}{M| \equiv S| \equiv M \overset{SK}{\leftrightarrow} S}$$

(Goal 11)

- S42: From A20, S41 and jurisdiction rule, we get:

$$\frac{M| \equiv S| \Rightarrow (N_2, N_3, N_4, V_m, SK), M| \equiv S| \equiv M \overset{SK}{\leftrightarrow} S}{M| \equiv M \overset{SK}{\leftrightarrow} S}$$

(Goal 12)

- S43: From S41, S30, we get:

$$\frac{M| \equiv S| \equiv M \overset{SK}{\leftrightarrow} S, G| \equiv S \overset{SK}{\leftrightarrow} G}{M| \equiv G| \equiv M \overset{SK}{\leftrightarrow} G}$$

(Goal 13)

- S44: From S29, S42 and jurisdiction rule, we get:

$$\frac{G| \equiv S| \equiv S \overset{SK}{\leftrightarrow} G, M| \equiv M \overset{SK}{\leftrightarrow} S}{G| \equiv M| \equiv M \overset{SK}{\leftrightarrow} G}$$

(Goal 14)

- S45: From S38, S33 and jurisdiction rule, we get:

$$\frac{S| \equiv G| \equiv S \overset{SK}{\leftrightarrow} G, D| \equiv G \overset{SK}{\leftrightarrow} D}{S| \equiv D| \equiv S \overset{SK}{\leftrightarrow} D}$$

(Goal 15)

- S46: From S32, S39 and jurisdiction rule, we get:

$$\frac{D| \equiv G| \equiv G \overset{SK}{\leftrightarrow} D, S| \equiv S \overset{SK}{\leftrightarrow} G}{D| \equiv S| \equiv S \overset{SK}{\leftrightarrow} D}$$

(Goal 16)

Hence, the above BAN logic analysis formally proves that the proposed scheme successfully achieves mutual authentication, and the session key SK, in Eq. (5.52), is mutually established between the U and the D_j through the G.

5.4.2 Informal Security Analysis

In this section, we show how our protocol is robust against various well-known attacks.

Replay attack

To resist replay attack, the random number method is utilized, so replay attack can be prevented by using the nonces which change in each session.

Eavesdropping attack

In our scheme, the adversary can easily intercept the messages between M, S, G and D since all messages are sent in plain text. However, the attacker can not access sensitive information from any messages because the confidential data is secured by secret parameters shared securely between the entities (e.g., V_m and V_g), and shielded by one-way hash function and bitwise XOR operator. The attacker would thus not be able to unfold the transmitted parameters, and thus can not extract any useful information.

Impersonation attack

Assume an attacker A attempts to impersonate a healthcare professional. A can not succeed because he/she does not know the password or the biometric needed for three-factor authentication to access the mobile device.

Man-in-the-middle attack

The proposed scheme offers mutual authentication, as stated in Section 5.4.1 of the BAN logic. The transmitted messages are further protected by the secret values and nonces, and no one could forge legally authenticated messages without knowing those secret values. The proposed scheme hence prevents the Man-in-the-Middle attack.

Forward/backward secrecy

The session key is built using four different random numbers that are generated by M, S, G and D in each session. Thus, if the session key SK is compromised by an attacker, the confidential information of past or future communication sessions can not be compromised. For this reason, the proposed scheme achieves forward/backward secrecy.

Session key Guessing Attack

The session key SK is constructed by all communication participants, namely M, S, G and D, and four randomly selected nonces. Thus security relies on the randomness of the input values, which makes it difficult for an attacker to guess. An attacker's probability of guessing the right key SK is negligible, provided that N_1, N_2, N_3 and N_4 are chosen randomly in every session.

User anonymity and untraceability

Anonymity of users and untraceability in authentication are two essential security properties. Anonymity ensures that the mobile device's real identity is maintained secure, and that the mobile device stays unidentifiable among other devices. Therefore, the attacker is unable to identify the devices' identities. Untraceability, on the other hand, means that the various sessions set up by a specific mobile device are not traceable, so that an attacker can not relate any sessions to a specific mobile device. These two main security properties were achieved by the use of the healthcare professional's dynamic identity, where we use different ID in each session.

Location-based authentication

The physical context awareness (location in the IoT system) used in our scheme involves checking the identities of the edge devices seen by the device D being authenticated, see Eq. (5.53). If the subset $\mathbb{D}_d$ is valid and does not contain identities of unkown devices, then the location of our device is authenticated.

Cloning attack

Cloning attack targets the unprotected IoT edge devices. Section 5.2.1 discussed incorporating PUF modules in the edge devices which provides a high degree of

tamper-resistant unique identity (fingerprint) without incurring extra costs in area, delay, power or specialized processing steps [68]. The unique device identity avoids using nonvolatile memory, whose contents can be easily obtained by an unsophisticated attacker. Instead the device ID is captured in the PUF circuitry which provides a random response with low entropy that imparts sufficient differences between the manufactured edge devices. Therefore, IoT edge devices are immune to cloning attacks.

Physical attack

Physical attack attempts to obtain the secret key of the device knowing that secret keys are typically stored in nonvolatile memories. The IoT edge devices are the most vulnerable to this type of attack since they are usually located in unsecured locations. We mentioned above in Sec. 5.2.1 PUF modules are installed in the edge devices which provides a high degree of tamper-resistant unique identity (fingerprint). The PUF response is used to extract the secret key instead of relying on nonvolatile memories. Section 5.2.7 discussed how the secret key is extract from the noisy response of the PUF. Therefore, IoT edge devices are immune to physical attacks.

5.4.3 Simulation Based on AVISPA Tool

The proposed scheme was formally validated by AVISPA that is a widely used tool for security protocol assessments. The message exchanges and entities were defined in the high-level property specification language (HLPSL). The definitions and information in details can be found in [43].

This subsection explores several roles for system entities, the session, the goal and the environment of proposed scheme. In Fig. 5.7-5.10, we illustrate HLPSL code for our proposed scheme. These figures show the HLPSL language code that defines the configuration of the sessions, the environment and security goals to be achieved by our proposed scheme. The figures also show the definitions of the security goals declared to be secrets in the entity's functions and the values that are authenticated by the entities.

Fig. 5.11 shows the protocol execution using SPAN software, where the all agents exchange the messages in authentication phase.

In conclusion, the results shown in Fig. 5.12-5.13 clearly show that the the proposed scheme is immune against man-in-the-middle and replay attacks.

```
role role_S(S,M,G,D:agent,H:hash_func,SND,RCV:channel
(dy))
played_by S
def=
    local
        State:nat,IDm,IDs,N1,N2,N3:text,V1:hash
(text.text),Vm,Vg:hash(text.message),
MS,SG,GD,GS,SM,M1,M2,DIDm,DIDs:message,Hms,Hsg,Hgs,Hs
(message)
    init
        State := 1
    transition
        1. State=1 /\ RCV(MS.Hms)  =|>  State':=3 /\
M2':=(DIDs.N1.N2) /\ SG':=xor(M2,Vg) /\ Hsg':=H(M2) /
\ SND(SG.Hsg)
        3. State=3 /\ RCV(GS.Hgs)  =|>  State':=5 /\
M2':=(N1.N2.N3) /\ SM':=xor(M2,Vg) /\ Hsm':=H(M2) /\
SND(SM.Hsm)

end role
```

Figure 5.7: Role of S in HLPSL code.

```
role role_M(M,S,G,D:agent,H:hash_func,SND,RCV:channel
(dy))
played_by M
def=
    local
        State:nat,IDm,N1,N2,N3,Lm:text,V1:hash
(text.text),Vm:hash
(text.message),DIDm,MS,SM,M1:message,Hms,Hsm:hash
(message),SK:hash(text.text.text)
    init
        State := 0
    transition
        0. State=0 /\ RCV(start) =|> State':=2 /\
DIDm':=xor(IDm,N1) /\ M1':=(DIDm.N1.Lm) /\ MS':=xor
(M1,Vm) /\ Hms':=H(M1) /\ SND(MS.Hms) /\ secret
(IDm,sec_idm,{S,M,G,D}) /\ secret(N1,sec_n1,
{S,M,G,D})
        2. State=2 /\ RCV(SM'.Hsm')  =|>  State':=4


end role
```

Figure 5.8: Role of M in HLPSL code.

```
role role_G(M,S,G,D:agent,H:hash_func,SND,RCV:channel
(dy))
played_by G
def=
    local
    State:nat,IDs,N1,N2,N3:text,V2:hash
(text.message),V3:hash
(message),SG,GD,DG,GS,M1,M2,M3,M4,M7,M8,DIDs:message,I
(message),Vg,Vd:hash(text.message),SK:hash
(text.text.text)
    init
        State := 30
    transition
        30. State=30 /\ RCV(SG',Hsg') =|>
State':=32 /\ M3':=(N1.N2.N3) /\ GD':=xor(M3,Vd) /\
Hgd':=H(M3) /\ SND(GD.Hgd)

        32. State=32 /\ RCV(DG',Hdg') =|>
State':=34 /\ M3':=(N1.N2.N3) /\ GS':=xor(M3,Vd) /\
Hgs':=H(M3) /\ SND(GS.Hgs)


end role
```

Figure 5.9: Role of G in HLPSL code.

```
role role_D(M,S,G,D:agent,H:hash_func,SND,RCV:channel
(dy))
played_by D
def=
    local

State:nat,IDd,IDsd,N1,N2,N3,N4,Dd:text,Vd:hash
(text.message),DG,GD,M2,M3,M4,DIDd:message,Hdg,Hgd:ha
(message),SK:hash(text.text.text)
    init
        State := 60
    transition
        60. State=60 /\ RCV(GD'.Hgd') =|>
State':=62 /\ DIDd':=xor(IDd,N4) /\ SK':=H
(N1.N2.N3.N4) /\ M4':=(DIDd.Dd.N4) /\ DG':=xor
(M4,Vd) /\ Hdg':=H(N4.SK) /\ SND(DG.Hdg)

end role
```

Figure 5.10: Role of D in HLPSL code.

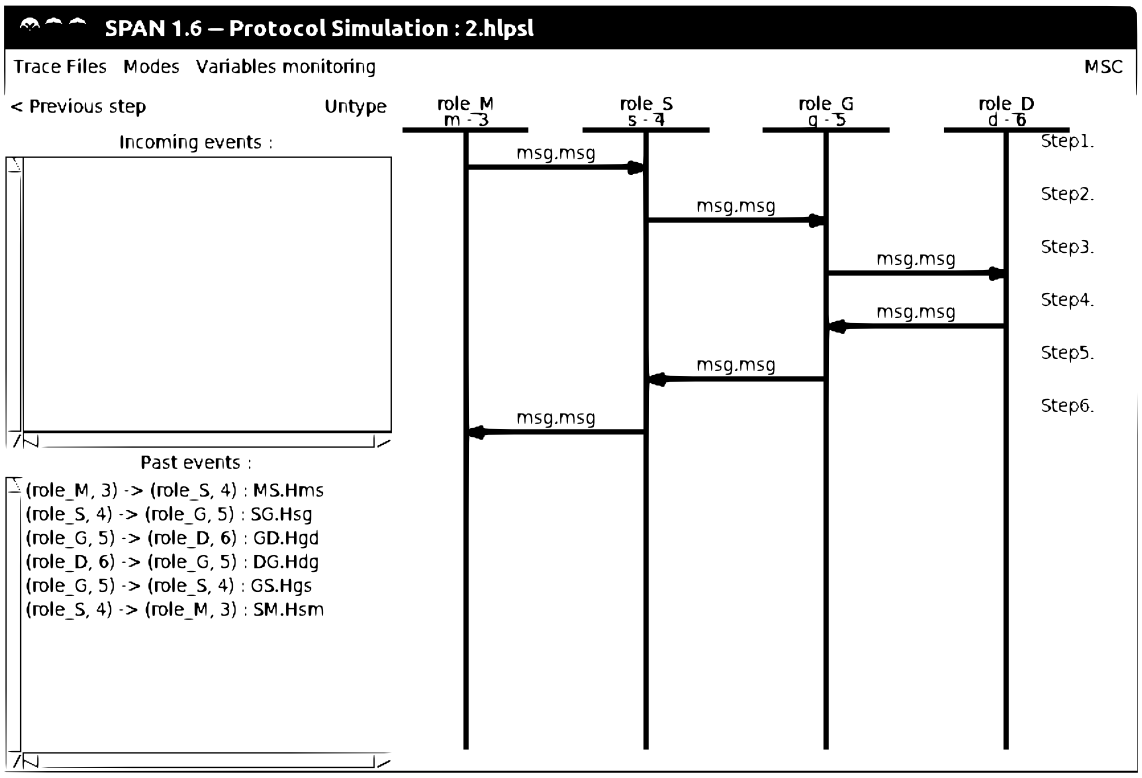


Figure 5.11: The protocol execution using SPAN.

5.4.4 Performance Comparison

In this section, we assess the performance of our proposed scheme in terms of storage cost, computation costs, and communication overhead.

Storage cost

We evaluate storage cost (in bits) for M, S, G and D of the four participants.

M stores ID_m and V_m. As an example of hash function we utilize SHA3-384, and output of SHA3-384 is 384 bits. Using SHA3-384 we get $V_m = 384$ bits [83]. While $ID_m = 128$ bits. Thus, the total storage required by M is 384+128=512 bits.

S stores ID_s, ID_m, ID_g, V_m and V_g. By applying SHA3-384, we obtain $V_m = V_g = 384$ bits. The ID_s=ID_m=ID_g=128 bits. Therefore, the total storage required by S is (2x384)+(3x128)= 1152 bits.

G stores ID_g, ID_s, ID_d, V_g and V_d. The ID_g=ID_s=$ID_d = 128$ bits and $V_g = V_d = 384$ bits. Therefore, the total storage required by G is (3x128)+(2x384)= 1152 bits.

D stores ID_d and V_d. The $ID_d = 128$ bits and $V_d = 384$ bits. Therefore, the total

```
SUMMARY
 SAFE

DETAILS
 BOUNDED_NUMBER_OF_SESSIONS
 TYPED_MODEL

PROTOCOL
 /home/span/span/testsuite/results/2.if

GOAL
 As Specified

BACKEND
 CL-AtSe

STATISTICS

 Analysed   : 0 states
 Reachable  : 0 states
 Translation: 0.03 seconds
 Computation: 0.00 seconds
```

Figure 5.12: Analysis of results using CL-AtSe.

```
% OFMC
% Version of 2006/02/13
SUMMARY
 SAFE
DETAILS
 BOUNDED_NUMBER_OF_SESSIONS
PROTOCOL
 /home/span/span/testsuite/results/2.if
GOAL
 as_specified
BACKEND
 OFMC
COMMENTS
STATISTICS
 parseTime: 0.00s
 searchTime: 0.14s
 visitedNodes: 54 nodes
 depth: 7 plies
```

Figure 5.13: Analysis of results using OFMC.

storage required by D is 128+384= 512 bits.

Computational cost

In this subsection, we provide the computation cost analysis of our proposed scheme. In order to ensure a precise computation cost of our scheme, the experimental data reported in [84] and [85] are used. The terms T_h, T_{exp}, and T_E/T_D as the computational time for hash function h(.), modular exponentiation operation, and symmetric encryption/decryption, respectively.

Table 5.3 Shows the time required to conduct certain operations. However, the execution time of the bitwise XOR operation is negligible. Our scheme performs 13 hash invocations and 19 XOR operations, which yields a total computation cost (13 $\times$ T_h). Hence, the computation cost of our proposed protocol is (13 $\times$ 0.5 ms)= 6.5 ms.

Table 5.3: Crypto-operations and the computational times needed.

Crypto-operations	**Computational time**
Execute/verify a signature (T_{sign})	331.7 ms
Asymmetric encryption/ decryption operation (T_A)	305.7 ms
Multiplication operation (T_M)	50.3 ms
Bilinear pairing operation (T_P)	62.1 ms
Symmetric encryption/ decryption operation (T_S)	8.7 ms
One-way hash function (T_H)	0.5 ms

A comparison of the computation cost between the proposed scheme and the other most related schemes in ms is shown in Table 5.4.

Table 5.5 provides security and functionality features compared to other existing related schemes.

5.5 Conclusion

Basic security requirements such as privacy, authentication, integrity, non-repudiation and key exchange are essential for telehealth delivery to remote communities and at-

Table 5.4: Comparison of computation cost between the proposed scheme and other most related schemes in ms.

Authentication scheme	**Total cost**	**Rough estimation**
Kumar et al. [86]	$8T_S + 10T_H$	74.6 ms
Chen et al. [28]	$2T_{sign} + 2T_P + 6T_S + 4T_H$	841.8 ms
Karthigaiveni et al. [87]	$2T_A + 3T_H + 2T_S$	630.3 ms
Alzahrani et al. [88]	$17T_H + 5T_S$	52 ms
Proposed scheme	$13T_h$	6.5 ms

Table 5.5: Security and functionality features comparison.

Functionality features	[86]	[28]	[87]	[88]	**Proposed scheme**
Mutual authentication	Yes	Yes	No	No	Yes
Session key agreement	Yes	Yes	Yes	Yes	Yes
User anonymity	Yes	Yes	No	No	Yes
Untraceability	Yes	Yes	No	No	Yes
Forward security	No	Yes	Yes	No	Yes
Password guessing attack	Yes	Yes	No	No	Yes
Mobile device loss attack	Yes	Yes	No	No	Yes
Privileged insider attack	Yes	Yes	Yes	Yes	Yes
Impersonation attack	Yes	Yes	No	No	Yes
Replay attack	Yes	Yes	Yes	Yes	Yes
Man-in-the-middle attack	Yes	Yes	Yes	No	Yes
Password change phase	Yes	Yes	No	No	Yes
Formal proof (BAN logic)	Yes	Yes	No	No	Yes
Formal verification (AVISPA)	Yes	No	Yes	No	Yes
Authentication based on contextual factors	No	No	No	No	Yes
Cloning attack	No	No	No	No	Yes
Physical attack	No	No	No	No	Yes

home patients. In this work a robust lightweight authentication and key exchange scheme is proposed among four entities involved in an telehealth system. After a round of secure authentication between a mobile device, server, gateway and an IoT edge device, a symmetric session key is established. Security of the proposed scheme is proved formally using BAN logic. In addition, informal security verification assures resistance of the proposed scheme in the face of the most common attacks. Finally, formal security of the proposed protocol is evaluated using the AVISPA tool that assures us of the security of the protocol.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The Internet of Things (IoT) plays an important role in all facets of our daily lives. It benefits different fields, including healthcare, industrial appliances, sports, homes, etc. The IoT consists of billions of devices connected together over the internet that are able to gather and exchange data using IoT nodes and controllers.

The number of IoT devices is increasing at a very fast pace. It has been predicted by Gartner that the number of IoT devices will reach 20.4 billion by 2020 [89][90] and 25 billion by 2025 [91]. The anticipated fast growth of IoT devices has led to serious security concerns for networks [92].

Cyber attackers are shifting their attention from traditional computers to IoT devices for malignant activities like exposing smart homeowner private information and/or to launch botnet attacks. As in conventional networks, the security of IoT networks rests on how properly the authentication process is done. However, unlike conventional networks, the IoT infrastructure faces an uphill battle in deploying and operating strong authentication schemes because of inherent limitations on the underlying storage and computation capability.

The first contribution of this work is the introduction of a new scheme for user authentication that combines physical context awareness and transaction history The new scheme offers two advantages: it does not maintain a verification table and avoids clock synchronization problem. Moreover, the security of the proposed scheme is augmented using dynamic identities and temporary secret session keys that change in every session, and are exchanged in an unlinkable manner, improve the security of

the proposed scheme.

The second contribution is the introduction of a secure telehealth system using multifactor authentication for the mobile devices as well as the IoT edge devices in the system. These two types of devices constitute the weakest link in telehealth systems. The mobile devices and edge devices are typically unsecured and contain vulnerable processors. The mobile devices use the healthcare professional's biometric and endowing the edge device with biometrics is accomplished by using physically unclonable functions (PUFs). The embedded PUF acts as a means of enabling mutual authentication and key exchange.

Furthermore, through the rigorous formal and informal security analysis of our protocols using the BAN logic and AVISPA tool, we show that our schemes are resilient against known attack methods. Besides, our schemes achieved the key security properties (e.g., anonymity, unlinkability) with a relatively limited performance overhead. Finally, we compared our schemes with other proposed schemes and showed that our schemes are in general more efficient than recently proposed schemes.

6.2 Future Work

Our plans for future work include the following:

- We will extend the proposed protocol suite to consider cases where the IoT node leaves one particular home network and joins another network.
- We will allow an IoT device in one home network to communicate with an IoT device in another home network regardless of the underlying communication protocols.
- We will also explore how to reinforce the current capability of our scheme to thwart impersonation by adapting continuous authentication schemes, such as the approach proposed by Tsai et al [93]. In their work [93], Tsai et al. presented a passive contin- uous authentication system based on physiological and soft biometrics technologies, namely face recognition and clothes'color recognition, using interactive artificial bee colony algorithm. In the system, face recognition is considered the key component to controlling the authentication process, while soft biometric is seen as a support- ing factor to overcome and remedy any potential security breach, such as account hijacking occurring while the user is temporarily away from the device.

Bibliography

[1] K. Ashton *et al.*, "That 'internet of things' thing," *RFID journal*, vol. 22, no. 7, pp. 97–114, 2009.

[2] C. Kolias, G. Kambourakis, A. Stavrou, and J. Voas, "Ddos in the iot: Mirai and other botnets," *Computer*, vol. 50, no. 7, pp. 80–84, 2017.

[3] Y. Lu and L. Da Xu, "Internet of things (iot) cybersecurity research: a review of current research topics," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 2103–2115, 2018.

[4] M. Abomhara *et al.*, "Cyber security and the internet of things: vulnerabilities, threats, intruders and attacks," *Journal of Cyber Security and Mobility*, vol. 4, no. 1, pp. 65–88, 2015.

[5] N. Kshetri, "Can blockchain strengthen the internet of things?" *IT professional*, vol. 19, no. 4, pp. 68–72, 2017.

[6] L. Pascu, "The iot threat landscape and top smart home vulnerabilities in 2018," 2018.

[7] J. Wurm, K. Hoang, O. Arias, A.-R. Sadeghi, and Y. Jin, "Security analysis on consumer and industrial iot devices," in *2016 21st Asia and South Pacific Design Automation Conference (ASP-DAC)*. IEEE, 2016, pp. 519–524.

[8] K. Gopalakrishnan *et al.*, "Security vulnerabilities and issues of traditional wireless sensors networks in iot," in *Principles of Internet of Things (IoT) Ecosystem: Insight Paradigm*. Springer, 2020, pp. 519–549.

[9] A. Bhattacharjya, X. Zhong, J. Wang, and X. Li, "Present scenarios of iot projects with security aspects focused," in *Digital Twin Technologies and Smart Cities*. Springer, 2020, pp. 95–122.

[10] P. Porambage, C. Schmitt, P. Kumar, A. Gurtov, and M. Ylianttila, "Two-phase authentication protocol for wireless sensor networks in distributed iot applications," in *2014 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2014, pp. 2728–2733.

[11] A. Pfitzmann and M. Köhntopp, "Anonymity, unobservability, and pseudonymity—a proposal for terminology," in *Designing privacy enhancing technologies*. Springer, 2001, pp. 1–9.

[12] S. Steinbrecher and S. Köpsell, "Modelling unlinkability," in *International Workshop on Privacy Enhancing Technologies*. Springer, 2003, pp. 32–47.

[13] V. Sureshkumar, R. Anitha, N. Rajamanickam, and R. Amin, "A lightweight two-gateway based payment protocol ensuring accountability and unlinkable anonymity with dynamic identity," *Computers & Electrical Engineering*, vol. 57, pp. 223–240, 2017.

[14] U. Blumenthal, F. Maino, and K. McCloghrie, "The advanced encryption standard (aes) cipher algorithm in the snmp user-based security model," *Internet proposed standard RFC*, vol. 3826, 2004.

[15] P. Barrett, "Implementing the rivest shamir and adleman public key encryption algorithm on a standard digital signal processor," in *Conference on the Theory and Application of Cryptographic Techniques*. Springer, 1986, pp. 311–323.

[16] C. Insiders, "Insider threat-2018 report," *CA Technologies. Accessed Jun*, vol. 20, 2018.

[17] J. Jeong, M. Y. Chung, and H. Choo, "Integrated otp-based user authentication scheme using smart cards in home networks," in *Proceedings of the 41st Annual Hawaii International Conference on System Sciences (HICSS 2008)*. IEEE, 2008, pp. 294–294.

[18] R. Roman, J. Zhou, and J. Lopez, "On the features and challenges of security and privacy in distributed internet of things," *Computer Networks*, vol. 57, no. 10, pp. 2266–2279, 2013.

[19] P. Kumar, A. Braeken, A. Gurtov, J. Iinatti, and P. H. Ha, "Anonymous secure framework in connected smart home environments," *IEEE Transactions on Information Forensics and Security*, vol. 12, no. 4, pp. 968–979, 2017.

[20] P. N. Mahalle, B. Anggorojati, N. R. Prasad, R. Prasad *et al.*, "Identity authentication and capability based access control (iacac) for the internet of things," *Journal of Cyber Security and Mobility*, vol. 1, no. 4, pp. 309–348, 2013.

[21] B. Vaidya, J. H. Park, S.-S. Yeo, and J. J. Rodrigues, "Robust one-time password authentication scheme using smart card for home network environment," *Computer Communications*, vol. 34, no. 3, pp. 326–336, 2011.

[22] H. J. Kim and H. S. Kim, "Auth hotp-hotp based authentication scheme over home network environment," in *International Conference on Computational Science and Its Applications*. Springer, 2011, pp. 622–637.

[23] F. K. Santoso and N. C. Vun, "Securing iot for smart home system," in *2015 International Symposium on Consumer Electronics (ISCE)*. IEEE, 2015, pp. 1–2.

[24] P. Kumar, A. Gurtov, J. Iinatti, M. Ylianttila, and M. Sain, "Lightweight and secure session-key establishment scheme in smart home environments," *IEEE Sensors Journal*, vol. 16, no. 1, pp. 254–264, 2015.

[25] M. Wazid, A. K. Das, V. Odelu, N. Kumar, and W. Susilo, "Secure remote user authenticated key establishment protocol for smart home environment," *IEEE Transactions on Dependable and Secure Computing*, 2017.

[26] M. Shuai, N. Yu, H. Wang, and L. Xiong, "Anonymous authentication scheme for smart home environment with provable security," *Computers & Security*, 2019.

[27] C. L. Chen, T. T. Yang, M. L. Chiang, and T. F. Shih, "A privacy authentication scheme based on cloud for medical environment," *Journal of Medical Systems*, vol. 38, no. 143, 2014.

[28] C.-L. Chen, T.-T. Yang, and T.-F. Shih, "secure medical data exchange protocol based on cloud environment," *Journal of medical systems*, vol. 38, no. 9, p. 112, 2014.

[29] S.-Y. Chiou, Z. Ying, and J. Liu, "Improvement of a privacy authentication scheme based on cloud for medical environment," *Journal of medical systems*, vol. 40, no. 4, p. 101, 2016.

[30] P. Mohit, R. Amin, A. Karati, G. Biswas, and M. K. Khan, "A standard mutual authentication protocol for cloud computing based health care system," *Journal of medical systems*, vol. 41, no. 4, p. 50, 2017.

[31] C.-T. Li, D.-H. Shih, and C.-C. Wang, "Cloud-assisted mutual authentication and privacy preservation protocol for telecare medical information systems," *Computer Methods and Programs Biomedicine*, vol. 157, pp. 191–203, 2018.

[32] B. Yu and H. Li, "Anonymous authentication key agreement scheme with pairing-based cryptography for home-based multi-sensor internet of things," *International Journal of Distributed Sensor Networks*, vol. 15, no. 9, 2019.

[33] R. Soni and G. Kumar, "A review on blockchain urgency in the internet of things in healthcare," in *International Conference on Intelligent Sustainable Systems*, 2019.

[34] S. M. R. Islam, D. Kwak, M. H. Kabir, M. Hossain, and K.-S. Kwak, "The internet of things for health care: A comprehensive survey," *IEEE Access*, vol. 3, no. 6, Jun. 2015.

[35] N. Mitton, H. Chaouchi, T. Noel, T. Gabillon, and P. Capolsini, "Interoperability, safety and security in iot," in *Second international conference, InterIoT 2016 and third international conference, SaSeIoT*. Springer, 2016.

[36] A. Lohachab *et al.*, "Ecc based inter-device authentication and authorization scheme using mqtt for iot networks," *Journal of Information Security and Applications*, vol. 46, pp. 1–12, 2019.

[37] L. Tanczer, I. Brass, M. Elsden, M. Carr, and J. J. Blackstock, "The united kingdom's emerging internet of things (iot) policy landscape," *Tanczer, LM, Brass, I., Elsden, M., Carr, M., & Blackstock, J.(2019). The United Kingdom's Emerging Internet of Things (IoT) Policy Landscape. In R. Ellis & V. Mohan (Eds.), Rewired: Cybersecurity Governance*, pp. 37–56, 2019.

[38] J. A. Manrique, J. S. Rueda-Rueda, and J. M. Portocarrero, "Contrasting internet of things and wireless sensor network from a conceptual overview," in *2016 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical*

and Social Computing (CPSCom) and IEEE Smart Data (SmartData). IEEE, 2016, pp. 252–257.

[39] N. Abbas, M. Asim, N. Tariq, T. Baker, and S. Abbas, "A mechanism for securing iot-enabled applications at the fog layer," *Journal of Sensor and Actuator Networks*, vol. 8, no. 1, p. 16, 2019.

[40] N. Saputro, A. I. Yurekli, K. Akkaya, and A. S. Uluagac, "Privacy preservation for iot used in smart buildings," in *Security and Privacy in Internet of Things (IoTs)*. CRC Press, 2016, pp. 155–186.

[41] M. Burrows, M. Abadi, and R. M. Needham, "A logic of authentication," *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, vol. 426, no. 1871, pp. 233–271, 1989.

[42] J. Wen, M. Zhang, and X. Li, "The study on the application of ban logic in formal analysis of authentication protocols," in *Proceedings of the 7th international conference on Electronic commerce*. ACM, 2005, pp. 744–747.

[43] A. Armando, D. Basin, Y. Boichut, Y. Chevalier, L. Compagna, J. Cuéllar, P. H. Drielsma, P.-C. Héam, O. Kouchnarenko, J. Mantovani *et al.*, "The avispa tool for the automated validation of internet security protocols and applications," in *International conference on computer aided verification*. Springer, 2005, pp. 281–285.

[44] L. Viganò, "Automated security protocol analysis with the avispa tool," *Electronic Notes in Theoretical Computer Science*, vol. 155, pp. 61–86, 2006.

[45] M. Branman, "6 fastest cars in the world right now," https://www.themanual.com/auto/fastest-cars-in-the-world/, online; accessed 3 November 2019.

[46] D. Dolev and A. Yao, "On the security of public key protocols," *IEEE Transactions on information theory*, vol. 29, no. 2, pp. 198–208, 1983.

[47] D. Basin, S. Mödersheim, and L. Vigano, "An on-the-fly model-checker for security protocol analysis," in *European Symposium on Research in Computer Security*. Springer, 2003, pp. 253–270.

[48] M. Turuani, "The cl-atse protocol analyser," in *International Conference on Rewriting Techniques and Applications*. Springer, 2006, pp. 277–286.

[49] A. Armando and L. Compagna, "Satmc: a sat-based model checker for security protocols," in *European workshop on logics in artificial intelligence*. Springer, 2004, pp. 730–733.

[50] O. Elkeelany, M. M. Matalgah, K. P. Sheikh, M. Thaker, G. Chaudhry, D. Medhi, and J. Qaddour, "Performance analysis of ipsec protocol: encryption and authentication," in *2002 IEEE International Conference on Communications. Conference Proceedings. ICC 2002 (Cat. No. 02CH37333)*, vol. 2. IEEE, 2002, pp. 1164–1168.

[51] D. He, N. Kumar, J.-H. Lee, and R. S. Sherratt, "Enhanced three-factor security protocol for consumer usb mass storage devices," *IEEE Transactions on Consumer Electronics*, vol. 60, no. 1, pp. 30–37, 2014.

[52] C.-C. Lee, C.-T. Chen, P.-H. Wu, and T.-Y. Chen, "Three-factor control protocol based on elliptic curve cryptosystem for universal serial bus mass storage devices," *IET Computers & Digital Techniques*, vol. 7, no. 1, pp. 48–55, 2013.

[53] J. Delvaux, D. Gu, D. Schellekens, and I. Verbauwhede, "Helper data algorithms for PUF-based key generation: Overview and analysis," *IEEE Transactions on Computers*, vol. 34, no. 6, pp. 889–902, 2014.

[54] J. Delvaux, "Security analysis of PUF-based key generation and entity authentication," Ph.D. dissertation, University of KU Leuven and ShangHai Jiao Tong University, 2017.

[55] Y. Dodis, R. Ostrovsky, L. Reyzin, and A. Smith, "Fuzzy extractors: How to generate strong keys from biometrics and other noisy data," *SIAM Journal on Computing*, vol. 38, no. 1, pp. 97–139, 2008.

[56] Y. Dodis, R. L., and A. Smith, "Fuzzy extractors: How to generate string keys from biometrics and other noisy data," in *EUROCRYPT*, C. Cachin and J. Camenisch, Eds. Springer, 2004, p. 523–540.

[57] P. Ravikanth, "Physical one-way functions," Ph.D. dissertation, Massachussetts Institute of Technology, Mar. 2001.

[58] P. Ravikanth, B. Recht, J. Taylor, and N. Gershenfeld, "Physical one-way functions," *Science*, vol. 297, no. 5589, pp. 2026–2030, Sep. 2002.

[59] B. Gassend, D. Clarke, M. V. Dijk, and S. Devadas, "Silicon physical random functions," in *Proceedings of the 9th ACM Conference on Computer and Communications Security*, 2002, pp. 148–160.

[60] G. E. Suh and S. Devadas, "Physical unclonable functions for device authentication and secret key generation," in *Design Automation Conference*, 2007, pp. 9–14.

[61] G. J., K. S.S., S. G. J., and T. P, "FPGA intrinsic PUFs and their use for IP protection," in *Cryptographic Hardware and Embedded Systems - CHES*, P. P. and V. I., Eds. Springer, 2007.

[62] R. Maes, P. Tuyls, and I. Verbauwhede, "Low-overhead implementation of a soft decision helper data algorithm for SRAM PUFs," in *Cryptographic Hardware and Embedded Systems (CHES)*, C. Clavier and K. Gaj, Eds. Springer, 2009, pp. 332–347.

[63] R. Maes, A. van Herrewege, and I. Verbauwhede, "PUFKY: A fully functional PUF-based cryptographic key generator," in *Cryptographic Hardware and Embedded Systems (CHES)*, 2012.

[64] R. Maes, *Physically Unclonable Functions: Constructions, Properties and Applications*. Springer, 2013.

[65] C. Herder, M.-D. Yu, F. Koushanfar, and S. Devadas, "Physical unclonable functions and applications: A tutorial," *Proceedings of the IEEE*, vol. 102, no. 8, pp. 1126–1141, 2014.

[66] J. P. Linnartz and P. Tuyls, "New shielding functions to enhance privacy and prevent misuse of biometric templates," in *Audio- and Video-Based Biometric Person Authentication. AVBPA*, J. Kittler and M. S. Nixon, Eds. Springer, 2003.

[67] X. Boyen, "Reusable cryptographic fuzzy extractors," in *11th ACM Conference on Computer and Communications Security — CCS*, Oct. 2004.

[68] D. E. Holcomb, W. P. Burleson, and K. Fu, "Power-up sram state as an identifying fingerprint and source of true random numbers," *IEEE Transactions on Computers*, vol. 58, no. 9, Sep. 2009.

[69] M. Hiller, "Key derivation with physical unclonable functions," Ph.D. dissertation, Universitat Munchen, 2016.

[70] D. P. Sahoo, P. H. Nguyen, D. Mukhopadhyay, and R. S. Chakraborty, "A case of lightweight PUF constructions: cryptanalysis and machine learning attacks," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (TCAD)*, vol. 34, no. 8, pp. 1334–1343, Aug. 2015.

[71] M. Yu, D. M'Raihi, R. Sowell, and S. Devadas, "Lightweight and secure PUF key storage using limits of machine learning," in *Cryptographic Hardware and Embedded Systems (CHES)*, B. Preneel and T. Takagi, Eds. Springer, 2011, pp. 358–373.

[72] D. Mukhopadhyay and R. S. Chakraborty, *Hardware Security: Design, Threats, and Safeguards*. CRC Press, 2015.

[73] S. Lin and D. Costello, *Error Control Coding: Fundamentals and Applications, 2nd Ed.* Prentice-Hall, Englewood Cliffs, NJ, 2004.

[74] Trusted Computing Group, "TPM certified products," https://trustedcomputinggroup.org/membership/certification/tpm-certified-products/.

[75] H. Akhundov, E. van der Sluis, S. Hamdioui, and M. Taouil, "Public-key based authentication architecture for IoT devices using PUF," *arXiv:2002.01277v1 [cs.CR]*, Feb. 2020.

[76] Y. Gao, Y. Su, W. Yang, S. Chen, S. Nepal, and D. C. Ranasinghe, "Building secure SRAM PUF key generators on resource constrained devices," in *The Third Workshop on Security, Privacy and Trust in the Internet of Things*, 2019, pp. 912–917.

[77] J. Delvaux, "Machine learning attacks on PolyPUF, OB-PUF, RPUF, and PUF–FSM," in *IACR Cryptology*, 2017.

[78] A. V. Herrewege, S. Katzenbeisser, R. Maes, R. Peeters, A.-R. Sadeghi, I. Verbauwhede, and C. Wachsmann, "Reverse fuzzy extractors: Enabling lightweight mutual authentication for PUF-enabled RFIDs," in *International Conference on Financial Cryptography and Data Security*, 2012, pp. 374–389.

[79] A.Aysu, E.Gulcan, D.Moriyama, P.Schaumont, and M.Yung, "End-to-end design of a PUF-based privacy preserving authentication protocol," in *International Workshop on Cryptographic Hardware and Embedded Systems*, 2015, pp. 556–576.

[80] M. Burrows, M. Abadi, and R. M. Needham, "A logic of authentication," *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, vol. 426, no. 1871, pp. 233–271, 1989.

[81] AVISPA, "Automated Validation of Internet Security Protocols and Applications," http://www.avispa-project.org.

[82] M. Fakroon, M. Alshahrani, F. Gebali, and I. Traorè, "Secure remote anonymous user authentication scheme for smart home environment," *Internet Things*, vol. 9, pp. 100–158, 2020.

[83] N. Bagheri, N. Ghaedi, and S. K. Sanadhya, "Differential fault analysis of sha-3," in *International Conference on Cryptology in India*. Springer, 2015, pp. 253–269.

[84] D. He, N. Kumar, J.-H. Lee, and R. S. Sherratt, "Enhanced three-factor security protocol for consumer usb mass storage devices," *IEEE Transactions on Consumer Electronics*, vol. 60, no. 1, pp. 30–37, 2014.

[85] C.-C. Lee, C.-T. Chen, P.-H. Wu, and T.-Y. Chen, "Three-factor control protocol based on elliptic curve cryptosystem for universal serial bus mass storage devices," *IET Computers & Digital Techniques*, vol. 7, no. 1, pp. 48–55, 2013.

[86] V. Kumar, S. Jangirala, and M. Ahmad, "An efficient mutual authentication framework for healthcare system in cloud computing," *Journal of medical systems*, vol. 42, no. 8, p. 142, 2018.

[87] M. Karthigaiveni and B. Indrani, "An efficient two-factor authentication scheme with key agreement for iot based e-health care application using smart card," *Journal of Ambient Intelligence and Humanized Computing*, pp. 1–12, 2019.

[88] B. A. Alzahrani, "Secure and efficient cloud-based iot authenticated key agreement scheme for e-health wireless sensor networks," *Arabian Journal for Science and Engineering*, pp. 1–16, 2020.

[89] R. van der Meulen, "Gartner says 8.4 billion connected "things" will be in use in 2017, up 31 percent from 2016," https://urlzs.com/LCEHn, note = Online; accessed 17 January 2021 ,.

[90] Nokia, "Nokia networks to power internet of things with 5g connectivity," https://urlzs.com/55pv4, note = Online; accessed 17 January 2021 ,.

[91] I. GSMA, "The mobile economy (2013)," *White Paper*, 2015.

[92] A. Giaretta, S. Balasubramaniam, and M. Conti, "Security vulnerabilities and countermeasures for target localization in bio-nanothings communication networks," *IEEE Transactions on Information Forensics and Security*, vol. 11, no. 4, pp. 665–676, 2015.

[93] P.-W. Tsai, M. K. Khan, J.-S. Pan, and B.-Y. Liao, "Interactive artificial bee colony supported passive continuous authentication system," *IEEE Systems Journal*, vol. 8, no. 2, pp. 395–405, 2012.