



INCORPORATING SECURITY INTO  
ELECTRONIC HEALTH RECORDS BASED  
HEALTHCARE SYSTEMS WITH WIRELESS  
SENSOR NETWORKS

A Thesis submitted by  
Mishall Hammed Awaad Al-Zubaidie

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## ABSTRACT

The potential for applying electronic health record (EHR), electronic medical record (EMR) and healthcare wireless sensor network (HWSN) in the healthcare (HC) industry is tremendous and boundless. However, the security and privacy issues of HC data must be addressed with great caution and as must accessibility. EHR system security and privacy are related to the confidentiality of protected health information (PHI), the integrity of EMR data and the authentication/authorisation of users. Furthermore, EHR data is collected and communicated between different users and patients' health data is shared within a system.

Working towards a solution, we have designed a secure and efficient HC application that integrates wireless sensor network (WSN) technology with EMR/EHR technology. First, the general architecture of the HC application system is proposed and then an EMR/EHR repository is described. The novelties of our approach include the introduction of the WSN's application to automatically collect patients' physiological information/data and securely store them as EMR/EHR records in the repository, making the EMR/EHR system more efficient. Second, a number of efficient security technologies including authentication and users' authorisation, and security protocols such as Elliptic Curve Cryptography (ECC), eXtensible Access Control Markup Language (XACML), have been adopted, modified or designed in our proposed HC application. Thus, security of HC application has been significantly improved and, as a consequence, the patients' privacy has been addressed.

Throughout this study, we have deepened our understanding of the security requirements in HC applications and appreciated the important role played by the latest wireless networking and sensing technology in achieving the security objectives in the modern HC industry. The results of this study include a framework for building secure and efficient HC applications, accompanied by a set of protocols which enable the auto-collection and secure transmission of patients' health and medical information. In addition, we offer two schemes: an authentication scheme for protecting users' identities and privacy and an authorisation scheme for user's differentiated access control (AC) or privileges to the patients' health and/or medical records. These schemes have been theoretically verified.



## CERTIFICATION OF THESIS

This thesis is entirely the work of Mishall Al-Zubaidie except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Principal Supervisor: Dr. Zhongwei Zhang

Associate Supervisor: Associate Professor Ji Zhang

Student and supervisors signatures of endorsement are held at the University.



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## DEDICATION

I would like to dedicate this thesis:

To my dear father . . .

Hammed Al-Zubaidie who planted in my heart the love of knowledge and the shining light that taught me the meaning of sacrifice and fulfillment.

To my dear mother . . .

Eeda Mutar, Paradise in this world and the Hereafter, my love and all my being, the symbol of purity and chastity, the beacon of peace and tenderness, the truth of eternal fulfillment, the inexhaustible river of tenderness.

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# List of abbreviations

$\oplus$	Exclusive or operation
$\parallel$	Concatenation operation
$A$	Aggregation function
$AS$	Attributes server entity
$ASK_{pu_i}, ASK_{pr_i}$	$AS$ public and private keys
$ASS_j/ASSig_j$	Signature generated by $AS$ and $j$ is signature number
$C_i$	Client entity
$C_iK_{pu_i}, C_iK_{pr_i}$	$C_i$ public and private keys
$C_iS_j/C_iSig_j$	Signature generated by $C_i$ and $j$ is signature number
$CH$	Cluster head
$CM$	Check MAC address
$CN_i$	Client's number
$CS$	Central server entity
$CSK_{pu_i}, CSK_{pr_i}$	$CS$ public and private keys
$CSS_j/CSSig_j$	Signature generated by $CS$ and $j$ is signature number
$Dec_i$	Decryption operation
$Dif$	Value proves $SN_i$ in the HWSN's area
$DS$	Data server entity
$DSS_j$	Signature generated by $DS$ and $j$ is signature number
$EI$	External intruder

$Enc_i$	Encryption operation
$GM$	Get MAC address
$h(.)$	One-way hash function
$I$	Internal, or external intruder
$II$	Internal intruder
$K_{pu_i}, K_{pr_i}$	Public and private keys
$LS$	Local server
$m$	Message sent by entity
$MID_i$	Medical centre identity
$MS$	Master secret/Master signature
$N, SN$	Random nonces and random secret nonce
$N_{C_i}, N_{CS}, N_{AS}$	Nonce random generated by $C_i, CS, AS$
$OP, SP$	Object 's pseudonym, subject's pseudonym
$OTP_i$	One time password to authenticate first time
$P$	Entity parameters
$Parity$	The value specifies the signature of even/odd
$Pseud$	Pseudonym generated by entities ( $SN, CH, LS, CS$ )
$PW_i, tmpPW_i$	$C_i$ 's password, temporary password
$R_i$	Role of patient, patient relative or provider
$RN$	The random number generated by entities
$RN_{op}, UN_{op}$	Role's number, user's number for $OP$
$RN_{sp}, UN_{sp}$	Role's number, user's number for $SP$
$RR_i$	Revocation reason
$S_{ID}, O_{ID}$	Subject ID, object ID
$S_NCHD$	Distance between $SN$ and $CH$



$S_N L_S D$	Distance between $SN$ and $LS$
$S_R, O_R$	Subject role, object role
$S_{sp}, S_{op}$	Signature of $SP$ , Signature of $OP$
$SigLS, SigCS$	Signatures generated by $LS, CS$
$SigSN, SigCH$	Signatures generated by $SN, CH$
$SigSnEi, SigLsEi$	Random ephemeral value the same length as the signature generated by $SN, LS$
$SL$	Sensor location
$SN$	Sensor
$SS$	One secret sharing
$tm$	Temporary
$TS$	Timestamp generated by entities
$TS_{AS}$	Timestamp generated by $AS$
$TS_{C_i}$	Timestamp generated by $C_i$
$TS_{CS}$	Timestamp generated by $CS$
$U$	User
$UID_i$	$C_i$ 's identity
$UN_i$	User's number
$UP_{CS}^{AS}, MP_{CS}^{AS}$	U and MC pseudonyms sent by $CS$ and verified by $AS$
$UP_{CS}^{C_i}, MP_{CS}^{C_i}$	U and MC pseudonyms sent by $CS$ and verified by $C_i$
$UP_{AS}^{CS}, MP_{AS}^{CS}$	U and MC pseudonyms sent by $AS$ and verified by $CS$
$UP_{C_i}^{CS}, MP_{C_i}^{CS}$	U and MC pseudonyms sent by $C_i$ and verified by $CS$
$UR_i$	User's role (patient, patient relative or provider)
dy	Dolev-Yao model
ABAC	Attribute-based access control
AC	Access control

CR	Collision resistant
DoS	Denial of service
ECC	Elliptic curve cryptography
ECDSA	Elliptic curve digital signature algorithm
ECIES	Elliptic curve integrated encryption scheme
EHR	Electronic health record
EMR	Electronic medical record
FPR	First preimage resistant
HC	Healthcare
HWSN	Healthcare wireless sensor network
MC	Medical centre
MITM	Man in the middle
PAX	Pseudonymization and anonymization with the XACML
PHI	Protected health information
RAMHU	Robust authentication model for healthcare users
RBAC	Role-based access control
REISCH	Reliable and efficient integrity scheme of data collection in HWSN
SPR	Second preimage resistant
XACML	Extensible access control markup language
XML	Extensible markup language

# Chapter 1: Introduction

In previous decades there have been many advances and research projects related to the novel technology for healthcare (HC) and innovative applications of the latest wireless sensing networking technology. In this thesis, we describe our research project which integrates wireless sensor network (WSN) technology with HC systems for electronic health record (EHR). In particular, this chapter will introduce the significance of the proposed research, and the specific research questions and objectives.

## 1.1 Overview of HC in Some Developed Countries

The health sector in the past has suffered from several problems such as management, access, complexity, storage and the protection of medical records (Meri et al. 2019). These problems have reflected negatively on the provision of quality care. Many governments, such as those in Australia, UK, USA and Canada, are concerned that the health sector provides citizens with adequate healthcare and alleviates the suffering of patients. For decades, researchers have continued to support the health sector through the development of healthcare applications that operate on electronic systems, such as EHR and electronic medical record (EMR) that provide stakeholders with accurate data in quick time from anywhere.

These systems are a huge development in the health sector and health services. This accurate data helps providers review data, diagnose diseases and prescribe medications to patients. For example, the European Union is actively pursuing research and development in the health sector that has contributed to disease prevention and healthy living (García-Holgado et al. 2019). Given the importance of the health sector, the European Union supports this sector with large sums of up to €449.4 million for the development of the Third Health Program. Therefore, in recent years, health sector institutions have relied on several technologies, such as eXtensible Markup Language (XML)/eXtensible Access Control Markup Language (XACML) to facilitate the handling and management of patient data and information. These technologies allow users in the health sector to share medical

records. However, this sharing requires strict precautions and security measures to prevent data from being destroyed or modified by intruders.

## 1.2 Information and Communications Technology

The integration of Information and Communications Technology (ICT) with HC is extremely important to increase the effectiveness of healthcare applications and to improve peoples' perceptions and hopefully the willingness to accept the service. ICT has revolutionised the health sector; supporting the provision of quality medical services for patients. ICT contributes to the HC of communities in terms of productivity, reduction of costs and facilitation of information sharing (Haftu 2019).

An analytical study on the use of ICT in the health sector indicated that technology is having a positive impact on healthcare development. This study covered 184 countries including Australia, Canada and Germany. ICT was found to offer technological breakthroughs in dealing with medical records via digital devices such as computers, telephones and WSNs (Carvalho et al. 2019). These technologies provided services to patients and healthcare providers, such as allowing patients access to medical reports, results of operations or even obtaining a medical history from a remote server. They have also contributed to the improvement of the quality of service, but more sophisticated techniques are still required to address security and privacy issues in support of the quality of service.

## 1.3 Security Concerns in HC Services

Security and privacy are two critical aspects in both the development of HC services and the delivery of HC applications. Security is the concept used to indicate that user authentication is necessary before access to the network services is granted (Hamidi 2019). For instance, a provider such as a doctor, has to authenticate before accessing patients' data. Privacy indicates the level of access to network data and services. This level depends on policies and decision engines. Privacy divides users into roles or privileges that specify access by legitimate users to specific data. For instance, a provider such as an emergency doctor, can access a specific patient's data, but he/she cannot access patient's personal information. Security is more comprehensive than privacy since security can be privacy and the opposite is not true. These concepts are critical in the health sector. Consequently, the health sector needs to apply security and privacy in three respects to ensure the protection of patient secrecy:

- Datasets storage: Using techniques such as hash functions and camouflage, to hide users' information on servers
- Authentication: Using techniques such as username and password, to allow user communication within the network
- Authorisation: Using techniques such as XACML and access models, to allow users to access a specific level in the server's repository.

To ensure that the aforementioned three aspects are achieved in healthcare projects, they should be supported with encryption and signature mechanisms.

### 1.3.1 Encryption for Preserving Users' Privacy

Encryption has been used to preserve patient record secrecy and users' identities. For example, encryption protects information, such as usernames and passwords, within the authentication request when moving from the user's device to the server. Encryption algorithms are divided into symmetric encryption, such as Advanced Encryption Standard (AES) and Data Encryption Standard (DES), and asymmetric encryption, such as Elliptic Curve Cryptography (ECC) and Rivest Shamir Adleman (RSA). In symmetric encryption algorithms, all network members use the same secret key, while with asymmetric encryption, each network member has a unique secret key (Dwivedi et al. 2019). Security in healthcare projects depends, not only on encryption itself, but also on factors that ensure that the encryption algorithm is effective in protecting patients' secrecy. Examples of such factors are key length, security level, randomness, support for privacy mechanisms and recommendations of prestigious encryption institutions.

### 1.3.2 Signature for Users' Authenticity

The signature performs mathematical operations on the data/information within the authorisation/authentication request in a way that allows the legitimate user to obtain complete, accurate and change-free data/information. For instance, the WSN collects and signs patients' data by the Elliptic Curve Digital Signature Algorithm (ECDSA) to prevent data from being changed as it travels from sensors to the server. There are several ways to perform digital data signature operations. For example, public key algorithms, such as ECDSA, RSA and Elgamal can be used. It is also possible to use hash functions such as Secure Hash Algorithm (SHA1), PHOTON, BLAKE and QUARK to perform signature processes (Heigl et al. 2019). Public key algorithms are more secure than hash functions, but the latter is the best performing for some algorithms. As mentioned earlier, security is the primary and first condition for accepting healthcare systems.

## 1.4 Significance of the Project

ICT applications in healthcare have offered great benefits to the society by providing care for patients and improving their health. However, collecting modified or inaccurate data (because of attacks) and storing these on servers as well as unauthorised access to a server's database can cause significant harm to patients' health. Also, data exchange between different devices in the network requires data security management to deal with medical records in a flexible and accurate manner. The lack of protection of patients' information adversely affects the treatment of patients, which leads to harm, reduced dignity, stigma, discrimination, embarrassment or even death.

Many research studies have shown that patients and professionals in hospitals or clinics have been interested in issues of information security (personal and health information) and protecting the rights of patients from data tampering. As far as we can see, however, the concerns with the security of patients' data/information have never been addressed effectively. The research described in this thesis addresses the security and privacy necessary to provide a safe environment for the storage and transfer of patients' medical records through the:

- Protecting of the patients' data collected continuously by WSN to prevent data modification
- Identification of legitimate network users (security)
- The determination of authorised users (privacy) of the database stored on servers, as well as secure data management.

## 1.5 Research Objectives and Questions

This section lists the objectives and problems for our research.

### 1.5.1 Research Objectives

The following objectives are laid out to achieve in our project research:

1. **Automate healthcare data collection using EMR, WSN and XML**  
Manually collecting healthcare data is expensive and prone to error. Using WSN to automatically collect and convert to electronic records can significantly improve quality and reduce the cost of the healthcare. As providers such as nurses and doctors need to continuously monitor patients,

WSNs help them collect data easily. WSN can be deployed to continuously monitor a patient's condition and gather data. Patients' data transmitted between sensors (nodes and cluster head) and network devices (such as a nurse and a server device) need data management algorithms to maintain both performance and security at the same time. The EMR which includes the patient's confidential data and private information, needs to be accessed by healthcare professionals. Thus, sharing such EMR without breaching a patient's privacy requires EMR management in an efficient and secure manner. XML technology has begun showing its superiority in the exchange of complex data over different systems

**2. Ensure communication of legitimate users using EHR and signencryption**

Preventing illegal users from connecting to the network and sending fake requests to the EHR server is a prerequisite for accepting healthcare systems. EHR requests include confidential information, such as usernames and passwords. The disclosure of this confidential information can lead to data change or even destruction of the network. Therefore, an efficient signencryption technique is required to protect users' information. In this objective, we focus on encrypting information only because encrypting the entirety of data will be expensive for users' devices and even more expensive for servers

**3. Improve healthcare privacy and security using XACML and signature**

When all patient information is stored on a server, that server becomes attractive to attackers. Therefore, the use of security mechanisms to determine access to the server is an immensely important issue. All protected health information (PHI) stored in the EHR repository should be anonymous, and XACML with signature technology would be applied to achieve maximum security. We have used signatures to prevent changing data and XACML to apply policies in making decisions and accepting legitimate requests.

### **1.5.2 Specific Research Questions**

In this section, we will describe some problems that might threaten the privacy and security of information/data in the proposed healthcare system. That is, we intend to investigate the following research problems to complete our study:

1. *How can WSNs help collect a patient's healthcare data within an EMR system efficiently?*

2. *How to transfer healthcare data for WSN to the EMR repository securely?*
3. *How to authenticate users (providers and patients) when communicating EHR services?*
4. *How to authorise healthcare professionals when accessing the healthcare information and data from the EHR repository?*
5. *How to update the EHR information stored in the repository while maintaining privacy?*

## 1.6 Organisation of this Thesis

This thesis is divided into eight chapters: Introduction, Literature review, General methodology, Storage scheme, Authentication scheme, Authorisation scheme, Discussion and results, and Conclusion and future research. All these chapters are interlinked to build a robust HC application project protecting against security and privacy threats. The chapters structure are as follows:

- Chapter 1: This chapter provides an introduction to the significance, objectives and questions of our project in protecting the security and privacy of HC users
- Chapter 2: This chapter introduces a review of the literature in security and privacy schemes in healthcare applications. It describes security problems and weaknesses in data storage, authentication and authorisation schemes in existing projects
- Chapter 3: This chapter presents details about architecture, repositories and cryptography techniques used in our project: Elliptic Curve Cryptography (ECC) and eXtensible Access Control Markup Language (XACML). In addition, it provides a general methodology for our whole project
- Chapter 4: This chapter focuses on our contributions and the methodology used to build the data collection scheme in HC application. This chapter was published as a journal paper
- Chapter 5: This chapter focuses on our contributions and the methodology used to build the authentication scheme in HC application. This chapter was published as a journal paper
- Chapter 6: This chapter focuses on our contributions and the methodology used to build the authorisation scheme in HC application. This chapter was published as a journal paper



- Chapter 7: This chapter discusses the theoretical and experimental analyses for our project's schemes. It describes the results of the implementation of our protocols in each scheme and proves its feasibility in securing medical records
- Chapter 8: This chapter summarises the conclusions and future research for our project.

## 1.7 Summary of the Chapter

In this chapter, we briefly described the importance of security and privacy in HC applications. A set of questions asked to identify the problems of access to medical records (information and data) is listed. We have also provided the project objectives to solve security and privacy issues in data collection, authentication and authorisation. Finally, the structure of the thesis is outlined to clarify the interconnections of the thesis chapters in the construction of an integrated and solid HC project.



# Chapter 2: Literature Review

Both ICT and E-technology have been used in medical and HC systems for decades. Wireless and sensing technology, in particular, have been adopted by medical staff and healthcare professionals. However, in addition to the many ethical problems, there are security concerns such as patient privacy and chronic disease history records. The ICT and E-technology make it easier to breach the security of such systems, rather than harder if the security of these systems was well addressed. This chapter surveys the challenges, opportunities and technologies with an emphasis on three important aspects of security: service availability, authentication and authorisation. It introduces the following themes:

- History of HC applications and WSN integration into HC applications
- Security and privacy issues associated with HC applications
- Security protocols of HC applications
- Investigation of drawbacks in existing HC application systems.

## 2.1 Healthcare Standards

Medical and healthcare technology and systems have human ethics' implications, and ethical standards must be applied in all countries. Many standards for healthcare applications, such as Health Level Seven (HL7), Health Insurance Portability and Accountability Act (HIPAA) (Rezaeibagha et al. 2015) and Personal Information Protection and Electronic Documents Action (PIPEDA) have been developed in countries like Australia, UK, USA, Canada and Germany. These standards have an important role to play in creating healthcare applications. For instance, many countries have reprioritized the healthcare industry after defence and the military in terms of budget and strategy (Consultants to Government and Industries 2015), and it is becoming increasingly evident that advanced ICT holds the key to the success of providing better healthcare quality at lower cost.

Digital HC or e-health includes many systems, such as EHR, EMR and personal health record (PHR). These systems are used efficiently to share medical records either globally (EHR) or locally (EMR), and are administered by the authority service provider (EHR and EMR) or by the patient (PHR) (Heart et al. 2017). Digital healthcare services have become diversified and demanding. They are used to deliver efficient but affordable services to individual healthcare users and the broader community (Asan 2017). Furthermore, WSNs promise to significantly enhance the quality of care over a wide range of client populations. At the same time, e-health systems provide services that allow providers and patients to share medical records across various health centers such as hospitals, clinics, and even the home. These services provide facilities to help improve the health of patients. Because of the efficiency of electronically sharing patient data (rather than traditional paper-based methods), patient health data is available anywhere at anytime to healthcare providers and patients. HC institutions and researchers are seeking to develop these applications to improve the quality of care, diagnosis, and remote medical surveillance (Khatoun & Zeadally 2017).

A growing number of people have begun to gradually accept e-health services. However, the main problem that threatens the acceptance of these systems for patients and providers is the security and privacy of patients' information and data. This issue should be addressed whether collecting data, or in the authentication and authorisation processes. In the following subsections, we will explain the concepts of EMR and EHR, the advantages and disadvantages of the electronic record, and the integration of EMR and EHR.

### **2.1.1 On the Electronic Medical Record**

An EMR is important compared to a paper medical record for many different features. A medical record is a communication tool used to record and review patients' health status for members of the medical staff and patients themselves. This tool is divided into two categories: paper and electronic record (Harman et al. 2012). The paper record is a traditional method used to check and record patient information. This type of medical record suffered from many problems when dealing with patient data. These problems include accessibility, availability, updating, delays, review, errors, data transfer, lack of coordination of care equality at different levels, management of health information and data, integration of scientific evidence into HC services, and decision-making practices (Beglaryan et al. 2017) and security issues. The second type of record is the electronic medical record. It rapidly processes and transmits data across digital devices. It is designed

to provide HC services continuously and accurately. It has attracted the attention of both the HC industry and researchers because it provides advantages in efficiency and effectiveness.

EMR efficiency is achieved through many features, and it supports the use of WSN. EMR is normally a one-organisation system. It provides quality of care and facilitates monitoring, evaluates health conditions, provides reliability, data quality, minimizes human error, facilitates access to information, and reduces the cost of information and communication technology (Muthee et al. 2018). EMR is rich with patient data and provides timely collection and retrieval of data (Muthee et al. 2018, Osmani et al. 2018). Currently, most of Australian professionals use EMR, and it is rated similarly in several countries such as Germany, New Zealand and the Netherlands (Heart et al. 2017).

EMR stores patient health data within a single institution and uses WSN to store patient data in a local repository for use in reports, diagnosis, and treatment. But, an EMR only contains a partial patient medical history (Heart et al. 2017). For example, doctors may use an EMR to identify a patient's prescription and avoid errors, and nurses may use an EMR to monitor tests and reports for a patient. But if the doctor needs complete data about a patient's medical history, he/she needs to send a request to the central server.

### **2.1.2 On the Electronic Health Record**

An EHR is an efficient system supporting large health enterprises by sharing data and providing HC services. Unlike the EMR, the EHR is defined as an inter-organisational system. It includes complete medical history data for each patient that can be provided to professionals. Moreover, it shares patient data among health centres across providers (Heart et al. 2017). EHR is widely deployed in healthcare (hospitals and medical clinics) (Alkureishi et al. 2018) due to its services to providers and patients. Such services are error reduction, increased efficiency, improved care, a rich source of data for researchers, health details including diagnosis and treatment, (Chiu & Hripcsak 2017, Levine et al. 2018), laboratory tests, clinical prescriptions and observations (Shickel et al. 2018).

The acceptance of the EHR system in health institutions has become increasingly important in recent decades. Although EHR was used as a tool for archiving patient data, it has recently become a basic communication tool for patient care and service provision (Asan 2017, Shickel et al. 2018, Czaja et al. 2018). According

Table 2.1: Comparison between EMR and EHR

No	Aspect	EMR	EHR
1	Database	One	Many
2	Cost	Less	More
3	Patients' history	Partial	Complete
4	Access data	Anytime	Anytime and anywhere
5	Communication technology	Wireless	Wireless and Internet
6	Support	Hospitals or clinics	Community, State or national organisation
7	Sharing data	One organisation	Inter-organisation

to the latest report from the Office of the National Coordinator (ONC) for health information technology, approximately 84% of hospitals have adopted the EHR primal system. The Health Information Technology for Economic and Clinical Health (HITECH) in the USA has provided \$30 billion as incentives for hospitals to adopt EHR (Shickel et al. 2018). EHR provides benefits for both individuals and institutions (Beglaryan et al. 2017). For example, physician researchers may use an EHR to determine a patient's history for use in a study developing a treatment.

EHRs store medical records for patients in a digital central database and it manage these records between medical centres. EHR provides patients risk assessment depending on the medical reports. In addition, it uses the Internet to transfer patient information/data. This information sharing between medical institutions makes it easier for doctors to diagnose and treat patients at any medical centre (Chen et al. 2012). However, EHRs also suffer from the problem of security weakness during the transfer of data over the Internet or when accessing data in the server database. Therefore, security mechanisms are considered the cornerstone of EHR systems. Table 2.1 presents a comparison between EHR and EMR.

### 2.1.3 Pros and Cons of Electronic Medical/Health Record

A number of projects developing healthcare systems have utilized EHR and/or EMR technology (Asan 2017, Alkureishi et al. 2018, Beglaryan et al. 2017). The prototype systems developed in these studies suffer the following drawbacks:

1. Increased burden on health professionals, negative impact on communication between patient and health professionals, the patient can connect with the doctor to ask him about a report and also can connect with the health centre to get information or data history.
2. The attendance of a small number of doctors treating a larger number of patients in a particular medical institution (Asan 2017)
3. Lack of transparency in patient information usage (Alkureishi et al. 2018)

4. On an individual level: impact on functionality, external control limits, resistance to change
5. On an organisational level: lack of legal framework, structural, financial, technical and lack of confidence in electronic communication (Beglaryan et al. 2017)
6. The problem of security and privacy when accessing patient data and information.

Recent studies (Asan 2017, Beglaryan et al. 2017, Gold et al. 2017, Alkureishi et al. 2018, Senteio et al. 2018) have also provided us with the following advantages:

1. Ease of reviewing the patient to his/her information and data
2. Many users can review the same medical record simultaneously
3. Auto-updating and search speed in information retrieval
4. Improved patient understanding of care services
5. Facilitation of patient participation and cooperation in decision-making
6. Reduced errors in documents
7. Reduced embarrassment for the patient when interacting with a health professional
8. Transparency of cooperation, and improvement in the interactions between the patient and providers
9. The use and quality of health information, quality of care, efficiency and cost of care
10. Facilitation of data collection, retrieval and use of patient data.

#### **2.1.4 Integration of EMR and EHR**

There is no doubt that the integration of EMR and EHR provides many benefits to healthcare providers and patients. These include providing an overview of the concept of patient care, providing the opportunity to study a patient's disease across several health centres (Osmani et al. 2018), providing a better understanding of chronic diseases, and the abundance of data in a central repository that can be an important source for researchers to develop and analyse treatments. One of the largest HC information technology suppliers, Actien-Gesellschaft für Anilin

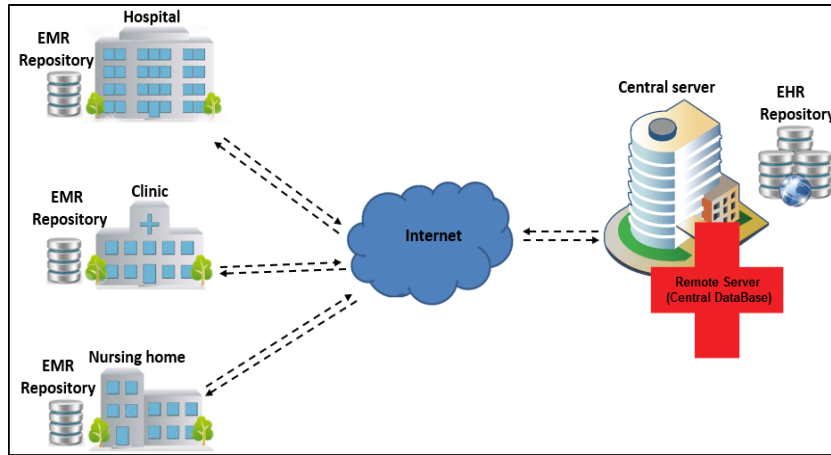


Figure 2.1: Integration of EMRs with EHR repository

Fabrikationen (AGFA), has enhanced the concept of integrating healthcare systems, such as EMR and EHR. This organisation claims that integration generates the best medical decisions and improve the quality of patient care at the individual level and the public health level (Heart et al. 2017). Figure 2.1 shows the integration of EMRs' local repositories with a central repository in EHR on the central server.

## 2.2 Acquiring EMR/EHR in HC Applications

The wireless sensor network (WSN) is one of the most promising technologies developed in recent times, and has been used in many areas (Al Ameen et al. 2012, El Barachi & Alfandi 2013, El-Semary & Abdel-Azim 2013). WSN technology is at the very early stage of adoption by the medical and healthcare sector. To our best of knowledge, there are just a few research projects being undertaken to automate the process of acquiring patient's medical records in hospitals or elderly healthcare records in the nursing homes.

### 2.2.1 Main Applications of HWSN

One such system is known as healthcare wireless sensor networks (HWSN) (Ayyildiz et al. 2019). The architecture of HWSNs is shown in Figure 2.2. The HWSN has primarily been used for the following purposes:

- **HC data collection**

In the first aspect, sensors continuously collect data about the patient and send it to the server (EMR repository). The data collected properly helps doctors diagnose diseases accurately. Furthermore, patient data collection needs protection from intrusion



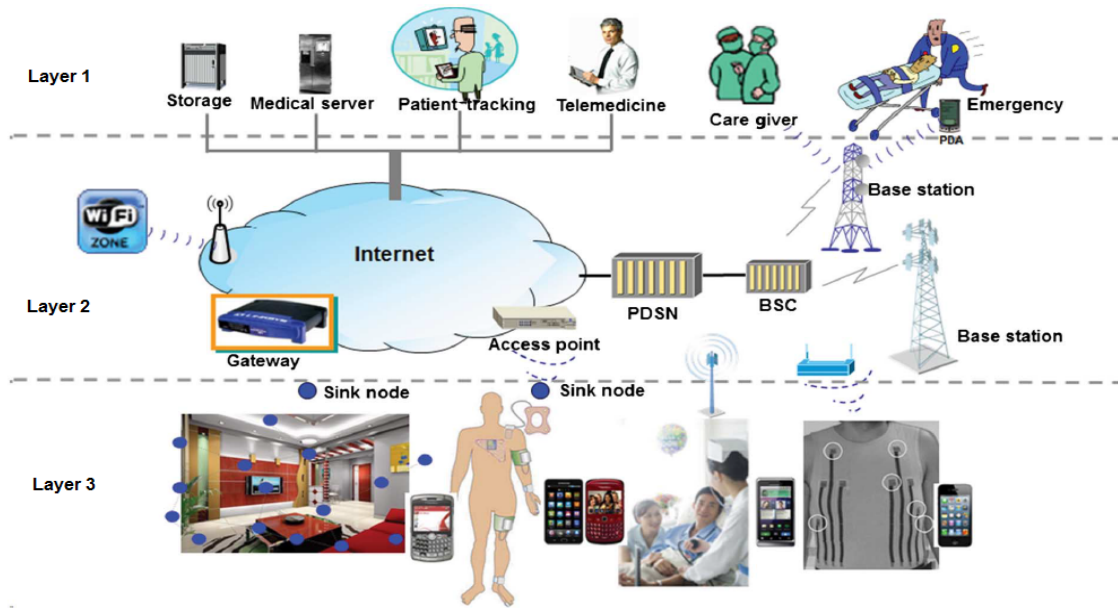


Figure 2.2: Architecture of healthcare based WSN (Zhang et al. 2014)

- **HC data structure**

The second aspect is the data storage in the form of the datasets in a server's database. The data structure for an EMR/EHR repository should be able to facilitate the sharing of a patients' health information among the HC professionals

- **HC data access and privacy**

The third aspect is to determine who has the right of users (doctor, nurse, general practitioner, pharmacist and government officer) in the access to these datasets in the data server. All these stages require security and privacy mechanisms to protect the EMR and EHR.

## 2.2.2 Security and Privacy in HWSN

There are some problems inherent in HWSNs. Figure 2.3 describes the attacks on the HWSNs which are used to infiltrate data collected/stored. Many attacks on, and threats to, the HWSN's security are relevant to the collection of patient data and the privacy of the EMR repository. These attacks have been classified into passive and active attacks (Aceto et al. 2018, Gao et al. 2018). In all types of passive attacks, an adversary eavesdrops on the transmitted packets between network nodes and the server. Also, the attacker analyses these packets to reveal information without changing it (i.e. trying to break the confidentiality), such as eavesdropping and traffic analysis attacks (Al Ameen & Kwak 2011). The active attack is extremely harmful to the networks of healthcare applications. An attacker

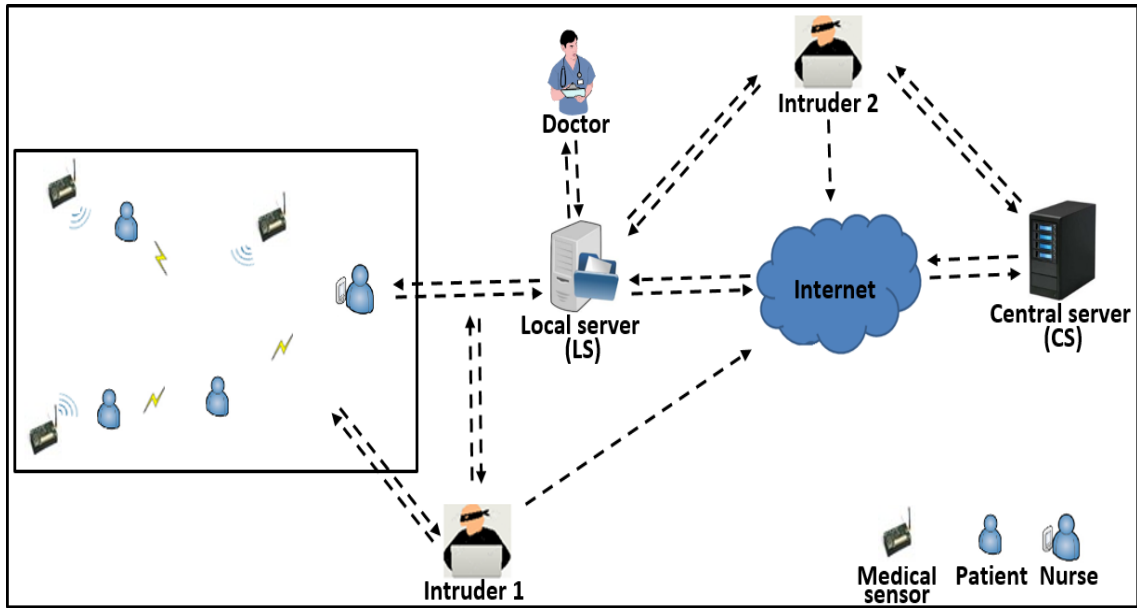


Figure 2.3: An attack on information security (Intruder 1) and device security (Intruder 2)

tampers with data packets and sends them back to their destination, such as masquerading, reply, modification and denial of service (DoS) attacks (Li et al. 2018). Another classification of attacks on healthcare applications is the internal and external attack. In the internal attack, the attacker is a member of the network. This type of attack is more dangerous than external attack because the internal attacker has the authority to send and receive messages/requests, which means an attack from the inside is easier.

Potential attacks on data transferred or stored in an EMR repository by WSN are a serious risk to HC systems. As we can see in Figure 2.3, Intruder 1 can listen to information as it is transferred from the patients' sensors to the server (local server or base station). When the attacker intercepts the message, he/she can obtain information about the physical location of the patient, identifier (ID), timestamps, source address, target address and the medical report sent by the sensors or directed by medical staff. The patient data transmitted through the sensor networks requires complete security and privacy, especially when movement through the network does not require the consent of the patient, such as moving the data of an emergency case. In addition, Intruder 2 can perform an attack on the local/remote server to penetrate the database to obtain patient information. Also, an attacker can get information from the database, such as the patient's name, age, address, type of disease, and the seriousness of the disease. This information allows the attacker to harm the patient in different ways, such as changing or destroying data (Kumar & Lee 2011, Pawar et al. 2018). Therefore, privacy and security issues are extremely important in healthcare applications. If these applications do not provide adequate security

for patient information, they become useless and unusable because the disclosure of patient information may affect patient health or even result in death.

## 2.3 Security of HC Applications

HC applications have their own special security requirements. For instance, these applications require security and privacy mechanisms, such as authorisation policies, encryption algorithms, and robust signatures. The task of these essential mechanisms is to protect medical repositories in EMR and EHR from malicious attacks. According to the Vormetric report on data security 2016, healthcare is one of the sectors that is most vulnerable to hackers' attacks and thus requires increased efforts to secure health data by 64% (Garrett 2016). On 21 January 2016, the report stated that 91% of enterprises suffer from vulnerability threatening data security (internal and external attacks). The study of data security included several countries including Australia, USA and Germany. Therefore, many systems, such as National E-Health Transition Authority (NEHTA) in Australia and the HIPAA in the USA, recommend the correct and accurate application of security and privacy in HC applications to prevent security threats (Gajanayake et al. 2014).

In the following subsections, we will describe HC applications in terms of security issues, possible attacks, security requirements and security protocols.

### 2.3.1 Specific Security Concerns of HC Services

Security concerns with HC applications include two aspects: security and privacy while acquiring EMR/EHR using WSNs; and the confidentiality of patient EMR/EHR, authenticity and/or authorisation of health professionals. These issues are critical to the acceptance and success of HC applications in the health sector. These issues are represented by the transfer of information and data between network entities (sensors, users' devices and EMR/EHR servers), the storage of databases on a server and the performance of computation processes in resource-constrained devices:

- **Communication Security**

To protect data and information between source and destination, security mechanisms, such as encryption and signature should be applied to prevent an attacker from accessing records transferred between network entities. These mechanisms resist attacks such as disclosure, alteration, replication and impersonation of medical records transmitted. The communication channel (wireless and Internet) should be protected end-to-end both at the wireless

level and the Internet through the integration of a set of security mechanisms and privacy (Manogaran et al. 2018, Bruland et al. 2018).

- **Dataset Security**

Data and information stored on the server repository become the target of malicious attacks. In particular, if a HC application is based on a single server, the process of hacking this server results in both data and information being detected (Chuang & Chen 2014). In addition, access to databases without pseudonym and anonymity mechanisms makes it easy for attackers to detect users' real identities. Therefore, HC applications should include separate servers with different tasks. To protect users' medical records, each server has separate duties for user information and data as well as the implementation of pseudonym and anonymity mechanisms to access patient data. For instance, one server contains only users' identities and another contains only users' data. Furthermore, the database should be available to legitimate users at any time and from anywhere, as should support authorisation policies for access to the repository (Griggs et al. 2018). Authorisation policies determine the level of access granted to legitimate users.

- **WSN Security**

WSN requires efficient security algorithms to work efficiently. EMR systems use WSN to collect patient data. However, a WSN is source-constrained in terms of energy, computing and memory. Therefore, when using encryption and signature mechanisms, security and performance should be efficient. The efficiency of these algorithms is a major challenge in HC applications. It means that sensor nodes continue to collect patient data accurately and for a long time while protecting the data collected from penetration (Al-Turjman & Alturjman 2018, Verma et al. 2018).

### 2.3.2 Possible Attacks on HC Applications

HC applications are vulnerable to a number of attacks. Here we present some real examples of possible attacks:

- **Authentication attacks** represent many examples of real-world security threats implemented against user authentication in HC applications:
  - In 2016, according to a cybersecurity firm's layer 8 security report analysis, attacks revealed a huge number of passwords and keys during the authentication processes of remote devices in HC organisations (Siwicki 2016)

- In 2017, a patient’s personal information was compromised at the AU Medical Centre, Children’s Hospital and Clinics of Georgia. However, information dataset attacks were not detected until 2018 (Donovan 2018)
  - In 2018, according to the proofpoint report, more than 100 million authentication attacks were carried out around the world against clinics, hospitals and insurance companies (proofpoint 2018)
  - In 2019, the Oregon Department of Human Services pointed out that cyber-attacks targeted and breached users’ credentials (625000 patients’ records) (Jessica Davis 2019).
- **Authorisation attacks** represent many examples of real-world security threats implemented against users’ authorisation in HC applications:
    - In 2013, penetration attacks were on healthcare data in US hospitals. These attacks revealed 85.4% of the medical records (protected health information (PHI)) and they are considered to be one of the five largest penetration incidents for patient data (Paganini 2014)
    - In 2016, Apple Health (Medicaid) was exposed to a data breach. This attack revealed 370,000 records for clients at Apple Health (Washington state) (Washington Health Care Authority 2016)
    - In 2017, an unauthorised individual penetrated the EHR at the New Jersey Diamond Institute for Fertility and Menopause. The hacker revealed the PHI of 14633 records containing patient information such as names, birth dates, social security numbers, and sonograms (Davis 2017)
    - In 2018, the US Department of Health and Human Services pointed out that unauthorised access/disclosure attacks targeted many health institutions and penetrated huge numbers of health records (U.S. Department of Health and Human Services 2018).

### 2.3.3 Security Requirements of HC Applications

In this section, we summarise the security requirements of HC applications. The security requirements of HC applications include:

- **Confidentiality** data encrypted through an encryption algorithm to prevent the attacker from seeing explicit data. When the attacker obtains the encrypted data, the attacker will not benefit from this data because it is incomprehensible (Kumar et al. 2018)

- **Authentication** an authentication service is used to authenticate legitimate users or data in the network to prevent anyone else from accessing data. This means that if the data is a trusted source in the network it is accepted but, if it is an unknown source, it is ignored (Rantos et al. 2018)
- **Authorisation** in the authorisation service, each node (sensor or user's device) in the network has specific sources that can access it. This security requirement is tremendously important in preventing unauthorised persons' access to the sources, for example, providing various privileges among users (doctors, nurses, practitioners and pharmacists) in access to the sources (Javadi & Razzaque 2013)
- **Integrity** an integrity service is used to ensure that the transmitted data is not tampered with or edited by the adversary (Sun et al. 2018).

In addition, the following concerns are closely related to patient's EMR/EHR:

- **Availability** some attacks attempt to disrupt network services by sending a large number of messages to the server, and thus, destroy the network. Network services should be available upon request (Di Pietro et al. 2014)
- **Anonymity** this service hides or distorts the network information and data as it transfers from the sender to the receiver or vice versa. When using anonymity with information and data, the attacker cannot distinguish this information and data to a specific patient (Shen et al. 2018)
- **Unlinkability** the attacker cannot reveal the identity of HC users when linking real information with random pseudonyms. However, the single pseudonym will expose user information to detection (Mehmood et al. 2018)
- **Scalability, Forward Secrecy and Backward Secrecy** environments of healthcare applications require a continuous expansion of the network size. But when a node leaves or joins the network, it does not have the right to access and decrypt the encrypted messages in the future after leaving the network or previous messages before entering the network (Dhillon & Kalra 2018)
- **Freshness and Non-repudiation** the message should be recent to prevent a replay attack, as the sender cannot deny his message to detect the compromised nodes (Di Pietro et al. 2014, Kale & Bhagwat 2018).

Table 2.2: Keys sizes and some information for public key algorithms

Algorithm	Keys sizes					Ratio	Author(s)	Year	Mathematical problem	Other algorithms
RSA	1024	2048	3072	7680	15360	1:6-30	Rivest, Shamir and, and Adleman	1978	Integer factorization	Rabin
Elgamal							Taher Elgamal	1985	Multiplicative group	Schnorr, Nyberg-Rueppel
DSA							David W. Kravitz	1991		
ECC/ECDSA	160-223	224-255	256-383	384-511	512-more		Scott Vanstone	1992	Elliptic curve discrete log. (ECDLP)	ECDH

### 2.3.4 Security Protocols in HC Applications

In this section, we present an overview of security protocols likely to be used in the HC applications. HC applications require robust protocols in terms of performance and security. Since HC applications normally rely on the traditional cryptographic protocols and/or primitives to achieve their security goals, and traditional encryption/decryption algorithm, public key-based authentication used very long keys. This has been identified as a major obstacle to efficiency.

ECC/ECDSA has been proven to be efficient in its performance because it uses small keys. This makes the cost of computation small compared with traditional public key cryptography algorithms such as RSA, traditional digital signature algorithm (DSA) and ElGamal. For example, ECC/ECDSA with a 256-bit key offers the same level of security as the RSA algorithm with a 3072-bit key (Varchola et al. 2015, Ever 2018). Table 2.2 (Barker & Dang 2016, Harkanson & Kim 2017, Tiwari & Kim 2018, Mi et al. 2018) shows a comparison of key sizes for public key signature algorithms in addition to some information about these algorithms. Security requirements are considered from three perspectives:

- **Performance and efficiency**

The preservation of efficiency in the ECC/ECDSA is critical in HC applications. Many approaches have been developed to improve the efficiency of the ECC/ECDSA algorithm, reducing the cost of computation, energy, memory, and consumption of processor capabilities. The ECC/ECDSA uses point multiplication (PM) or scalar multiplication (SM) where ECC uses PM for encryption and decryption, while ECDSA uses this operation to generate and verify signatures (Pan et al. 2017). One can improve PM efficiency by improving finite field arithmetic (such as inversion, multiplication, and squaring), elliptic curve model (such as Hessian and Weierstrass), point representation (such as Projective and Jacobian), the methods of PM (such as Comb and Window method) (Al-Zubaidie et al. 2019a) or improve hash function.

Several researchers have made improvements to increase the performance of the ECC/ECDSA. First, in De Dormale & Quisquater (2007) performance and flexibility were investigated in the ECC algorithm with accelerators through hardware implementations. Many issues associated with hardware implementations for ECC were discussed, such as selecting curves, group law, PM algorithms, and the selection of coordinates. In addition, it was pointed out that the architecture of multiple PM in ECDSA verification should be supported because this architecture leads to efficiency in hardware implementation. Much research has pointed out that using hardware accelerators leads to high performance. But, accelerators sacrifice flexibility where reduction circuits should be used to retrieve the flexibility feature. Similarly, Driessen et al. (2008) compared many different signature schemes (ECDSA, XTR-DSA, and NTRUSign) in terms of energy consumption, memory, key length and signature, and performance. Through implementation, the authors found that the NTRUSign algorithm is the best in terms of performance and memory. However, the NTRUSign algorithms weak when under attack.

Zhong et al. (2016) investigated the ECDSA algorithm and found that it contains some problems that make it inefficient because of the inversion processes used to generate and verify the signature. They removed the inversion process and the results demonstrated that this scheme is more efficient than the previous scheme as it had less running time. Unfortunately, there is no proof of ECDSA security without inversion processes for repelling attacks. Liu et al. (2017) adopted the Montgomery method with the lightweight elliptic curve (twisted Edwards curve (p159, p191, p223, and p255)) to improve speed and balance between memory and performance (cost of communication, execution time, memory). During the implementation, they noted that their scheme offers better memory efficiency than the traditional Montgomery scheme. They recommended the exact selection of ECDSA's parameters curves and a balance between security and efficiency requirements.

- **Security and countermeasures**

The security improvement in ECC/ECDSA is no less important than its efficiency because this algorithm is designed primarily for the application of security properties. ECC/ECDSA, like previous algorithms, may possibly suffer from some of security vulnerabilities. Random weak, bad random source (Bos et al. 2014), collision, preimage and second preimage in hash value or leaking bits of the private key are all considered weaknesses in ECC/ECDSA.



Also, several researchers have made improvements that close security gaps in the ECC/ECDSA algorithm. The aim of these improvements is to provide countermeasures against various attacks. But when selecting countermeasures, there should be a balance between security and efficiency (Danger et al. 2013). To maintain the security of these algorithms, it is important to use finite fields (either prime or binary) recommended by credible institutions. For instance, the Federal Information Processing Standard (FIPS) or National Institute of Standards and Technology (NIST) are considered reliable. Choosing appropriate curves and finite fields according to authoritative organisations' standards leads to secure ECC/ECDSA's implementations (Mathur et al. 2017). Therefore, we note from the above, that any encryption algorithm or signature should possess a security level appropriate for use in HC applications. Many schemes have measured ECC/ECDSA in terms of security weakness issues and countermeasures.

Many studies support appropriate countermeasures in ECC/ECDSA. Fan et al. (2010) presented a detailed study on attacks and countermeasures in ECC algorithm. They divided attacks into passive and active attacks. They explained that the countermeasure for a specific attack may be vulnerable to other attacks. In addition, countermeasures should be selected carefully. Therefore, the authors have made some recommendations for selecting countermeasures.

Some surveys have studied public cryptography algorithms in terms of the computation of hard problems (integer factorization problem (IFP), discrete logarithm problem (DLP), lattices and error correcting codes) in quantum and classical computers (Abdouli et al. 2011). These authors described RSA, Rabin, ECC, ECDH, ECDSA, ElGamal, lattices (NTRU) and error-correcting code (McEliece cryptography). They pointed out that ECC provides a higher security level than other cryptosystems. In addition, it presents advantages such as high speed, less storage, and smaller keys sizes. But they did not discuss the use of ECC/ECDSA in applications and implementations of different technologies.

Meanwhile, Fan & Verbauwhede (2012), Danger et al. (2013) explained physical attacks on ECC algorithms. They focused on two known physical attacks: side channel analysis (SCA), and fault attacks. They also described many attacks, including these two, as they presented countermeasures against

these attacks. The countermeasures included simple power analysis (SPA), differential power analysis (DPA) and fault attack (FA) countermeasures. Also, some recommendations were presented for countermeasures that add randomness, countermeasures selection, and implementation issues.

Bhatia & Verma (2017) discussed security issues in terms of network security, identity theft, and insider threats in preventing many attacks, such as man-in-the-middle (MITM), address resolution protocol (ARP) poisoning, insider privileges, reply, DoS, guessing and impersonation. They noted that ECC/ECDSA is the best of the public encryption algorithms. It provides a security solution for data protection through the integration of cryptography mechanisms in ensuring remote authentication and authorisation.

- **Implementation and applications**

ECC/ECDSA is suitable for implementation in resource-constrained environments and various applications. A study on security techniques investigated WSNs (Yang et al. 2015). It focused on three features in WSN security: key management, authentication, and secure routing. It pointed out that the ECC algorithm was convenient for resource-constrained devices. In addition, a survey of attack strategies was given in relation to ECC/ECDSA in Bitcoin and Ethereum applications (Mayer 2016). The author pointed out that different standards for curves (such as ANSI X9.63, IEEE P1363, and safecurves). This survey focused on safecurves with SECP256k1 through using ECDSA. Also, it referred to safecurves as one of the strongest curves standards. The author suggested many basic points to prevent attacks on ECDSA or ECC.

Finally, Harkanson & Kim (2017) compared RSA and ECC/ECDSA. They pointed out that ECC/ECDSA exhibited the highest performance with the same level of security from RSA. They noted that 69% of websites applications use ECC/ECDSA, 3% used RSA and the rest used other algorithms. They also described ECC with some applications (such as vehicular communication, e-health and iris pattern recognition). However, they had a duplication between implementation and application. For example, RFID is a technology that can be used to implement a particular application.

## 2.4 Some Studies Related to our Research

This section discusses a few recent studies, related to our research, in terms of storage, authentication and authorisation.

### 2.4.1 Storage of User Data

This section briefly discusses the existing storage schemes (Wander et al. 2005, Wang & Li 2006, Trakadas et al. 2008, De Meulenaer et al. 2008, Fan & Gong 2012, Kodali 2013, Lavanya & Natarajan 2017 $a,b$ , Staudemeyer et al. 2018, Malathy et al. 2018, Sharavanan et al. 2018, Sui & de Meer 2019, Hathaliya et al. 2019, Furtak et al. 2019) designed to secure patient data in the EMR, and highlights their shortcomings.

The performance and security presented by the ECC/ECDSA algorithm make it suitable for use in implementation on WSN. Digital signatures in ECDSA have better efficiency in resource-constrained devices than DSA and RSA. Many authors have pointed to the possibility of using ECC/ECDSA with resource-constrained environments (memory, energy, and CPU capability). Public key cryptographic algorithms have been investigated in many schemes to test their applicability in WSN. For example, Wander et al. (2005) presented a study in energy for the public key cryptography (ECC/ECDSA, RSA) on sensor node Mica2dot with Atmel ATmega128L (8-bit). They found that transmission cost is double the receiving cost. They analysed signatures in ECDSA with a key of 160-bit and RSA with a key of 1024-bit. Where signature verification cost in ECDSA is larger than a signature generation while RSA verification is smaller than a signature generation. They noted that ECDSA has less energy cost than RSA. They concluded that ECC/ECDSA is more effective and feasible than RSA in constrained-source devices (WSN) because it generates small keys and certificates with the same security level as RSA. 160-bit ECC/ECDSA and 1024-bit RSA algorithms were also applied on a sensor node MICAz (Wang & Li 2006). The authors used hybrid multiplication to reduce access memory. ECDSA results on MICAz are signature generation=1.3s and signature verification = 2.8s. For the purpose of comparison, the authors also implemented ECDSA on TelosB. MICAz results were slightly less than TelosB's results. The authors proved the possibility of using public key cryptography on WSN. None of the aforementioned researchers addressed the optimal use of public key cryptography whether verification cost in Cluster Head ( $CH$ ) or computational operations. In our project, we are addressed these problems to obtain lightweight signatures. Consequently, our protocols perform computations with more speed and less time.

Costs of computation and communication in WSN should be efficient when applying security protocols, such as ECC/ECDSA. ECDSA (SHA1) and RSA (AES) were analysed in several types of sensor nodes in terms of energy (communication and computation) and time (Trakadas et al. 2008). ECDSA uses short keys

(160-bit), which reduces memory, computation, energy and data size transmitted, and thus is better than the RSA. De Meulenaer et al. (2008) discussed the cost evaluation of energy (communication and computation) on the WSN through the symmetric key distribution protocol and public key agreement protocol (asymmetric encryption). They noted that symmetric encryption performs faster than asymmetric cryptography. However, their research did not address security issues in symmetric cryptography. Moreover, Fan & Gong (2012) implemented ECDSA on WSN with the binary field (163-bit). They improved signature verification via cooperation of the adjacent nodes. Also, ECDSA's implementation was presented in the sensor node (Kodali 2013). But, because this node supported 8-bit of the microcontroller, the author modified the SHA1 code from the 32 bits original to 8 bits. Through implementation, the original algorithm is better in size and time than the modified algorithm. The author explained the possibility of using the ECDSA algorithm with the sensor node held 8-bit microcontroller. However, these papers applied public key cryptography with a traditional hash function that increased the computational and communication costs of servers.

To store patient data accurately, data collection schemes should rely on reliable and fast hash algorithms in ECDSA. Lavanya & Natarajan (2017*a,b*) have applied the ECDSA algorithm as a light-weight authentication scheme in the WSN. This demonstrates the effectiveness and efficiency of using ECDSA in WSN in terms of security and performance. Staudemeyer et al. (2018) designed an ECC/ECDSA-based scheme to provide privacy in WSN. However, they did not provide a performance analysis of the security algorithms during exchange of data in the WSN. Malathy et al. (2018) focused on the efficiency of transmission in WSN to extend the lifetime of sensor nodes with the use of ECDSA and generated message digest (MD) with data. Their scheme relied on a colony optimization scheme to save energy in the WSN. But, it did not support privacy parameters during data transfer. Sharavanan et al. (2018) proposed a scheme to monitor the heterogeneous network environments in WSN and protect the medical information of patients using ECDSA. Unfortunately, their scheme addressed only the computation processes of transport. It did not address the complicated computation processes that generate and verify the signature in ECDSA. The main problem with these studies is that they do not provide mechanisms to prevent localisation attack such as Sybil. Our project includes a mechanism to hide sensor location. As a result, the server receives accurate data from sensors without illegitimate changing.

Recently, Sui & de Meer (2019) designed a data aggregation scheme that focused on computation in demand-response management to improve performance and

security efficiency. Their scheme was based on the identity signature (Bilinear Map) to protect information and data aggregated by integration and authentication. Hathaliya et al. (2019) have proposed an elliptic curve cryptography (160 bits) scheme to encrypt and authenticate patients' biometric properties. They used wearable sensors to collect patient data and used a mobile device to send and store this data in the medical repository (cloud server). Finally, Furtak et al. (2019) designed a framework based on RSA-2048 bits and trusted modules to secure the sensors' domain and prevent unauthorised threats. They categorised sensors into the master, replica and gateway categories in the network area and data structure in the sensor memory. In their framework, security procedures for the domain and sensor were used to support both integrity and authentication. Moreover, many researchers (Kittur & Pais 2019, Kuang et al. 2019, Marino et al. 2019, Zhao et al. 2019, Liu et al. 2019) have pointed out that ECDSA is particularly appropriate for authentication and authorisation schemes because it performs the lightweight processes during security procedures.

Many recent studies (Xia et al. 2016, Rasjid et al. 2017, Chiriaco et al. 2017, Merrill 2017, Yang et al. 2017, Giechaskiel et al. 2018, Brockmann 2018, Park & Kim 2018) have also pointed out that SHA1 suffers from collision, preimage and second preimage attacks. However, no schemes addressed SHA1 performance and security (collision, preimage and second preimage) problems in ECDSA. Furthermore, these schemes did not support the protection of signatures transferred between sensors and server. Our storage scheme uses a lightweight hash function and signature camouflage to secure security parameters.

#### **2.4.2 User Authentication to HC Applications**

This section briefly discusses the design of authentication schemes to secure healthcare users in the health network as suggested by existing studies, (He & Zeadally 2015, Giri et al. 2015, Li et al. 2016, Farash et al. 2016, Kumar et al. 2016, Jiang et al. 2016, Rajput, Abbas, Wang, Eun & Oh 2016, Das et al. 2017, Chandrakar & Om 2017, Nizzi et al. 2019, El-Tawab et al. 2019), and highlights their shortcomings.

Authentication scheme becomes insecure when using the same IDs with unreliable key size in all authentication phases. He & Zeadally (2015) proposed an authentication scheme based on ECC and advanced encryption standards (AES) algorithms. Their scheme uses three entities: user, server, controller. Their scheme accomplishes registration, login, and authentication phases. The authors claimed that their scheme fulfills many requirements, such as mutual authentication,

anonymity, and forward confidentiality. The problem with their scheme is that user and controller identities are statically sent to all three entities. If the attacker can penetrate the encryption, he/she can see that the user and controller identities related. The attacker can then generate a random number, temporary key, timestamp, message authentication code. After that, he/she encrypts the user and controller identities and obtains the message authentication code. Then, the attacker sends a message to the network to become a legitimate and authenticated user. Their scheme also used a 160-bit key with ECC, which is considered unreliable by trusted institutions, such as NIST. Our authentication scheme does not exchange real information for user/device between client and server.

The storage of medical records (data and information) on a single server represents a serious risk in terms of performance and security. Farash et al. (2016) proposed an authentication scheme based on ECC for healthcare environments. They claimed that their scheme provides forward secrecy. Their scheme accomplishes two stages: setup, and authentication. It provides authentication during the exchange of messages between the server and RFID's tag. However, their scheme shows that the information (identities) and data are stored on a single server. When the server is hacked, the users' information and data are exposed to the detection, tampering, and modification.

Jiang et al. (2016) also designed a three-factor (biometric, smart card and password) authentication protocol to protect e-health clouds. Their scheme protects authentication requests from impersonation attacks and off-line password guessing if a mobile device is lost or stolen. Their scheme relies on ECC to support the confidentiality and authentication of healthcare users. They used a fuzzy extractor to keep the biometric secret. But, this scheme relied on a single server to authenticate users, which is an attacker's target. In addition, it performs seven hash operations that can exhaust the single server capabilities if the network has a huge number of healthcare users, especially if it is not using a lightweight hash. Our authentication scheme uses a lightweight hash that reduces running time and increases the speed of computation operations. Consequently, our scheme reduces the burden on servers.

Leakage of information of legitimate users or using unnecessarily large keys destroys the authentication process. An authentication protocol was proposed to protect patients' passwords by RSA against off-line password guessing attacks (Giri et al. 2015). Their scheme consists of five phases: initial, registration, login, authentication, and password change. The main problem in their scheme is that the authors used RSA with the 1024 key. This algorithm affects the performance of

huge healthcare networks. Many schemes recommend using ECC (Timpner et al. 2016, Sojka-Piotrowska & Langendoerfer 2017, Meddah et al. 2017, AbdAllah et al. 2018) as the ECC-160 is equivalent to RSA-1024 with the same security level. Also, their protocol suffers from sending an ID clearly from client to server at the registration phase. This case causes authentication information to be detected for analysis attacks, leaking any information that an attacker could use to disclose authentication information.

Furthermore, the ECC and a Petri Nets model was proposed to achieve an authentication requirement to protect healthcare applications through the mobile cloud (Kumar et al. 2016). This scheme consists of two phases initial setup and authentication. The authors claimed that their scheme is resistant to attacks of eavesdropping, tracking, replay, spoofing, and cloning. However, their scheme did not address the issue of steal/loss of tag or device and internal attacks that are more serious than external attacks in accessing patient data. They gave no indication of the signature algorithm used to ensure integrity. The other problem is that the tag's ID explicitly sends from server to tag, which makes it easier for the attacker to parse the authentication request. Our authentication scheme adopts lightweight public key cryptography, fast hash function and anti-leakage information instead of tradition public key cryptography that is vulnerable to penetration.

HC applications are continuously expanding and become vulnerable to failing if they are not able to offer scalability. Using shared-key to implement authentication mechanism was designed to prevent known attacks, especially DoS attacks (Li et al. 2016). They used the wrong password detection mechanism to reduce the risk of DoS attacks. However, the registration phase of this scheme is not reliable if the ID of patients is sent in an unsafe channel. This research also suffers from scalability because of the use of the single shared-key mechanism that needs protection from all parties.

Das et al. (2017) provided a user authentication scheme for healthcare applications based on AES and secure hash algorithm (SHA1). They used user biometrics and the anonymity feature to repel attacks, such as replay, MITM, and privileged insider. However, symmetric encryption suffers from the problem of scalability, as well as the difficulty of managing the single secret key. Their scheme will suffer from key management problems if applied to a large health institution with hundreds of users whose accounts must be managed during data changes such as additions and deletions. Furthermore, the attacker can submit a forgery attack on the login message if it detects the single secret key. Our protocols depend on public key encryption to solve the scalability problem and key management. Also, we hide the private key with security parameters to prevent attackers from detecting the

private key even if they can penetrate the client's device.

Pseudonym and mutual authentication are important mechanisms to build robust authentication. Cloud-assisted conditional privacy preserving authentication (CACPPA) (Rajput, Abbas, Wang, Eun & Oh 2016) have been proposed to authenticate a network's nodes. This scheme used the elliptic curve integrated encryption scheme (ECIES) and ECDSA algorithms with a timestamp and pseudonym integration to perform the authentication process. The problem with this scheme is that it does not provide mutual authentication to prevent an attack from a counterfeit party. Neither did the authors explain the size of the keys in the algorithms to make sure their scheme was able to repel various attacks. Furthermore, a single pseudonym cannot separate the link to real information to prevent analysis and tracking attacks for authentication requests. Chandrakar & Om (2017) provided an authentication scheme based on ECC and hash. Their scheme was supported on several servers in user authentication with three factors (biometric, smart card, and password). The user could connect to any server to perform the authentication process. In this scheme, the authors did not specify which hash algorithm was used and the size of the message digest (MD). These procedures are essential to repel attacks such as collision, preimage and second preimage. Using multiple servers means that the same user information is stored on more than one server. As a result, penetrating any server can cause user information to be detected or modified. Moreover, this scheme did not use a mechanism to prevent the association of real user information with an authentication request, such as pseudonyms. Our authentication scheme uses a reliable multi pseudonym and mutual authentication to ensure only legitimate users are connected to the network.

Recently, Nizzi et al. (2019) proposed the address shuffling algorithm (AShA) method to protect devices' MACs when these addresses transferred from sender to recipient. They used keys and hashes to shuffle MAC addresses in the network and prevent intruders from executing collisions or privacy breaches. However, their method is vulnerable to security threats especially as it does not provide resistance against the second preimage. Similarly, El-Tawab et al. (2019) relied on MAC addresses to protect users' privacy. They used techniques such as MAC randomisation and a hash function (SHA-256) to prevent the penetration of users' devices. But, these techniques are still weak in ensuring the authenticity of MAC addresses. Our authentication scheme does not need additional computation operations by shuffling/randomisation for MAC because it uses the check MAC mechanism. It simultaneously provides high-speed computations and reliable



security.

### 2.4.3 User Authorisation/Privacy to HC Applications

This section discusses related works about authorisation (Chadwick et al. 2006, Riedl et al. 2008, Quantin et al. 2011, Gajanayake et al. 2014, Sun et al. 2011, Jo & Chung 2015, Seol et al. 2018, Wang et al. 2019, Shafeeq et al. 2019), and highlights their shortcomings.

Authorisation schemes require a unique signature in authorisation policy for each user to prevent the disclosure of user IDs to unauthorised medical staff. As early as 2006, the PERMIS project was proposed by (Chadwick et al. 2006) with the role-based access control (RBAC) model. It described the conceptual authorisation of the credential validation service (CVS) before the approval stage of access decisions for the resource as well as the distributed management of the credentials. However, the PERMIS system does inadequately protect the CVS. PERMIS also suffers from the problem of inheriting managers for all the attributes of their followers (hospital department managers or specialist doctors who inherit all their practitioners' attributes and thus have access to patient data, which can lead to significant internal attacks). In addition, their project uses one signature of a public key cryptography (PKC#12) file for policies and attributes. Our authorisation scheme provides a secure decision engine and flexibility to create/manage policies with different signatures for each user.

HC server resources, such as memory and processing speed, are crucial in implementing the authorisation scheme in large health environments. The pseudonymization of information for privacy in an e-health (PIPE) project is designed to protect health data in the EHR through a layered system. PIPE includes many keys, such as an external key pair, an internal key pair, a symmetric key pair, and a shared key. It relied on RBAC to protect the keys (Riedl et al. 2008). This scheme used the Shamir scheme as a backup mechanism to retrieve patient keys in the case of the loss of the smart card. But, this scheme did not explain the symmetric and asymmetric encryption algorithms used to generate pseudonyms for users. Also, the scheme increases the complexity of the server system with the use of many keys, especially if the scheme is used by a large health institution. In addition, the server must use the keystore to store the keys, and this requires protection and storage space on the server. Our authorisation scheme does not suffer from memory and speed problems because it does not depend on different complex algorithms and many keys.

A robust authorisation scheme requires uniform structures and contexts in requests and responses securely without complex operations on the HC server. Quantin et al. (2011) suggested using non-central medical records to eliminate issues of standardization and structure in data access requests. They used two medical record search engines (MRSEs) and one data aggregator. The first search engine was used to authorise healthcare providers. The second search engine was used to authorise patients. In addition, a hash was used to increase the pseudonym of patients' IDs. However, this scheme suffered from the use of a single aggregator that was similar to the dataset on the central server, which is vulnerable to attacks. Also, patient data comes from different sources and have different structures and standards. This difference causes a burden on the aggregator. Moreover, the authors used the RSA's encryption algorithm, and this algorithm uses a large key size of 1024 bits, which causes a burden on the server. Also, the aggregator needs time and storage to convert the data into a single context. Furthermore, their scheme suffered from collision and doubleton problems due to the transference and transformation of patient data contexts. Our authorisation scheme does not suffer from the costs of complex operations because it separates duties between three servers which reduces performance overheads on each server.

Internal attacks on the repository or transfer of medical records clearly during the network is a serious risk to patients' health. Gajanayake et al. (2014) integrated four access control models (discretionary [DAC], mandatory [MAC], role-based [RBAC], and purpose-based access control [PBAC]). Their target is to obtain a single model that limits illegal user access control of the medical record. They relied on the sensitivity label for data in the hierarchical structure of the database. They also suggested defining the purpose of accessing patient data. However, their scheme addressed only the doctor and the patient and did not address different classes of healthcare providers. Furthermore, data and requests are clearly transmitted between client and server. In addition, Jo & Chung (2015) proposed an extensible markup language (XML) access control system (XACS) that enables users to access specific elements in an XML document. This system relies on removing certain parts of the XML document to allow users who are authorised to see certain parts of an XML document. However, requester information is transmitted explicitly over the Internet to a server, which makes it easier for an attacker to penetrate the privacy of users. In addition, it does not address internal attacks that are applied by legitimate users even though certain parts of the XML document have been removed. Our authorisation scheme provides robust privacy by ensuring that request, policies, and data do not contain the real personal information of users.

Cryptographic processes for patient data are extremely expensive on the server compared with the mechanisms of authorisation policies and pseudonyms in the authorisation scheme. The healthcare system for patient privacy (HCPP) project was designed for the EHR to protect the privacy of patient data (Sun et al. 2011). Researchers focused on an emergency scenario regarding the protection of patient data. They used a backup mechanism that allows the doctor to access patients' health information without access to confidential parameters. However, this search relies on encrypting all patient data. When a client wants to access patient data, the server uses a keyword (searchable symmetric encryption (SSE)) to perform an encrypted data-mining operation. This process is exceedingly expensive for the server for two reasons. First, the server must encrypt the entire massive database with the continuous addition of new records and, second, the server must continuously mine each access request. In addition, their system does not support levels of authorisation and privileges (roles and attributes) that are more secure in providing privacy to patient records. Also, researchers have reported that the patient has not been exposed to collusion because the patient does not attack himself. But this is not true because there are impersonation attacks that do the job without the theft or loss of the patient's device. Moreover, this research did not specify the type of encryption algorithm used, which is greatly important for security and server performance, and it addressed only emergency cases.

Seol et al. (2018) proposed an access control model based on partial encryption and XML signing in EHR's documents within a cloud environment. Their model is supported in two phases: the first phase is access control using extensible access control markup language (XACML) and the second is to encrypt and sign data with XML. However, the cloud environment presents multiple security and privacy problems in the EHR system because of the distributed exchange of data between the various health centres. In addition, their scheme uses encryption in XML requests and responses. Encryption processes will be extremely costly for legitimate entities exchanges in healthcare systems. Also, in the first phase, requests and responses are clearly sent between legitimate parties and, therefore, will be exposed to attack. Neither did they address the pseudonym mechanism that prevents access to real user information. These researches suffered from encryption costs while our authorisation scheme uses a fast mechanism such as random pseudonyms instead of encryption overheads.

Recently, Wang et al. (2019) relied on attribute based encryption (ABE) and searchable encryption to authorise users' access to patient data. Their scheme

focuses on supporting privacy and efficiency in hidden policy with search keywords. In addition, their scheme is based on constant expenses for encryption and the secret key. However, their scheme suffers from internal attacks in addition to the heavy costs to access the data. In addition, Shafeeq et al. (2019) has proposed a decentralized authorisation scheme to grant users' access to patient data. They used XACML, Merkle tree-based signature and symmetric encryption to prevent unauthorised users from penetrating the repository. Although their scheme provides efficient management by XACML and message integrity support by multi-signature, it is vulnerable to threats of single symmetric key penetration as well as the storage expenses required for the Merkle tree signatures. Our authorisation scheme uses public key cryptography and nonce that mean the generation of different signatures for each authorisation request. In addition, our authorisation scheme does not require the storage costs of the Merkle tree and expenses associated with accessing the dataset by search keywords.

## 2.5 Summary of the Chapter

In this chapter, we have presented details about HC application history, and HC systems such as EMR and EHR. We have also discussed security and privacy issues when medical records are transferred by a communication channel or saved on an EMR/EHR server. Security protocols for HC applications have been investigated. Finally, existing schemes' gaps have been described as a basis for building new data collecting, authentication and authorisation schemes.

# Chapter 3: Designing a Secure and WSN Based Healthcare System Application

The development of efficient and low-cost HC application systems involves three categories of issues: ethical issues, medical/health issues, system design and security issues. In this chapter, we will focus on the last one; that is, on the technical and security considerations for the development of HC applications. More specifically these developments are:

- General architecture and EMR/EHR repositories of the proposed HC application
- Techniques proposed for data collection, authentication and authorisation of the proposed HC application
- General proposed network model of HC application
- General methodology for the proposed HC application.

## 3.1 General Architecture of Proposed HC Application

Figure 3.1 shows our project architecture. The proposed HC application system is shown in Figure 3.2. There are three major components: data collection by WSNs, EHR/EMR storage or repositories, and an online system of HC application for professionals. Our study will carry out the investigations into three aspects as follows:

1. Secure and efficient application using algorithms/protocols to integrate HWSN and EMR in the HC industry

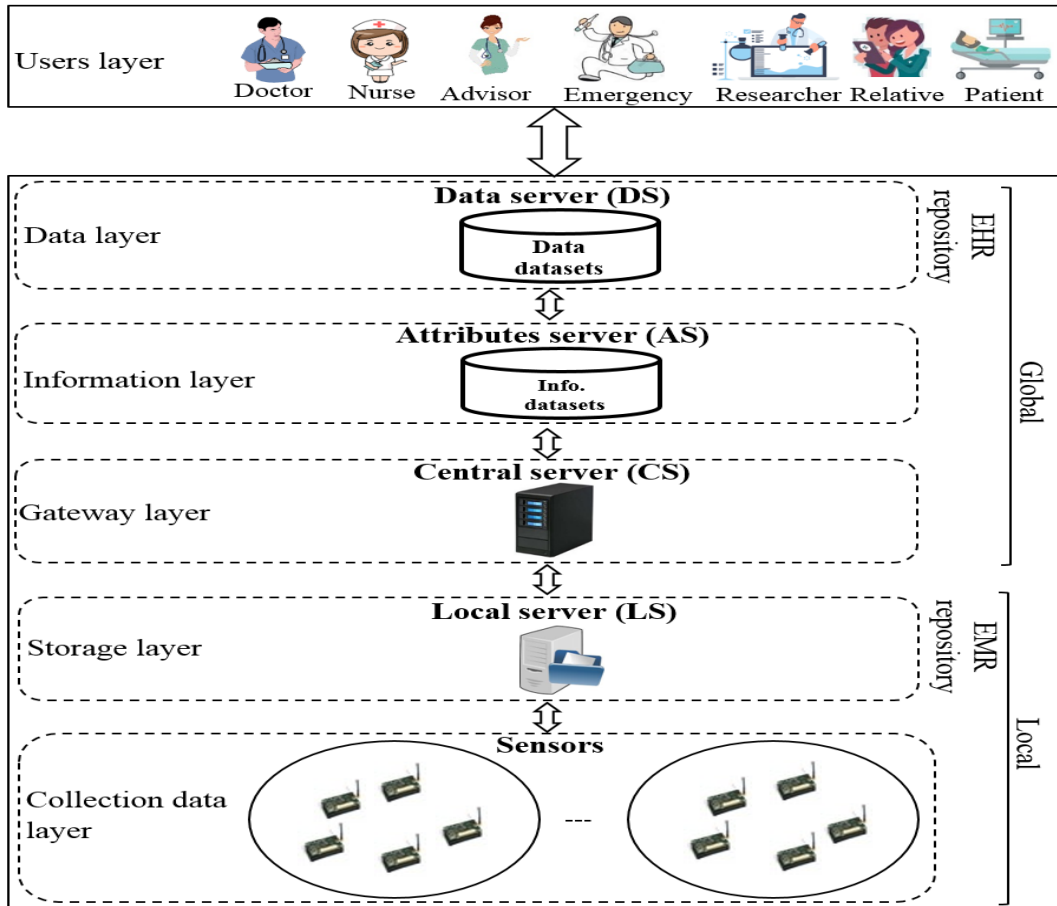


Figure 3.1: General architecture of proposed HC application

2. Techniques to provide an authentication mechanism to legitimate users in the HC application
3. Techniques protecting users' privacy, and increasing the users' confidence in the advanced HC systems in access EHR repository.

### 3.2 EMR/EHR Repository

Disclosure of medical records in the EMR/EHR's repository is a result of weak security in these systems. For many years, electronic health record (EHR) and electronic medical record (EMR) systems have been extremely useful for managing patients' data. These systems are widely disseminated in the health sector (Sarkar 2017). The main problem with these systems is how to maintain the security and privacy of sensitive patient data and information. Furthermore, protecting EMRs/EHRs is essential for ensuring the stability of a patient's condition. Due to their inability to protect the records from unauthenticated and unauthorised users, some of current EMR/EHR systems fail to provide security and privacy for PHI

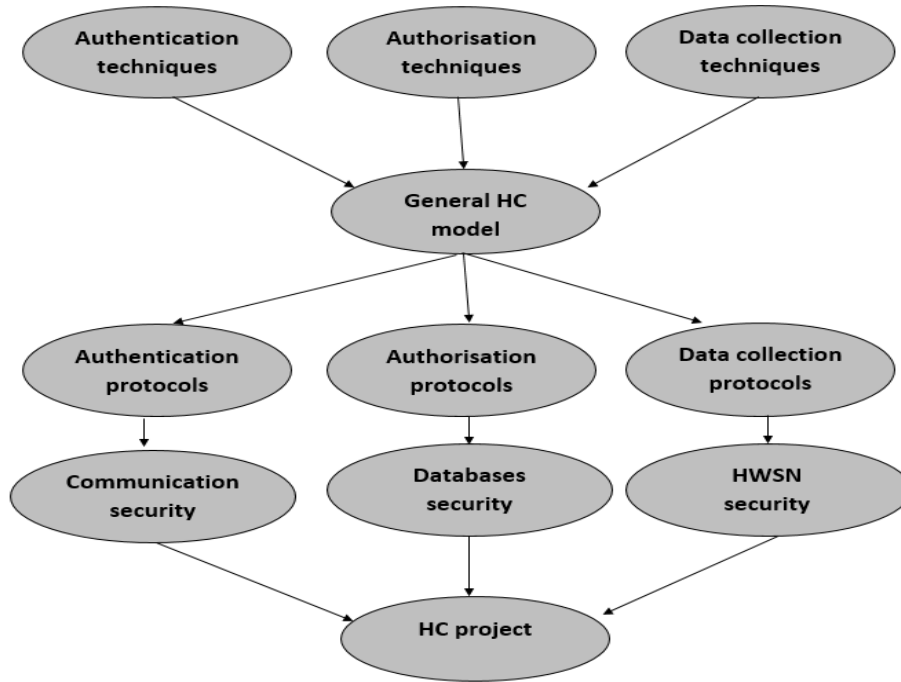


Figure 3.2: The proposed project system

(Entzeridou et al. 2018, Sittig et al. 2018). They also possibly allow authorised users to exceed their specific privileges. Thus, those systems are not a trustworthy source and are undesirable for patients and healthcare providers. Various attacks expose patients' data to malicious tampering or destruction. For example, access to the EMR/EHR repository (data and information) without authentication mechanisms and authorisation policies exposes them to penetration by adversaries (Liu, Xia, Yang & Yang 2018, Manogaran et al. 2018).

Penetration of the EMR/EHR repository may be prevented by improved system security. Many medical records transfer schemes have been developed with data collecting, authentication and authorisation mechanisms. These schemes ensure that only legitimate users are authenticated and authorised to connect. Nonetheless, these schemes still suffer from vulnerable security as discussed in Section 2.4. Specifically, security and privacy precautions should be raised for specific categories of users, doctor advisors, physician-researchers, emergency doctors, and patients' relatives. Presently, these users can break into electronic systems and even violate patients' privacy. The main reason for these breaches is the privileges granted to them or the inadequate security and privacy mechanisms of these systems (Madhavi & Lincke 2018). Providing mechanisms to collect data, authenticate and authorise the users is an essential security requirement to prevent both external and internal attackers. This requirement acts as a barrier against penetrating patients' identities and revealing their sensitive data. Therefore, to address EMR/EHR repository

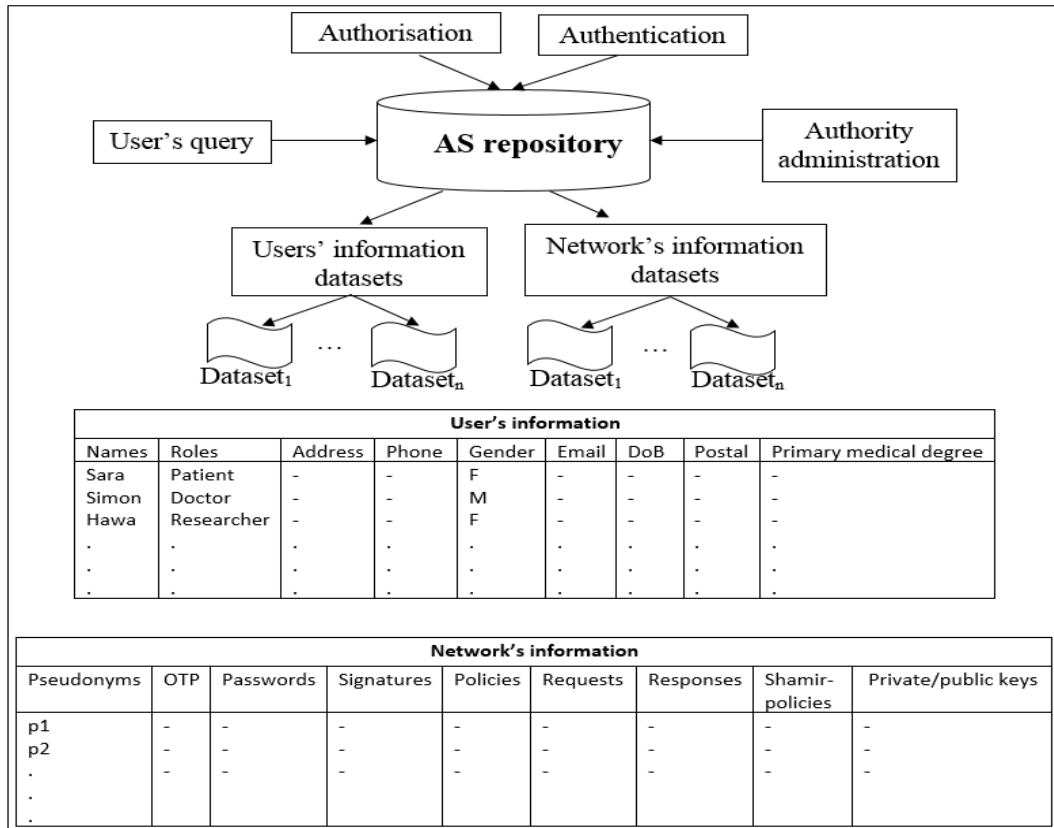


Figure 3.3: Information repositories

issues, we develop data collecting, authentication and authorisation schemes that provide security and privacy when collecting or accessing the EMR/EHR repository.

The repository is an important component of HC applications because it provides management and regulation. It is an efficient way to handle EMR/EHR user data and information smoothly and flexibly. It enables patients and providers to obtain health data without incurring management and storage problems. We use an EMR/EHR repository in our project because it offers several advantages such as ease of handling datasets, alleviation of technical details in EMR/EHR systems and efficient storage/management of datasets.

Our project includes several repositories, for instance, Attributes Server (*AS*) includes information repositories such as user information and network information as shown in Figure 3.3. Also, the Data Server (*DS*) includes a data repository as shown in Figure 3.4. *DS* stores data previously received from the HWSN in the repository. When *AS* receives an authorisation request from users, *AS* uses authorisation policies to verify a user's information such as name, and network's information such as signature. *AS* sends an authentication request to the *DS* to receive data from the policy retrieval point (RPR) repository.



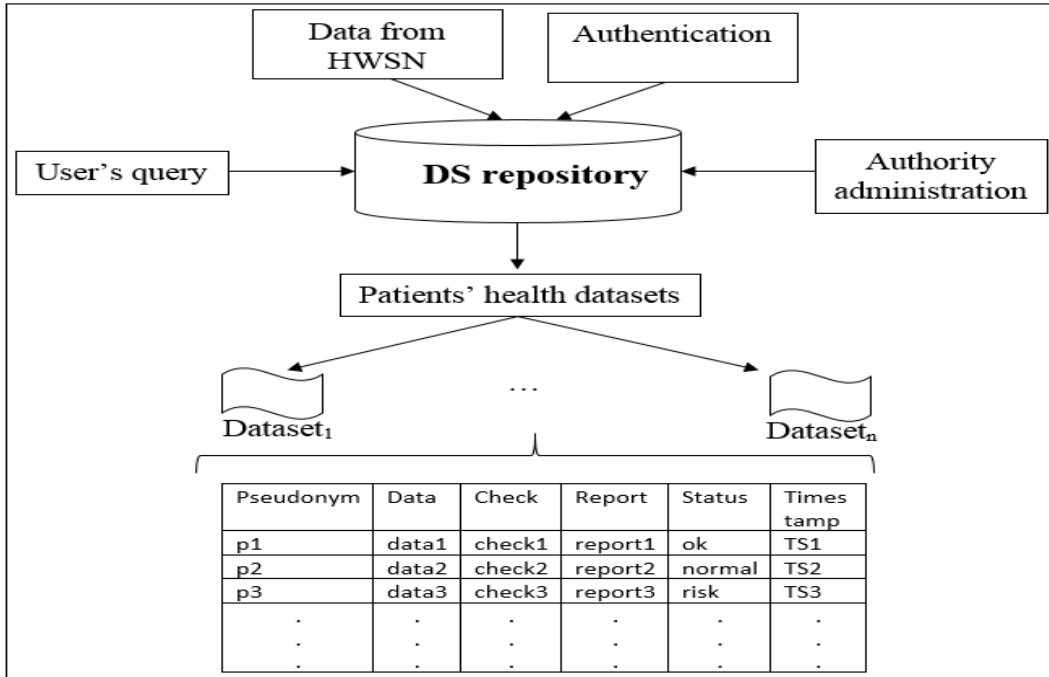


Figure 3.4: Data repository

### 3.3 Storage Scheme in the Proposed HC Application

In this section, we will illustrate the storage scheme in the proposed HC application. To the best of our knowledge, there are no other studies addressing this issue in the field.

#### 3.3.1 Threat to Storage Scheme

Building a threat model in HWSN is important to identify serious attacks on patients' data and subsequent disclosure. HWSN provides important services to the health sector compared to traditional networks, such as local area network (LAN) and metropolitan area network (MAN), but they are more vulnerable than the latter. These networks rely on self-organisation and synchronization to increase the flexible communication of sensor nodes, but HWSN suffers from a security vulnerability. Due to wireless radio signals in WSN, it is easy for an attacker to access data transmitted among sensors, Cluster Heads (*CHs*) and Local Server (*LS*). These networks are targeted for many attacks that exploit resource-constrained, untrusty communication and unattended processes. HWSN threats are as follows:

- The attacker performs a MITM attack to modify or replay attack to resend the data to the *CH/LS*. The attacker's aim is to use his/her device as legitimate sensors in the network

- The attacker can execute a DoS attack on the *CH/LS*. This attack exploits a heavy transmission of duplicate or counterfeit data to destroy the HWSN
- The attacker can apply several types of localisation attacks such as:
  - The attacker uses several IDs of legitimate sensors with incorrect data (such as wrong and duplicate IDs) and sends them to the network (Sybil attack)
  - The attacker uses more than a fake node to transfer data between different locations via a tunnel that connects counterfeit sensors. This attack leads to a disguise of communication between the legitimate sensors (Wormhole attack)
  - The attacker uses a malicious sensor node to attract all data sent from the sensors. Then, he/she prevents the correct data from accessing to the *LS* (Sinkhole attack)
- The attacker performs an attack to penetrate the EMR repository in the *LS*, to access the patient's data and reveal their identities
- The attacker can launch an eavesdropping attack to obtain patients' data, and then perform an analysis of these data to detect the linkability between data, information, and pseudonyms
- The attacker can copy a legitimate sensor ID in more than one counterfeit sensor. These counterfeit nodes send modified data to the network (node replication attack)
- Collision, preimage and second preimage attacks can be implemented to change signatures and data transferred between network's devices.

### 3.3.2 SHA Hash Function

During the implementation of the proposed storage scheme in the *LS*, another technique is used: the traditional hashing algorithms in ECDSA, such as SHA1. For more details of this traditional hashing function, see Appendix A.

### 3.3.3 BLAKE Hash Function

During the implementation of the proposed storage scheme in the *LS*, another technique to speed up the procedures of the storage scheme is to use one of the lightweight hashing algorithms such as BLAKE. This hash function provides features, such as simplicity, speed, memory availability and parallel procedures in

hardware/software implementations. These features qualify it for efficient use in restricted source devices. It is capable of preventing hash function attacks. For more details of these lightweight hashing functions, see Appendix A.

### 3.3.4 De-identification Mechanism

Encryption and k-anonymity mechanisms are applied to hide patients' data but, these mechanisms suffer from serious drawbacks. For instance, encryption of collected data (Neubauer & Heurix 2011) has the following drawbacks:

1. Temporary HC providers such as a researcher doctor, will not get benefit from the encrypted data, and if he/she is able to get the collected data by the decryption process, this is a security weakness in the HWSN system
2. Huge datasets' encryption burdens the *LS* system, causing complex operations and processor power consumption (Zhou et al. 2017)
3. The datasets of collected data perform intensive and continual operations on medical records, such as add, delete and edit. If the records are encrypted, this will multiply the burden on the *LS* (Vatsalan et al. 2017)
4. Encryption can contain implicitly direct information about the patients. A breach of this encryption will expose patients' information to the intruders (Bogos et al. 2018).

The k-anonymity of collected data suffers from the following:

1. The removal process of all the patients' information obstructs the HC provider from dealing with linked patient data (Neubauer & Heurix 2011)
2. Inserting a large set of false medical records, namely, greatly reduplication the dataset size. This process consumes *LS* resources, particularly the intensive and continual access of the datasets by HC providers.

To address these disadvantages, we use random pseudonyms in REISCH's requests to hide the correlation of patients' information with data. The medical records transmitted/stored among the sensors, *CHs* and *LS* do not contain any of the patients' real information. This mechanism prevents intruders from identifying patients' IDs. In addition, this mechanism is fast and does not need complex operations. When the EMR system wants to add a new HC provider/patient, the REISCH sends a request to the remote servers (Central Server (*CS*) and *AS*) which provides the *LS* with the required information for updating random pseudonyms. These random pseudonyms are linked with the users' IDs. This mechanism enables sensors to access and store a specific patient's data without exceeding granted privileges.

### 3.3.5 Efficient HWSN Data Management Using XML

The other important part of the proposed EMR system is the repository. Repositories contain data in various contexts since these systems have difficulties dealing with the different coordinates for data. The extensible access control (XML) is considered convenient for the exchange of various data via different environments. XML is the symbolic, simple and flexible language designed to manage, describe and exchange data across the Internet. It divides data into a useful form of information through data organisation, the purpose of sharing data across different systems and stored in the dataset. Also, XML has several features that make it suitable for data management, such as support for unicode, the representation of computer data structures (trees, records and lists), use a formula read by both human and computer. However, XML should support the security mechanisms to provide different levels of protection of sensitive data in the whole or part of the XML document (Jo & Chung 2015).

But this information needs mechanisms to identify the arrival of unauthorised users to protect patients' data. Patient data transmitted between sensors (nodes and *CHs*) and network devices (such as a nurse and a *LS* device) need data management algorithms to maintain both performance and security at the same time. EMR, including patients' confidential data and private information, needs to be accessed by HC professionals. Thus, sharing such EMR without breaching a patient's privacy requires EMR management in an efficient and secure manner. XML technology has begun showing its superiority in the exchange of complex data over different systems.

### 3.3.6 Homomorphic Scheme

Homomorphic is a mechanism for merging all messages and signatures together to improve both performance efficiency and security. This mechanism consists of many types such as linearly, polynomial, fully and aggregate signature (Emmanuel et al. 2018). In this study, we focus on the aggregate signature because it deals with multi-sensors signatures, messages and different private keys depending on different devices, such as sensors. Furthermore, this process is extremely suitable for multihop-based networks during the integration of signatures in a single signature. We assume that we have a range of messages  $M = \{m_1, \dots, m_n\}$  and a range signatures  $S = \{s_1, \dots, s_n\}$ ,  $M$  contains all of a group's messages,  $S$  is one signature for all signatures,  $A$  is an aggregate function and  $V$  is a verification function. The process of homomorphic signatures is as follows:

- Each device generates  $K_{pr}$  and  $K_{pu}$  keys and broadcasts the  $K_{pu}$  keys to the network members

- Each device signs the  $m$  by the signature algorithm, which includes the device's ID, message and private key  $s(K_{pr}, m_i, ID)$
- The aggregation procedure in the intermediate nodes, such as  $CH$  relies on  $A$  to collect all public keys, messages and signatures  $A(K_{pu_1}, \dots, K_{pu_n}; m_1, \dots, m_n; s_1, \dots, s_n)$
- The verification procedure will be in the final entity, such as  $LS$ , which uses  $V$  to validate the signatures  $V(K_{pu_1}, \dots, K_{pu_n}; m_1, \dots, m_n; s_1, \dots, s_n)$ . If the verification process fails, it means that the data integrity operation is incorrect.

The homomorphic aggregate signature scheme is important to support the performance of network devices by making the intermediate nodes, such as  $CH$  performs a single signature process for all members' signatures of the group rather than the signature verification process (the ECDSA verification process consumes more time and energy than the signature process) (Luo et al. 2019). In addition, homomorphic increases security measures in preventing the tracking of patients' information and data or changing signatures of legitimate network devices (Kapusta et al. 2019).

### 3.4 Elliptic Curve Cryptography for Authentication

First, we focus on the security aspect of authenticating legitimate users. To ensure only legitimate users are associated with the HC application network, our scheme includes a set of techniques (Elliptic Curve Integrated Encryption Scheme (ECIES), PHOTON, one-time password, mutual authentication, and media access control (MAC) address) to validate the authentication request. Efficiency and security are important determinants of health applications. Sensitive patient records require protection from intruders and at the same time require efficiency because health applications involve frequent and continuous exchanges between a large number of users (patients and professionals). Our scheme relies on algorithms that provide lightweight operations and a high-security level for encryption and signature operations. This section describes the threat model and the basic concepts of these techniques.

#### 3.4.1 Threat to Authentication Scheme

In the architecture of our proposed HC application, the  $AS$  is responsible for users' authenticity. The  $AS$  must be authentication proof against a number of attacks. In this section, we list possible attacks against the authentication scheme used in the  $AS$  of the proposed HC system.  $AS$  is trustworthy. It resists repository penetration

attacks. This server contains only users' information datasets. We impose threats in our authentication model as follows:

- The attacker can steal the client application and its files to analyse the data, retrieve the parameters, and reveal the secret key of the user. Then, the attacker can use this application on different devices
- The attacker can listen for authentication requests in the insecure environment and execute interception, replay, MITM, and modification attacks. The attacker's goal is to become a legitimate user in the network
- The attacker can execute a forgery or masquerading attack in an attempt to penetrate the authentication process
- A legitimate user (such as a doctor, nurse, or patient) can perform a privileged insider attack based on his/her legitimacy in the network
- The attacker can successfully guess the real username, password, role and pseudonym associated with it. This guess can be accomplished during an intensive analysis of many authentication requests.

### **3.4.2 Elliptic Curve Integrated Encryption Scheme (ECIES)**

To implement the authentication scheme in the *AS*, Elliptic Curve Cryptography (ECC) will be adopted. As ECC is no longer dependent on the discrete logarithm problem (DLP); ECC can be performed very quickly. In this section, we will provide an introduction to ECC and its applications. For more details of ECC cryptography, see Appendix B.

### **3.4.3 Lightweight Hash-Function Algorithm**

During the implementation of the proposed authentication scheme in the *AS*, another technique to speed up the authentication is to use the best of the lightweight hashing algorithms which is PHOTON-256. This algorithm is extremely beneficial in information signature processes, providing high-performance efficiency and satisfying the security principles of signature compared to traditional hash function algorithms. This lightweight function is exceedingly convenient for our scheme as a signing mechanism in our authentication protocols to provide information integrity by generating a robust and reliable signature. For more details of these lightweight hashing functions, see Appendix B.

### 3.4.4 One Time Password (OTP)

OTP is a way to authenticate legitimate users by generating a passcode or nonce only once in a specified time. It becomes not applicable in the next times for authentication. OTP is an effective method for authenticating users in HC applications if used with robust encryption and signature technologies. Using a static password, or nonce, without other authentication mechanisms makes a system weak and prone to attack. Therefore, OTP significantly provides support to the authentication process. This mechanism prevents many attacks, such as replay, MITM, and guessing (Thirinant et al. 2015, Chen et al. 2017). The attacker cannot use this passcode or nonce to connect to the network later. Each client receives a random OTP from the authorities provider via a secure channel, and this is used for the login session. The client sends the OTP as part of an authentication request. If the authentication process is valid, the server will delete the OTP from the dataset and will not accept it in the future. OTP is a powerful mechanism to mitigate the risk of hackers' communication in the network.

In this scheme, we apply the OTP to generate a random password (to prevent hackers from expecting the OTP) with the first link to users. This procedure is to ensure only legitimate users are connected to the network. In our authentication scheme, users (patient or provider) only use the OTP once and will not need to use the OTP with name and password in future authentication operations. This mechanism allows the server to record the original physical address in the dataset. Even if the attacker detects the OTP, he will not benefit from it in the next times. We also use other mechanisms (such as timestamp, checking the original physical address and multi pseudonyms) with the OTP.

### 3.4.5 Mutual Authentication

The network parties (clients and server) exchange requests for authentication remotely (Internet) or locally (WLAN). This process plays an important role in connecting users to HC applications. The authentication request can include many security parameters such as name, password, OTP, nonce, pseudonym, signature, and encryption. A robust authentication protocol should include security requirements that are critical to protecting patients' information and data. In addition, traditional methods of authentication (password and name) are not suitable for health applications (Liu & Chung 2017). In general, two kinds of authentication have been applied in the various projects (as described in Figure 3.5); simple and mutual.

In simple authentication, one party performs the authentication process, such as

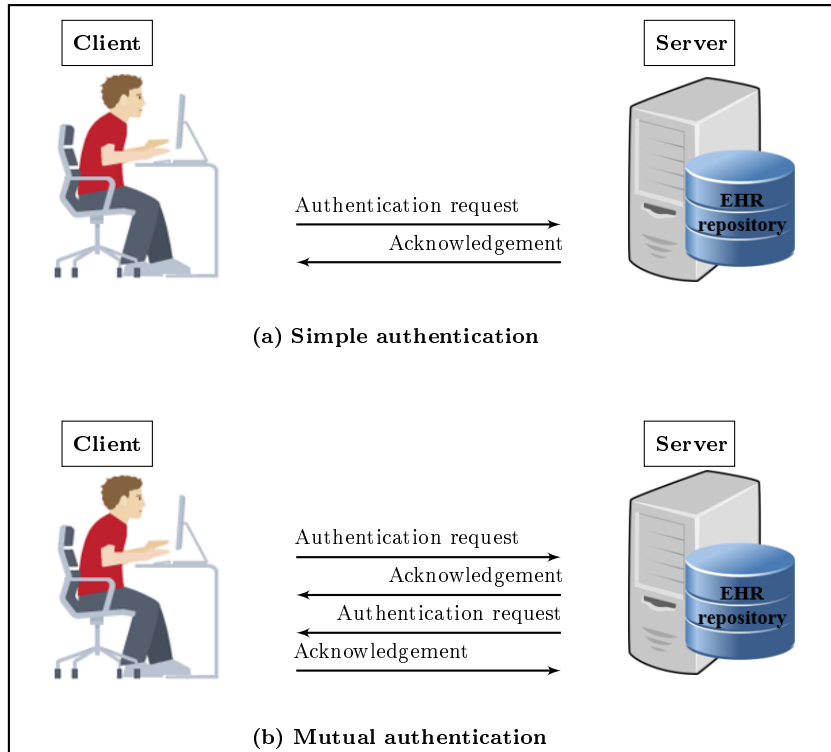


Figure 3.5: Types of authentication schemes

server verifying the authentication request for the client. This type of authentication is vulnerable to attacks such as masquerading, spoofing, and impersonation. The attacker can use his/her device as a fake server to receive all clients requests. Mutual authentication provides a security solution to prevent known attacks. In this type of authentication, each party authenticates the other party and thus prevents counterfeit attacks by both client and server. Our scheme adopts the mechanism of mutual authentication in the preservation of users' information and data.

### 3.4.6 Media Access Control (MAC) Address

Network devices of all types should contain a hardware card (interface) to connect to the local or global network. Each wire or wireless interface has a media access control (MAC) or physical address that consists of 48-bit. It is divided into six octets and written in hexadecimal, such as "8C: 70: 5A: 41: 49: BC". This address is a unique identifier (no duplication of addresses) for devices that are defined globally and are persistent (Martin et al. 2017). MAC address is the identifier of the device that can connect to the network. This address is used in WLAN networks because it offers advantages, such as reducing costs and speed in access control procedures (Mattos & Duarte 2016). It can be changed programmatically in various operating systems, such as Linux and Windows. In addition, anyone can use Address Resolution Protocol (ARP) to detect the MAC address of another user



in the network (after entering his IP address) (Dallaglio et al. 2015).

The main problem with this address is that the attacker can execute an eavesdropping attack to access the MAC addresses of legitimate devices in the network. Then, he/she selects a legitimate MAC address to use it. For example, an attacker could execute an ARP poisoning or spoofing attack by using a fake identifier of the MAC address (for a legitimate client or server). Consequently, the attacker gains illegal privileges that would enable it to perform other attacks, such as MITM and DOS (Xiao et al. 2016, Masoud et al. 2015). Moreover, randomization operations for the MAC address have become useless in the protection against tracking attacks (Matte et al. 2016, Vanhoef et al. 2016). Therefore, if the server does not have a mechanism to detect MAC address change, the attacker becomes a legitimate user in the network and has access to network resources.

## 3.5 XACML Techniques for our Authorisation Scheme

The second major component in the proposed HC application, as shown in Figure 3.8, is the EHR repository. Its primary purpose is to store patients' health records or medical records. All kinds of users, including the patients themselves and HC professionals, need to access the repository legally and ethically. In this section, we will introduce the techniques used to authorise the legitimate users.

### 3.5.1 Threat to Authorisation Scheme

Many serious risks to HC authorisation systems that require the building of a threat model to detect weaknesses in these systems. We assume that attacks can be internal, external, active, and passive. In summary, the existing HC applications are vulnerable to the following attacks:

- The attacker can flood the server with intensive authorisation requests which is to stop the service from legitimate users and destroys the network
- To access patient data and reveal patient identities, the attacker performs an attack to penetrate the repository in the *CS*
- The attacker performs a MITM attack to modify data and to become a legitimate user in the network
- The attacker sends a fake authorisation request during the execution of a forgery/impersonation attack to gain access to patient data

- The attacker can launch an eavesdropping attack to obtain authorisation requests, and then perform an analysis of these requests to detect the correlation between data, information, and pseudonyms
- The attacker can execute timing attacks by using the time period to reveal user authorisation information.

### 3.5.2 Elliptic Curve Digital Signature Algorithm (ECDSA)

To implement the authorisation scheme in the *AS*, the ECDSA will be adopted. It depends on the use of the points on the curve to integrate and sign data. ECDSA uses small parameters which expedites performance of computations, thus reducing time and storage (Sojka-Piotrowska & Langendoerfer 2017). These features are very important for large organisations and constrained-source devices, such as WSN, because these networks require processing power, memory, bandwidth, or power consumption (Dou et al. 2017). In this section, we will provide an introduction to ECDSA and its applications. For more details of the ECDSA algorithm, see Appendix C.

### 3.5.3 Models of Access Control to the EHR Repository

Any system needs access control models to determine users' access to the data repository. Many access control models, and each one depends on a particular method and set of rules. One of the most distinct access control models is Role-Based Access Control (RBAC). This model relies on the classification of users into roles, and each role has privileges and rights regarding data access (Gajanayake et al. 2014). With RBAC, the security of the system is based on the structure of the system's roles assigned to users (Sánchez et al. 2017). Each role in the system is assigned according to the job of the user in the organisation (Alturki 2017). RBAC was introduced to solve problems with previous access models, such as Mandatory Access Control (MAC) and Discretionary Access Control (DAC). As shown in Figure 3.6, the RBAC model divides users into roles (such as patient, doctor, and researcher). For example, the researcher role can access the data assigned to that role, which enables him/her to develop medical research to find a cure for a medical condition.

In recent years, there has been significant interest in using the Attribute-Based Access Control (ABAC) model for the protection of data privacy. This model is designed to access data more accurately (fine-grained) and securely. It handles user attributes (such as name, address, age, mobile, location, time) to allow users to

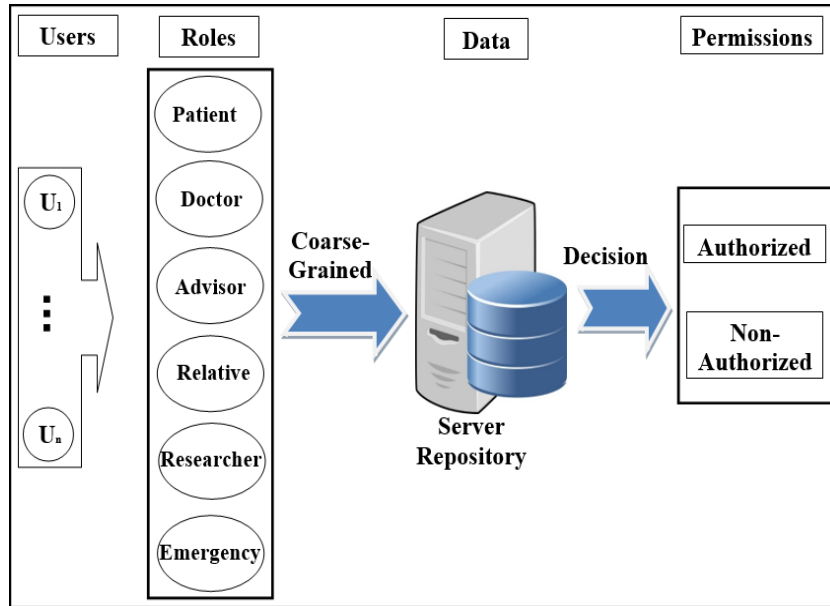


Figure 3.6: Scheme of RBAC model

access the server’s repository. ABAC is proposed to go beyond the limits of the rules and design of the most well-known control access models (DAC, MAC, and RBAC) (Jin et al. 2012, Zhang & Zhang 2017). ABAC is a rich model because it deals with a wide range of user attributes. ABAC supports administration, authorisation of context-aware, risk-intelligence, and scalability in various applications, such as the Internet, IoT, Big Data, cloud computing, and VANET (Brossard et al. 2017). The attributes in ABAC are categorized into subject, object, action, and environment. As shown in Figure 3.7, each user has a set of attributes that allows him/her to access data in the server. In our authorisation scheme, we combine ABAC and RBAC to obtain a model that depends on both roles and attributes.

### 3.5.4 Distributed AC Implementation Technology

The most important component in the proposed EHR system is the EHR repository. Access to data is a major challenge in big data management systems (EHR) that use different techniques. In addition, the exchange of information over the Internet has become essential and requires access authorisation, particularly in HC applications. XACML standards include both access control (authorisation) and data management based on XML in the different systems (Lu & Sinnott 2018). Effectively, XACML offers features for data access and authorisation for the users at the fine-grained level.

Many techniques, such as an Open Authentication (OAuth), XML Access Control Language (XACL), Enterprise Privacy Authorisation Language (EPAL), Open

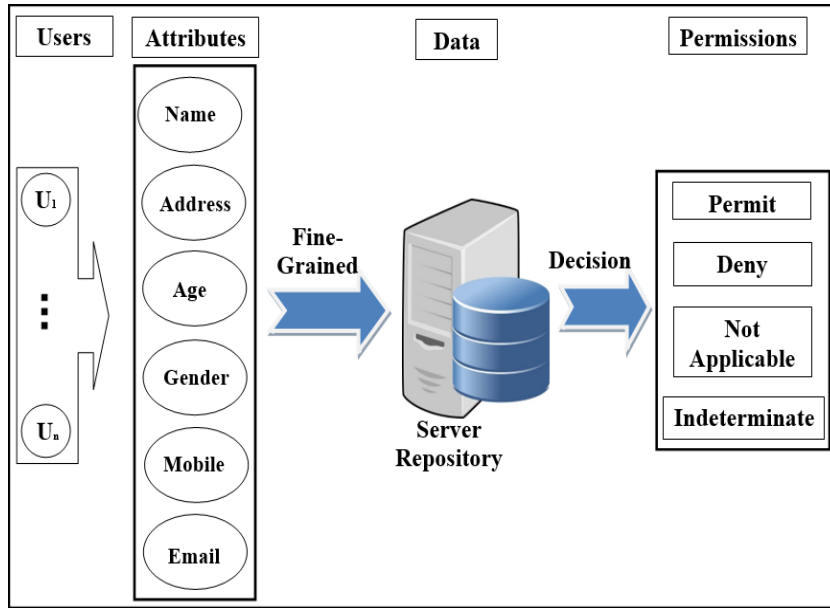


Figure 3.7: Scheme of ABAC model

Digital Rights Language (ODRL), and Security Assertion Markup Language (SAML) have used in authorisation projects. However, OAuth suffers from password management; XACL suffers from few functions and is non-extensible; EPAL does not support multiple subjects, error handling and a hierarchical role; ODRL suffers from common vocabulary, conflict between serialization and does not support combining algorithms; SAML is extremely expensive, difficult to use and uses a single sign-on (SSO), namely, it uses one password for all applications which may be reason for penetration. XACML is the most flexible and effective technique (Grace & Surridge 2017, Beltran et al. 2017, Turkmen et al. 2017). This technology is presented by the organisation for the advancement of structured information standards (OASIS). This standard has many of the features that qualify it for use on the Internet, such as combining policy, combining algorithm, attribute, multiple subjects, policy distribution, implementation independency and obligations (Zhang & Zhang 2017, Turkmen et al. 2017, Deng et al. 2018).

This technique is based on the specific policies first and then on many modules, such as policy enforcement point (PEP), policy decision point (PDP), policy administration point (PAP), policy information point (PIP), and policy retrieval point (PRP) to evaluate the request for access (Calvillo-Arbizu et al. 2014). As shown in Figure 3.8, PEP sends and receive requests and access responses to the repository; PDP evaluates the decision; PAP creates policies based on users' attributes; PIP retrieves users' attributes; and PRP retrieves users' data from the repository. The result of the decision (permit, deny, not applicable, indeterminate) is sent to the subject via PEP (Zhang & Zhang 2017).

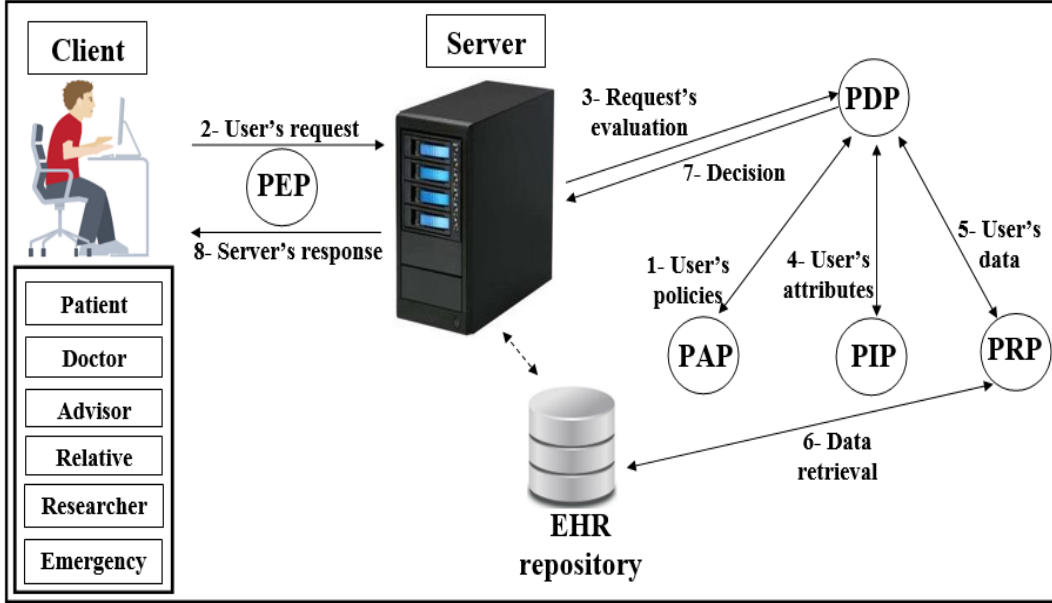


Figure 3.8: Scheme of XACML

### 3.5.5 Shamir Scheme

The secret sharing or the Shamir scheme depends on a set of keys/secrets sharing ( $SS_s$ ) and threshold ( $TH$ ) to produce a master key/secret ( $MS$ ). The master secret can be created from some or all of the  $SS_s$  (Liu, Yang, Wang, Zhu & Ji 2018). In this scheme,  $TH$  specifies the minimum number of keys/secrets that allow reconfiguring  $MS$  (Ahmadian & Jamshidpour 2018, Stinson & Wei 2018). This scheme consists of two phases: generation and reconstruction. In the generation phase, the server divides  $MS$  into a set of secrets sharing ( $SS_1, SS_2, \dots, SS_n$ ), and each Client ( $C_i$ ) securely receives one secret sharing ( $SS$ ) that is part of  $MS$ . In the reconstruction phase,  $C_i$  needs to achieve any set of secrets ( $SS_s$ ) required by relying on the value of  $TH$  to construct  $MS$  (correctness and homomorphism properties). If  $C_i$  has  $TH-1$  from  $SS_s$ ,  $C_i$  fails to obtain information from server (secrecy property).

Calculating the  $MS$  is an immensely difficult operation for the attacker. In addition, the secrets configured for the  $MS$  are anonymous users; the attacker does not know if these secrets belong to any of the users (Huang et al. 2016). The Shamir scheme provides an anonymity solution to generate a  $MS$  with several features. It provides full security in hiding  $C_i$ 's'  $SS_s$ , a  $MS$  size equal to  $C_i$ 's'  $SS_s$  sizes, easy creation of a  $MS$  from a set of keys/secrets, and creation of a new key/secret for one-time use (Dikshit & Singh 2017). Our authorisation scheme uses the Shamir scheme ( $TH = 3$ ) with ECDSA. This security procedure prevents attackers from accessing or modifying patients' data during the implementation of security objectives (authorisation, authentication, authenticity, and integrity).

## 3.6 Development of EMR/EHR System

### 3.6.1 Patient's Confidence in HC Services

HC services include not only patients' health records, but also their personal information such as age, chronic disease history, and even sexual orientation. Therefore, security and privacy issues should be addressed carefully by developers of the health applications. Information privacy in HC applications is of interest to HC providers on the one hand, because privacy issues affect the legal and operational environments, and on the other hand, they affect the patient's confidence in the use of HC applications (Rathert et al. 2017). Therefore, earning the trust of patients in health applications depends on two factors. Those are the understanding of providers for security weaknesses and the development of health applications facing these threats.

### 3.6.2 HC and EMR/EHR Users

Patients need to trust their HC providers such as doctors, nurses and have confidence in the HC services and HC instruments. Patients in HC institutions need services that are efficient, fast and continuous, and at the same time prevent disclosure of their information (i.e. restrict access to only authorised persons) (Ganiga et al. 2018). Access to HC networks has several challenges in security and privacy, such as validation of medical devices to prevent members using unauthorised devices, restrict the access of guests and visitors to the HC applications (such as researchers doctors and specialists) and control access to medical records for patients by identifying the role of each of the medical staff members. For instance, the nurse can access only data of mental health that to apply the doctor's directives, the doctor can access identity data and information of mental health, the pharmacist can access only health data to specify prescription as well as the method of taking medication and so on. In addition, it is important to be compliant with medical standards for HC organisations (such as HIPAA standards to ensure data confidentiality) (Bradford Networks 2012). All of these challenges require a great effort and can be a burden on IT staff.

Figure 3.9 shows the taxonomy of HC users. This Figure is divided into users (such as patient, nurse and doctor) and datasets or medical records (information and data). Also, information includes personal information (such as name, age and address) and network information (such as password, OTP, MAC and signature). Patient data includes specific disease data (such as sexual, mental and dermatological).

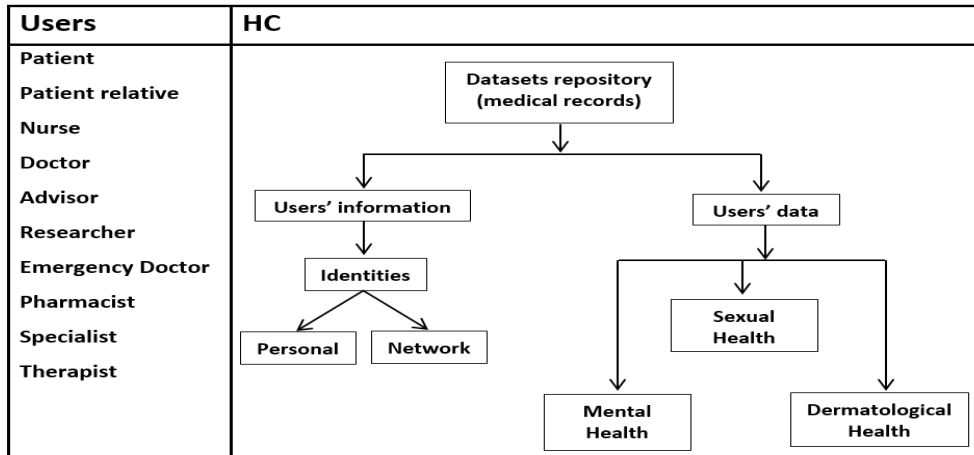


Figure 3.9: Taxonomy of HC users

### 3.6.3 Administration/Management of Health Organisations

Patients must also be confident that their medical records have been stored where security has been absolutely well addressed. Because of the increasing challenges to health organisations, these organisations require another feature, such as data management in addition to the privacy and security issues (Consultants to Government and Industries 2015, Lokshina & Lanting 2019). The different data contexts in network exchanges cause a heavy burden on authorisation systems. Also, the network security in the HC systems requires the integration of all the different network units in the security system. In addition, the authorisation system should support the connection with the proper adoption of the security context of each device in the network (such as a computer, sensor and phone). Furthermore, providing the vision of information with access control in real-time helps to build an efficient security system for HC (Bradford Networks 2012).

## 3.7 Integrating WSN with HC Application

In this section, we will focus on how to address the protection issue in our HC application system. This proposal includes medical records protection in three areas: data collection (WSN), transferring authentication and authorisation information, and accessing server datasets (EMR/EHR repository) as shown in Figure 3.10. The components used in the proposed scheme are sensor nodes, a Local Server (*LS*), communication devices (laptop and desktop) and a remote server (Central Server (*CS*), Attribute Server (*AS*) and Data Server (*DS*)). *LS* contains data collections by WSN, *CS* is considered to be as a portal to authenticate and authorise users' requests, *AS* contains users' real identities (IDs) and *DS* stores patients' data.

Sensor nodes are used to gather patients' data in an environment (hospital or clinic) and stored it in the *LS* (EMR repository). Collecting patients' data through sensor nodes requires protection from risks and threats such as internal and external attack. Also, the transfer of patient's data from and to the local or remote server datasets requires the application of critical security policies to prevent the various attacks. Communication devices are used to send and receive medical records, such as medical reports. These devices are used by patients or providers (medical staff) and that are authenticated and authorised access to confidential data for patients. Servers are used to store patients' medical records and control access to datasets. For example, a provider, such as a doctor in a hospital can send authentication and authorisation request by his/her communication device to earn access to a specific patient's data. Also, the patient can obtain his/her medical record history by sending a request directly to the remote server (*CS*) over the Internet. This situation obtains if the patient is authenticated and authorised to grant access to his/her information and data.

Our framework offers the following capabilities to ensure security and privacy requirements in the HC application:

- WSN data management and use of the proper context (XML) for the exchange of data on different devices, as well as protection of the WSN's data through signature (ECDSA) with the fast hash function and MD anonymity
- Use of lightweight algorithms, such as ECIES and PHOTON (signencryption) to address the performance and security in authentication protocols
- Controlled access for authorised users and datasets management via the Internet by authorisation protocols.

### **3.8 Protocols to Improve the Security of WSN and EMR**

In this section, we will present a set of protocols used in the HC application based on the WSN. This scheme will be detailed further in Chapter 4 to explain our security protocols in the HWSN among sensors, *CH* and *LS*.



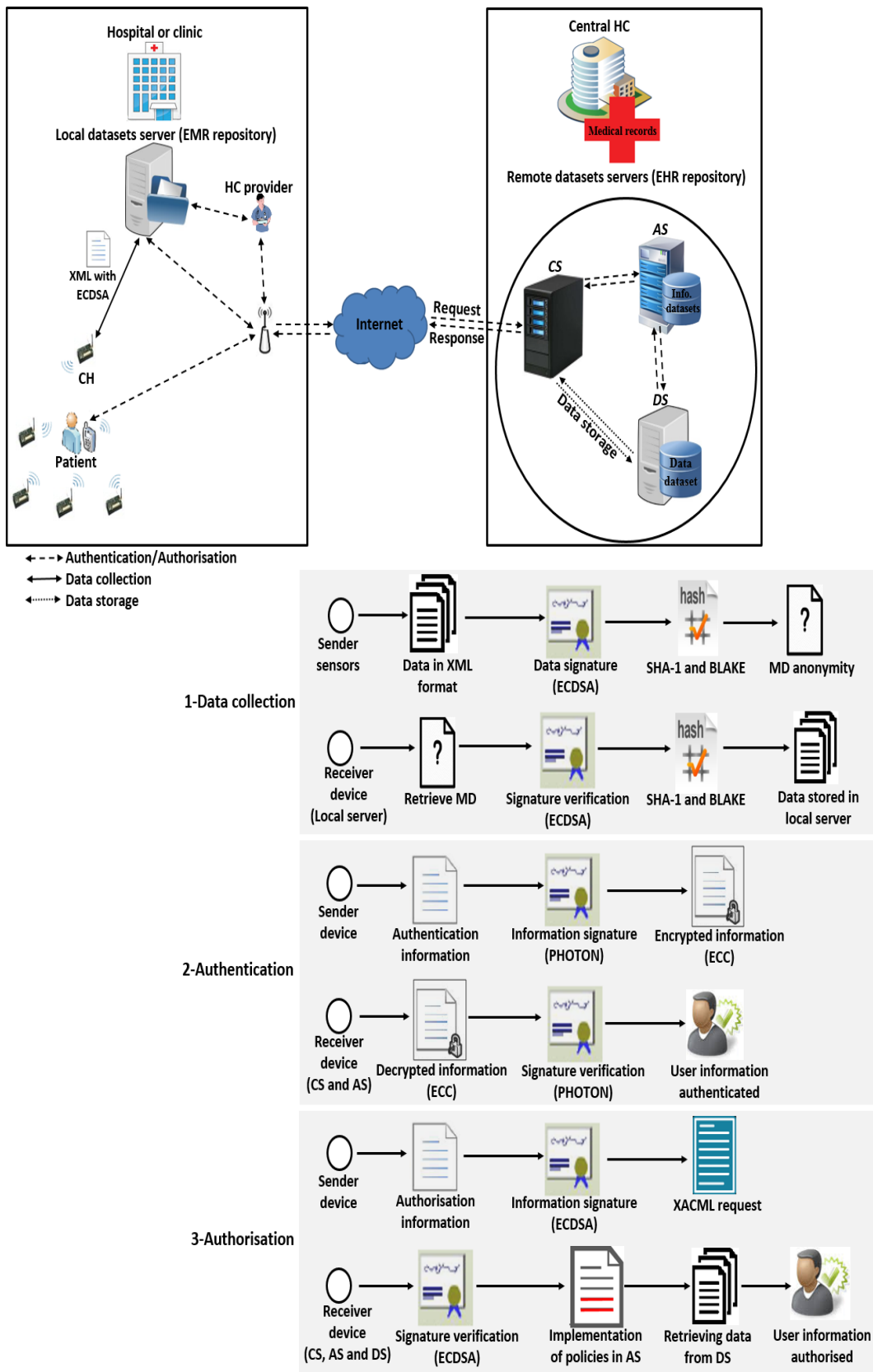


Figure 3.10: The proposed project model in HC environment

### 3.8.1 HC Data Management and the EMR's Storing/Exchanging

We propose to use of XML to manage the wireless local area network (WLAN) data. This descriptive language enables all devices to read data in a simple and meaningful way. In addition, we propose using the mechanism of signature (ECDSA) with XML file for the management and protection of patient data at the same time.

The process of verifying collected signatures from sensors consumes  $CH$  energy and time quickly. The ECDSA algorithm accomplishes the operations the public key, signature generation and signature verification. The operation of signature verification in the ECDSA algorithm consumes more time and energy than a signature generation (Jariwala & Jinwala 2012, Othman et al. 2013). We assume that we have a clinic or a hospital care scheme as shown in Figure 3.11. We propose using homomorphic property with the signature in all sensor nodes. Homomorphic property means the direct computation on signed data. Each sensor node signs the message, and then sends it to the  $CH$ . Thereafter, the  $CH$  combines all signed messages without verifying the messages. Afterwards, the  $CH$  sends signed messages to a  $LS$  (unrestricted resources). As the transport operations consume more energy from the computation operations, the collection of signed messages without verify in the  $CH$  reduces the transport operations and thus saves time and energy.

### 3.8.2 Integrity and Authentication of EMR

We propose to use the BLAKE and anonymity with the ECDSA algorithm in the authentication of EMR. For more details about the BLAKE and ECDSA algorithm, refer to Appendix A.3.

We propose adding an anonymity property to ECDSA's signature to hide information of a signature's parameters  $r$  and  $s$  (each of  $r$  and  $s$  have the same number of bits) from the attackers. We accomplish this property in the original signature  $(r, s)$  depending on the value sent from the server ( $LS$ ). If the value is odd, we divide the signature into three parts. If the value is even, we divide the signature into four parts and exchange parts. In both odd and even cases, a counterfeit signature and padding are added to the original signature to support signature anonymity. After the completion of this operation, the value is sent with the message to specify the odd or even division in the receiver. Afterwards, the receiver can verify that the message and return the same parts of the signature to

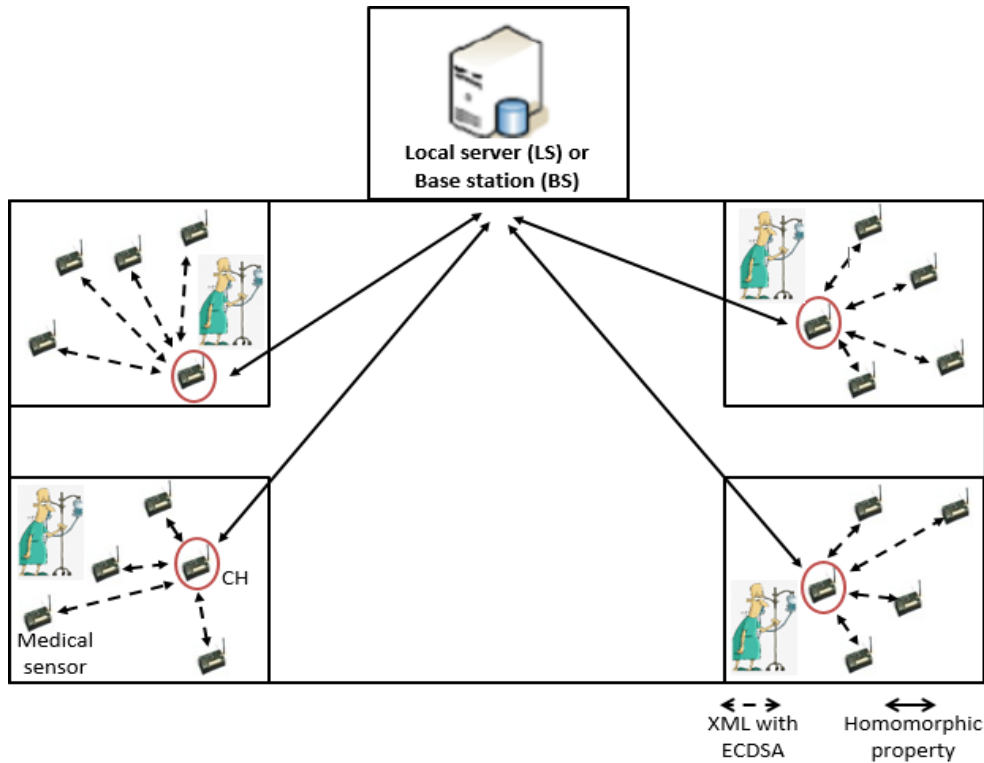


Figure 3.11: Homomorphic and 1 scalar multiplication with signatures

its original place. This mechanism prevents attacks from penetrating the ECDSA signatures because the attacker, when he/she gets on the value of  $r$  and  $s$ , he/she does not have the original value for  $r$  and  $s$ . As a result, the attacker cannot derive the private key and the patient's data is protected from the change.

### 3.9 Users' Authentication in EHR

In this section, we will briefly explain the design of the authentication scheme. This scheme will be discussed in more detail in Chapter 5 to explain authentication protocols among network entities.

#### 3.9.1 Information Confidentiality in EHR

Users' information is a sensitive part of the definition of users in the HC application. This information proves their legitimacy in accessing the network services. The authentication process is the first security procedure when connecting to a HC application network. Therefore, user authentication information needs mechanisms that apply the requirements of confidentiality and integrity to prevent disclosure or changes to information. Signcryption (encryption and signature) for users' small information is critical to repressing attacks, especially, external. However, EHR systems require efficient security protocols because of the large volume of

communications exchanged between users and the EHR repository. We propose using ECIES 256-bit for encryption and PHOTON 256-bit for signature. These algorithms perform efficient operations as specified in the Appendix B.

Although, encryption is extremely expensive for server resources when used with large data in HC environments, it is suitable when used with small authentication information. Therefore, we use efficient ECIES to encrypt only users' information in our authentication scheme. In this scheme, we rely on three entities (communication devices, *CS* and *AS*) to complete the authentication process. The communication device sends the authentication request after signing and encrypting the user information to the *CS* and *AS*. These servers validate the authentication request by decrypting the authentication request, verifying signatures, and checking user security parameters such as pseudonym, password and timestamp. Failure of the authentication request prevents the user from accessing the network services, such as the authorisation process of data access is not allowed when the authentication process fails.

### **3.9.2 Ensure User and Device Authenticity**

The design of authentication protocols in the HC application requires robust mechanisms to demonstrate legitimate users and their devices. There are several reasons for penetration of the authentication process in health applications. For instance, the theft or loss of the legitimate user's device, the analysis of requests for login, registration and authentication transferred among network entities, the use of real information for a legitimate user (internal attack) or disguise as a legitimate user (external attack) are serious risks of penetration of the authentication process.

The process of separating real information from authentication protocols and security parameters (such as password and private key) from user communication devices greatly limits the penetration of the authentication process. Therefore, we propose using techniques, such as OTP, mutual authentication and MAC with encryption and signing to prevent the aforementioned attacks on the authentication process. OTP is used to establish the user's legitimacy in the HC network registration process. Mutual authentication is used to prevent imitation attacks either from the communication device or server. MAC is used to prove the legitimacy of the device. Additionally, we propose hiding the private key of the ECIES algorithm in a computation process that includes the signature and password, while preventing the password from being stored explicitly on the user's device. Consequently, the use of these techniques within authentication protocols provides

authenticity to the legitimate user and the device.

## 3.10 Privacy of Users' Authorisation in EHR

In the previous section, we addressed the authentication issues; while we will briefly address the authorisation issues in this section. This scheme will be detailed further in Chapter 6 to explain authorisation protocols among network entities.

### 3.10.1 Access Control with EHR Datasets

The other important part of HC applications is the protection of patient's data stored in the server datasets (*DS*). These data need protection mechanisms from internal and external attackers. Therefore, patients' datasets in the server require defining the access privileges of each user (such as patient, patient relative, nurse, doctor, advisor, researcher, emergency doctor, pharmacist) wants access to this data. The access control (AC) property only allows authorised users access to certain data. AC provides confidentiality in the EHR by restricting access rights for authorised users (Rezaeibagha et al. 2015).

AC models are the cornerstone of robust privacy in authorisation systems. We propose to merge two models' RBAC and ABAC to specify the role of each user with a specific task and attributes that grant more privileges. In addition, we propose the use of features XACML to protect patient's data from illegal and unauthorised access. Initially, users (providers or patients) should be authenticated to the HC network. Our authentication scheme prevents external attackers through the use of signencryption (ECC/PHOTON).

The next stage is the use of XACML to determine the medical records that the user can access. At this stage, our application involves identifying the capabilities of each user to determine the access of each user to certain data and define the tasks of each user. We propose signing of the attributes and information in an XACML request. XACML defines the policies and the semantic to apply those policies. XACML formats are used for request and response between the entities PEP and PDP to determine AC of the source (Sartoli & Namin 2019). Furthermore, XACML is composed of policies and rules. Policies define the applied of request, while the rules govern limitations for the application of XACML. The request consists of attributes associated with the request sender, and the response contains the decision (permit, deny, not applicable and indeterminate).

### 3.10.2 Using Pseudonym and Anonymity with EHR to Hide the Medical Records

Pseudonym and anonymity are privacy properties in unlinking, hiding and disguising the medical records of patients. The pseudonym property is applied to the patients' data by unlinking real information with data about users who are not required to know the data identity. For example, the nurse is not required to know the information about patient identities (IDs). But it is possible to know some issues, such as the medical name (pseudonym), the range of age and medical reports. The doctor can know some of the personal information of the patient. But it is not important to know the criminal status of the patient information. In addition, if a doctor asked to consult another doctor, the latter is allowed to access only health data and medical reports. Suppose the patient's information and data are stored in the datasets and only the central HC administrator has the authority to access all medical records. We assume the use of four datasets (users' attributes (patients and HC providers), pseudonyms, policies (on *AS*) and patients' data (on *DS*)). Each patient has a number and pseudonym in the central database in addition to the use of the concept of multiple pseudonyms between the communication device and servers (*CS*, *AS* and *DS*). For instance, if the patient or provider sends an authorisation request to the network, the user's pseudonym will be different when the request is transferred between the communication device and network entities (*CS*, *AS* and *DS*). The use of a multi pseudonyms mechanism prevents an attacker from tracking requests and responses when they are transferred between network entities.

Users' information requires the anonymity property to disguise and prevent disclosure of their IDs. We propose the use of information anonymity with XACML to protect patients' data from illegitimate and unauthorised access. The anonymity property is applied to the users' information by concealing signatures (ECDSA) and using the Shamir scheme. The addition of the anonymity property with XACML leads the increased privacy of data by hiding data and limiting access for authorised users.

Authorisation protocols become more robust when implementing a Shamir scheme with signatures because a set of secrets is created to produce the master signature. These secrets provide anonymity (depending on the number of secrets or threshold) in each authorisation request. We use the anonymity property with information rather than data for two reasons. First, to disguise and protect the users' information, and second, to maintain network efficiency. Because the use of

anonymity with large patient data is extremely expensive for the network's resources compared to the small size of user information being interrogated during the user authorisation process. In addition, we use multiple pseudonyms with both information and data to prevent the association of real information with data.

### **3.11 Summary of the Chapter**

In this chapter, we have described the general architecture, EMR/EHR repository and methodology of our proposed project. In addition, a detailed explanation of cryptography techniques used in the authentication, authorisation and data storage schemes is provided. Also, we have described the general framework of the proposed project that includes our general network model that connects/links three security schemes in one system. In Chapters 4, 5 and 6, we will provide a detailed explanation of our authentication, authorisation, and data collection schemes.





# Chapter 4: A More Efficient and Secure EMR Storage and Repository

In traditional HC, the collecting and storing of patients' health and medical records has been slow and insecure; a costly and 'privacy-intrusive' practice. ICT advances have made it possible to use electronic health and medical records which can be collected by sensor networks and securely stored in a data server. In this chapter, we will put forward to taking advantage of the wireless sensor network for collecting EMR records in a local data server or a data repository.

## 4.1 Data Collection by HWSNs

EMRs are widely applied in the health sector (Sarkar 2017). Moreover, EMR needs patients' data collection technology such as HWSN. In terms of sensor devices, HWSN consumes its resources through computations, communications and transportation. Because these networks have limited memory, energy and bandwidth, sensors suffer from many issues that limit their ability to accomplish necessary data security. For instance, routing protocols are important to reduce energy consumption when sending authentication requests. Also, the heavy computations of complex signatures are a serious problem for the energy consumption of sensors. In addition, remote sensors consume considerable energy when connected to a network cluster. Furthermore, signatures verification in each  $CH_i$  (per round) is a huge burden on the energy consumption and time of  $CHs$ . In addition, joining malicious sensors to wireless clusters quickly destroys  $CHs$ . Therefore, in addition to location security, protecting information sensors is essential for data security.

Unauthenticated communications and transfers cause complex computations that waste the time of the EMR server. In each round, the EMR server requires

verification of signatures for both *CHs* and *SNs*, in addition to the complex operations of storing the collected data. Furthermore, privacy breach issues in access to the repository are a very serious problem in EMR systems. The loss of data/information due to repository penetrations takes a long time to retrieve accurately. Additionally, continual and systematic updating of medical records and the difficulty of classifying data, provide opportunities to hack an EMR server. Therefore, preventing attackers from breaking into the EMR server is important to the provision of data security. As a result, data security issues in both sensors and the EMR server should be addressed to build a reliable data collection scheme.

#### 4.1.1 A Reliable and Efficient Scheme for Data Collection

We propose a **Reliable and Efficient Integrity Scheme for Data Collection in HWSN (REISCH)** to ensure that patient data is transferred/stored to the *LS/BS* securely and efficiently. The REISCH has been characterized as follows:

- Applying the Elliptic Curve Digital Signature Algorithm (ECDSA) with BLAKE2bp instead of ECDSA with a Secure Hash Algorithm 1 (SHA1) to improve HWSN lifetime and prevent intruders from altering/changing patients' data
- Using the homomorphic mechanism with *CHs* to reduce energy consumption when aggregating patient data from sensors
- Hiding the sensor's identification (SID) and location (SL) by using random pseudonyms. This mechanism prevents intruders from detecting sensor information transmitted between network terminals.

## 4.2 Our Proposed Data Storage Model

Within any HC application system, the security of the EMR/EHR repository is important but, privacy is more important because if a hacker penetrates the repository and detects user identities, then his/her harm will be greater. In this section, we introduce the model and develop protocols for data collection and storage.

### 4.2.1 Network Model

The REISCH scheme includes a set of entities, as shown in Figure 4.1:

1. Sensor (*SN*): This entity collects raw data related to a specific patient. It sends this data to the *CH*

2. Cluster head (*CH*): This entity aggregates data from the sensors that followed it. Then, it sends this data to the *LS*
3. Local server (*LS*): This entity receives data from all *CHs* in each round and stored it in the EMR's repository. This data is subsequently sent periodically to the central server (*CS*)
4. Central server (*CS*): This entity is gateway access remote servers such as the attributes server (*AS*) and the data server (*DS*). It receives data from the *LS* and sends data to the *DS* after being authenticated by the *AS*. Security procedures in *AS* and *DS* are left for the Future Directions chapter.

Our network model works with a low-energy adaptive clustering hierarchy (LEACH) protocol for WSN. LEACH uses clustering architecture to improve WSN lifetime. More details about this protocol are available in Awaad & Jebbar (2015). Each group of *SNs* collects raw data for a specific patient (Al-Zubaidie et al. 2020). These *SNs* sign data before sending them to *CHs*. Each *CH* aggregates data and signatures from his followers. Then, each *CH* uses the homomorphic property with all data and signatures without verifying the signatures to reduce energy consumption on the *CH* and send them to the *LS*. As the *LS* has unlimited resources, it verifies and validates collected data from *SNs*. The *LS* sends data stored on the EMR's repository to the central repository to allow HC users (patients and providers) to access them by sending authentication/authorisation requests to the central server (*CS*), attributes server (*AS*) and data server (*DS*). This chapter focuses on performance and security issues in *SNs*, *CHs*, *LS* and *CS*. Security issues for datasets and transferred data in *CS*, *AS* and *DS* are left for future works.

#### 4.2.2 Design Goals of REISCH

To develop a reliable data collection scheme, REISCH adopts the following security requirements:

- **Information confidentiality:** This requirement is achieved to hide *SNs*/patients' identities and to protect patients' secrecy from disclosure by intruders.
- **Data integrity:** This is to protect the patient data from intruders' tampering. The collected data should arrive at the intended target without alteration to provide a reliable communication channel between the *SNs*, *CHs*, *LS* and *CS* (Al-Zubaidie et al. 2019c)
- **Non-repudiation:** This is to prove that the message is sent by a particular *SN* in the HWSN. If a legitimate entity in HWSN performs internal attacks,

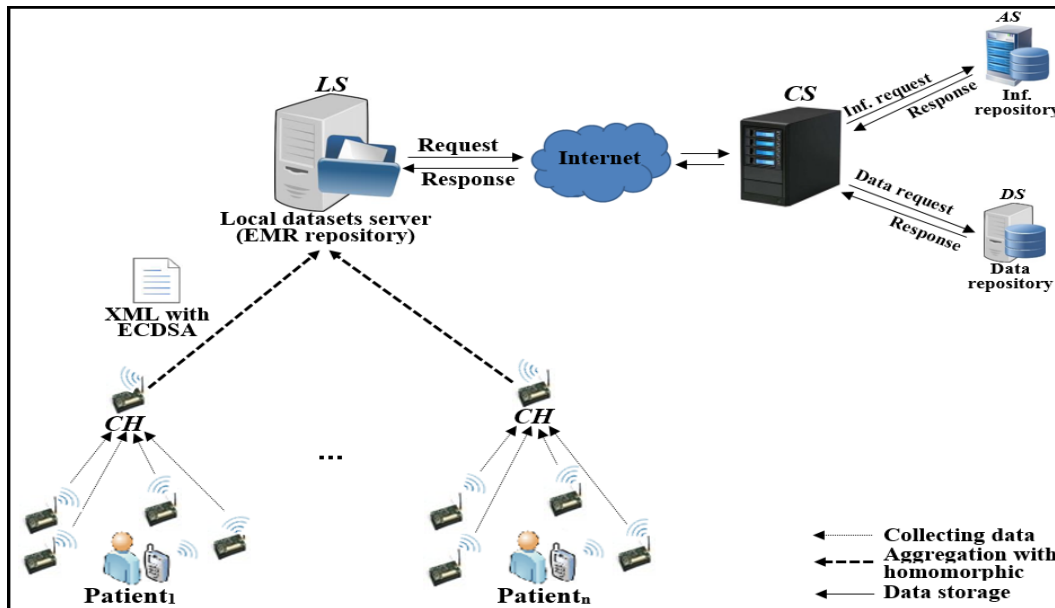


Figure 4.1: General REISCH model

he/she cannot deny his/her messages while using the privileges granted to him/her

- **Freshness:** It indicates that the data collection message is new and updated to guarantee that the intruder cannot replay the previous message at a later time. This goal is accomplished by a checking of time, a random passcode, and random signatures within each data collection round to counteract spoofing risks such as replay, MITM, and impersonation
- **Security of Localisation:** This feature ensures that the patient/sensor's real location is protected from detection, or sends error messages to the *LS* by an intruder
- **Scalability:** HWSN applications elaborate in a scalable environment in both data and devices. Thus, these applications need data collection schemes capable of processing and adapting to the ever-increasing number of devices of the HWSN. This feature indicates the ability of the data collection scheme to properly handle huge HWSN devices. Public key signature schemes are ideal for providing this requirement (Kumar et al. 2016)
- **Survivability:** It provides a certain level of services in patient data collection or network capability to withstand failure/threats in an appropriate manner and continue to provide services between the *SNs* and *LS* for as long as possible
- **Accountability:** This property means tracking the behaviour of malicious

threats/suspicious activities by legitimate users/counterfeiting attacks in accessing the EMR repository

- **Efficiency:** HWSN sources such as energy, storage, and processor should be within the design objectives of security protocols in HWSN.

### 4.3 REISCH's Scheme

In this subsection, we will explain REISCH details in terms of entities preparation, using ECDSA-BLAKE2bp, applying a camouflage signature, implementing homomorphic and REISCH protocols.

#### 4.3.1 Entities Preparation

To start collection and storage processes, it should prepare the HWSN network with the following points:

- Each sensor ( $SN_i$ ) and  $LS$  server is provided  $SN_i$  pseudonym ( $SN_{Pseud}$ ),  $SN_i$  pseudonym signature ( $SigLS_i(SN_{Pseud})$ ) and  $SN_i$  location ( $SN_{SL}$ )
- All entities ( $SN_i$ ,  $CH_i$ ,  $LS$  and  $CS$ ) generate  $K_{pu_i}$  and  $K_{pr_i}$  to apply asymmetric cryptographic
- Each entity broadcasts  $K_{pu_i}$  to network members
- Each  $SN_i$  uses ECDSA signatures ( $SigSN$  and  $SigCH$ ) to achieve collected data integrity
- Each server ( $LS$  and  $CS$ ) uses ECDSA signatures ( $SigLS$  and  $SigCS$ ) to achieve storage data integrity.

#### 4.3.2 Integrity of EMR being Transmitted

For the integrity of patient records being transmitted between the HWSNs and the  $LS$ , the REISCH signs all EMR/EHR records using the ECDSA algorithm, in which its hash function will be BLAKE2bp, rather than the traditional SHA1. In REISCH, we used ECDSA-BLAKE2bp to ensure data integrity as well as adding  $SN_{Pseud}$  within  $SigSN$  to prevent changing data. The  $LS$  and  $CS$  accept only a valid signature after verification. The high performance and security of the ECDSA-BLAKE2bp algorithm makes it an appropriate choice for protecting EMR health records. Also, using ECDSA-BLAKE2bp with XML adds the feature of medical records management in HWSN.

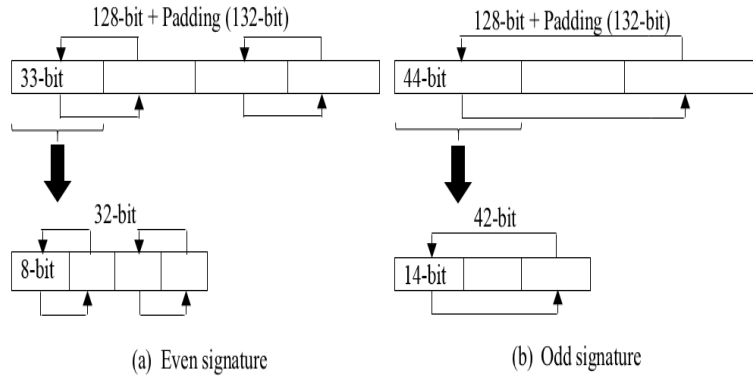


Figure 4.2: Camouflage signature

### 4.3.3 Applying Camouflage Signature

REISCH uses the camouflage process to hide the data signature completely and prevent traceability, analysis or alteration of data. The camouflage process starts by signing the data to obtain a 64-bit MD and then adding a 64-bit counterfeit signature to a total length of 64-bit + 64-bit = 128-bit. In addition, each  $SN_i$  adds padding (0000) to become the total length of the 132-bit signature as shown in Figure 4.2.  $SN_i$  performs the process of exchanging data signature segments based on Parity (even / odd) value. It receives this value invisibly from the  $LS$  because this value is included in the ephemeral random value ( $SigLsE_i$ ).  $SN_i$  tests  $SigLsE_i$ , if "even" it divides 132-bit into four segments (each segment to 33-bit) and exchanges the segments. Then,  $SN_i$  truncates 32-bit from the first segment and divides it into four segments (each segment to 8-bit). If  $SigLsE_i$  is "odd", it divides 132-bit into three segments (each segment to 44-bit) and then exchanges the segments. It then truncates 42-bit and divides the first segment into three segments (each segment to 14-bit). Because the exchanging operation is based on Parity sent from the  $LS$ , this process prevents the detection of the original signature of the data and prevents the data from being changed. Thus, this process protects patient data from tampering or alteration.

### 4.3.4 Implementing Homomorphic

REISCH uses the homomorphic property with the ECDSA-BLAKE2bp algorithm to increase network performance. Because the verification process in ECDSA consumes more time and processing than the signature process, it is very convenient to use the homomorphic property in HWSN to support both performance and security. The LEACH protocol is based on the principle of clustering to reduce energy consumption, thus REISCH uses the aggregate signature to allow  $CH_i$  to aggregate signatures and data without using verification. To double security in REISCH,  $CH_i$

performs the process of aggregating temporary signatures such as  $SigSnT_{3s}$  and  $SigSnT_{4s}$  in addition to random numbers ( $SN_{RN_s}$ ) and data. Temporary signatures contain unclear original signatures that prevent an intruder from penetrating patient data. The homomorphic procedure reduces energy consumption and thus increases the possibility of using the ECDSA algorithm with the HWSN for as long as possible.

### 4.3.5 REISCH's Protocols

REISCH scheme consists of three protocols. During these protocols, REISCH provides reliable data collection processes to protect collected patients' data.

- **Protocol 1 between  $SNs$  and  $CHs$**

This protocol performs the data collection process (Figure 4.3 shows the first protocol processes between  $SN_i$  and  $CH_i$  in the data collection). At the beginning of each round, each  $SN_i$  receives a one-time passcode ( $LS_{OTP_i}$ ) and a random number ( $SN_{RN_i}$ ). This  $LS_{OTP_i}$  contains an ephemeral random value ( $SigLsE_i$ ) of the same length as the signature.  $SN_i$  extracts  $SigLS_i(SN_{Pseud})$  from the dataset and executes  $\oplus$  to extract the secret value  $SigLsE_i$ . Then,  $SN_i$  executes the *Parity* (as shown in Section 4.3.3) process based on  $SigLsE_i$  to get the temporary signature ( $SigSnT_1$ ). After that,  $SN_i$  generates an ephemeral random value ( $SigSnE_i$ ) with the same signature length and uses it with  $SigSnT_1$  to compute the  $SigSnT_2$  value. Next,  $SN_i$  computes the *Dif* value that represents the subtraction value of the distance between  $CH_i$  and  $SN_i$  ( $SN_{CHD}$ ) and the distance between  $LS$  and  $SN_i$  ( $SN_{LSD}$ ). *Dif* specifies that  $SN_i$  is within the HWSN framework (1000m  $\times$  1000m). Additionally,  $SN_i$  computes a new timestamp ( $SN_{TS}$ ) and one time passcode ( $SN_{OTP}$ ). Thereafter,  $SN_i$  performs a hidden process for  $SN_{TS}$  and  $SN_{OTP}$  at a temporary value ( $SN_{TS_t}$ ) with the addition of a value of only seconds ( $SS$ ) at the end of the  $SN_{TS_t}$ . Furthermore,  $SN_i$  uses  $SN_P$  to concatenate secret parameters such as  $SN_{TS_t}$ ,  $SN_{OTP}$ ,  $SN_{RN_i}$ ,  $SN_{Pseud}$  and  $SN_{SL}$  to match them at the  $LS$ . To protect both  $SN_P$  and  $SigSnE_i$ ,  $SN_i$  uses the  $\oplus$  operation to hide them by calculating the temporary values of  $SigSnT_3$  and  $SigSnT_4$ . At this point,  $SN_i$  computes the message ( $SN_m$ ) and sends it to  $CH_i$  which is a sequence of  $SigSnT_3$ ,  $SigSnT_4$ ,  $SN_{RN_i}$ , *Dif*,  $SN_{TS_t}$  and data collection.

In the  $CH_i$  side, it also receives  $LS_{OTP_i}$  of the  $LS$  and  $SN_m$  of  $SN_i$ . Afterwards,  $CH_i$  truncates *Dif<sub>i</sub>* and tests its value within the HWSN framework by computation  $Dif_i \leq \text{Maximum value}$ , where the Maximum value should be less than or equal to 707.1068. Then,  $CH_i$  computes the timestamp ( $CH_{TS_1}$ )

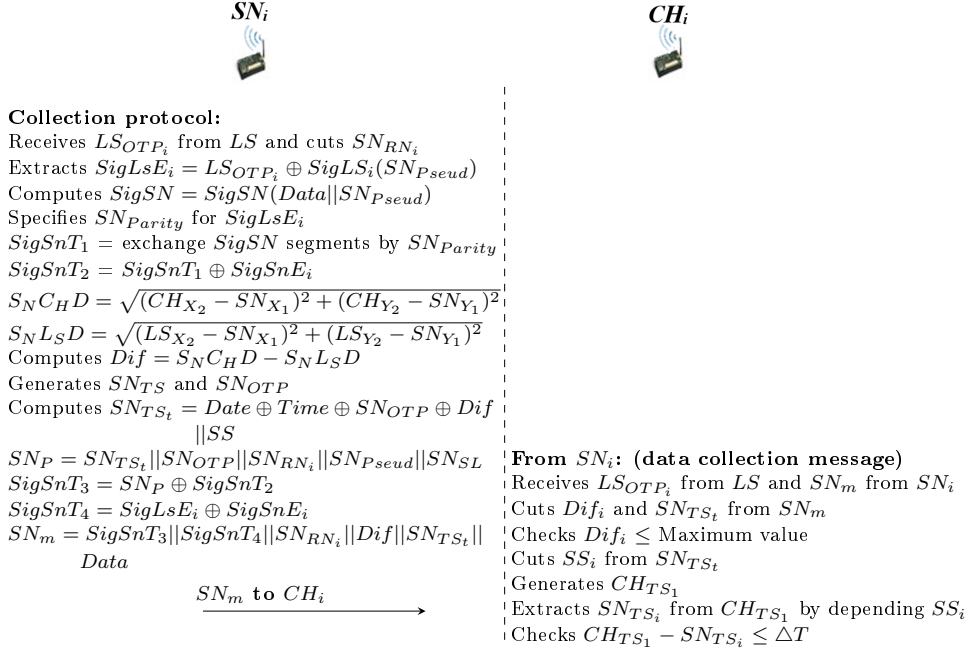


Figure 4.3: Data collection protocol

to prevent late messages.  $CH_i$  truncates  $SS$  from  $SN_{TS_t}$  to obtain  $SN_{TS_i}$ . If the difference between  $CH_{TS_1}$  and  $SN_{TS_i}$  is less than the  $\Delta T$  delay rate (we assumed that  $\Delta T = 3$ ), namely, that the message is fresh.

- **Protocol 2 between CHs and LS**

This protocol performs the data aggregation process (Figure 4.4 shows the second protocol processes between the  $CH_i$  and  $LS$  in the data aggregation). Each  $CH_i$  receives temporary signatures, random numbers and collected data from its  $SN_i$  followers. Then,  $CH_i$  executes the signature process  $SigCH$  for the temporary signatures received ( $SigSnT_{3_s}$ ) from its  $SN_i$  followers. Thereafter,  $CH_i$  extracts the  $SigLsE_i$  unique value from  $LS_{OTP_i}$  similar to the first protocol based on  $SigLS_i(CH_{Pseud})$  stored. Next,  $CH_i$  performs the  $CH_{Parity}$  process based on  $SigLsE_i$  extracted (as described in Section 4.3.3) to compute  $SigChT_1$ . Moreover,  $CH_i$  computes  $SigChT_2$  depending on the  $SigChT_1 \oplus SigLsE_i$  operation. After that,  $CH_i$  generates  $CH_{TS_2}$  and  $CH_{OTP}$  to prevent the problem of replaying messages later.  $CH_i$  calculates  $CH_P$  which represents the sequence of secret parameters. Also,  $CH_i$  computes  $CH_A$  to complete the process of aggregating temporary signatures ( $SigSnT_{3_s}$  and  $SigSnT_{4_s}$ ), random numbers ( $SN_{RN_s}$ ) and collected data ( $Data_s$ ). Finally,  $CH_i$  computes  $CH_m$  and sends it to the  $LS$ .

In the  $LS$  side, after the  $LS$  sends  $LS_{OTP_i}$  for all  $SN_i$ , it waits to receive  $CH_m$  of all  $CH_i$  per round. The  $LS$  truncates  $CH_{RN_i}$ ,  $SS_i$  and  $CH_A$  from



each  $CH_m$  received. It uses  $SS_i$  to reconfigure  $CH_{TS_2}$ , the  $LS$  also generates a timestamp ( $LS_{TS_1}$ ) and tests  $\Delta T$  between  $LS_{TS_1}$  and  $CH_{TS_2}$  to confirm the freshness of the message. Then, it tests whether  $CH_{RN_i}$  matches the value previously sent. If  $CH_{RN_i}$  is correct, it is used to determine  $CH_{Pseud_i}$  and the latter is used to determine  $CH_i$  location ( $CH_{SL_i}$ ). Then, the  $LS$  retrieves the temporary signatures and random numbers ( $SigSnT_{3_s}$ ,  $SigSnT_{4_s}$  and  $SN_{RN_s}$ ) from  $CH_A$ . The  $LS$  uses the  $SigLsE_i$  value to specify a *Parity* (even/odd) value for all  $SN_i$  and  $CH_i$ . It computes a signature ( $SigLS_{1_i}$ ) for all  $SN_i$  signatures that followed a specific  $CH_i$  ( $SigSnT_{3_s}$ ) and exchanges the  $SigLS_{1_i}$  segments based on  $CH_{Parity}$ . After that, the  $LS$  calculates  $SigLsT_{1_i}$  which equals  $SigChT_2$  in  $CH_i$  based on  $SigLS_{1_i} \oplus SigLsE_i$ . To ensure the legitimacy of  $CH_i$ , the  $LS$  extracts the secret parameters at  $CH_{P_i}$  and tests the match  $CH_{Pseud_i}$  and  $CH_{SL_i}$  in the datasets. At this point, the  $LS$  checks for data integrity collected by  $SN_i$ . Similarly, the  $LS$  uses  $SN_{RN_i}$  to determine  $SN_{Pseud_i}$ , and performs data signature ( $SigLS_{2_i}$ ) that equals the  $SigSN$  in  $SN_i$  and exchanges the  $SigLS_{2_i}$  segments based on  $SN_{Parity_i}$ . Next, the  $LS$  uses  $SigSnT_{4_i}$  and  $SigLsE_i$  to extract  $SigSnE_i$ . Thereafter, the  $LS$  uses  $SigSnT_{3_i}$  and  $SigSnE_i$  to compute  $SigLsT_{2_i}$ . Finally, the  $LS$  extracts the secret parameters for  $SN_i$  from  $SN_{P_i}$  and tests matching  $SN_{Pseud_i}$  and  $SN_{SL_i}$  in datasets. If all signatures and parameters are validated correctly, then the data collected by  $SN_i$  is legitimate and correct, and has not been tampered with by the intruder.

- **Protocol 3 between  $LS$  and  $CS$**

This protocol performs the data storage process (Figure 4.5 shows the third protocol processes between the  $LS$  and  $CS$  in the data storage). Initially, the  $LS$  generates a new pseudonym ( $LS_{Pseud_n}$ ) and timestamp ( $LS_{TS_2}$ ) to prepare for the process of sending data to the  $CS$ . Then, the  $LS$  computes the  $SigLS$  signature based on the  $CS$ 's old pseudonym ( $CS_{Pseud_o}$ ). After that, the  $LS$  generates and sends  $LS_{OTP}$  to the  $CS$ , which is based on the  $SigLS$ ,  $LS_{Pseud_n}$ ,  $LS_{TS_2}$  as well as append  $SS$  at the end of  $LS_{OTP}$ .

On the  $CS$  side, it generates  $CS_{TS_1}$ ,  $CS_{Pseud_n}$ ,  $CS_{OTP}$  and  $CS_{RN}$ .  $CS$  uses  $CS_{TS_1}$  to test the message arrival time of the  $LS$ . Depending on generated secret parameters, such as  $CS_{OTP}$ , the  $CS$  computes  $CsT_1$  and  $CsT_2$  temporarily. In addition, the  $CS$  generates a  $SigCS$  signature that includes the temporary value ( $CsT_2$ ). At this point, the  $CS$  computes and sends  $CS_m$  to  $LS$  containing the sequence of parameters such as  $SigCS$ ,  $CsT_1$ ,  $CsT_2$ ,  $SS$  and  $CS_{RN}$ .

On the  $LS$  side, it truncates parameters embedded within  $CS_m$ . Thereafter,



Figure 4.4: Data aggregation protocol

the  $LS$  generates  $LS_{TS_3}$  to check the arrival time of  $CS_m$ . Furthermore, the  $LS$  computes  $CS_{OTP}$  that relying mainly on  $LS_{Pseud_n}$ . Afterwards, the  $LS$  extracts  $CS_{Pseud_n}$  to calculate  $SigLS_3$ . The  $LS$  tests matching  $SigLS_3$  and  $SigCS$ , and if the result is identical, this means that the mutual authentication process between the  $LS$  and  $CS$  is performed correctly and legitimately. After this stage, the  $LS$  prepares the data storage request to  $CS$ . First, the  $LS$  generates  $LS_{TS_4}$  and  $LS_{RN}$  to ensure randomness and freshness. After that, the  $LS$  computes the  $SigLS_4$  signature that depends on the  $LsT_1$  temporary parameters. Then, the  $LS$  computes the  $SigLS_5$  data signature that depends on temporary parameters such as  $LsT_2$ ,  $LsT_3$ , and  $SigLS_4$  as well as the  $Data$ . Finally, the  $LS$  sends  $LS_m$  which includes  $SigLS_5$ ,  $SS$ ,  $LS_{RN}$  and  $Data$  to  $CS$ .

On the  $CS$  side, it receives  $LS_m$  of  $LS$ . The  $CS$  generates  $CS_{TS_2}$  new to test access time  $LS_m$ . The  $CS$  calculates  $SigCS_1$  and  $SigCS_2$  similarly to  $SigLS_4$  and  $SigLS_5$  respectively. At this point,  $CS$  checks matching  $SigCS_2$  and  $SigLS_5$ , and if the result is identical, it means that the  $CS$  received patients' data from the  $LS$  correctly and integrated it without any changes by malicious attacks.

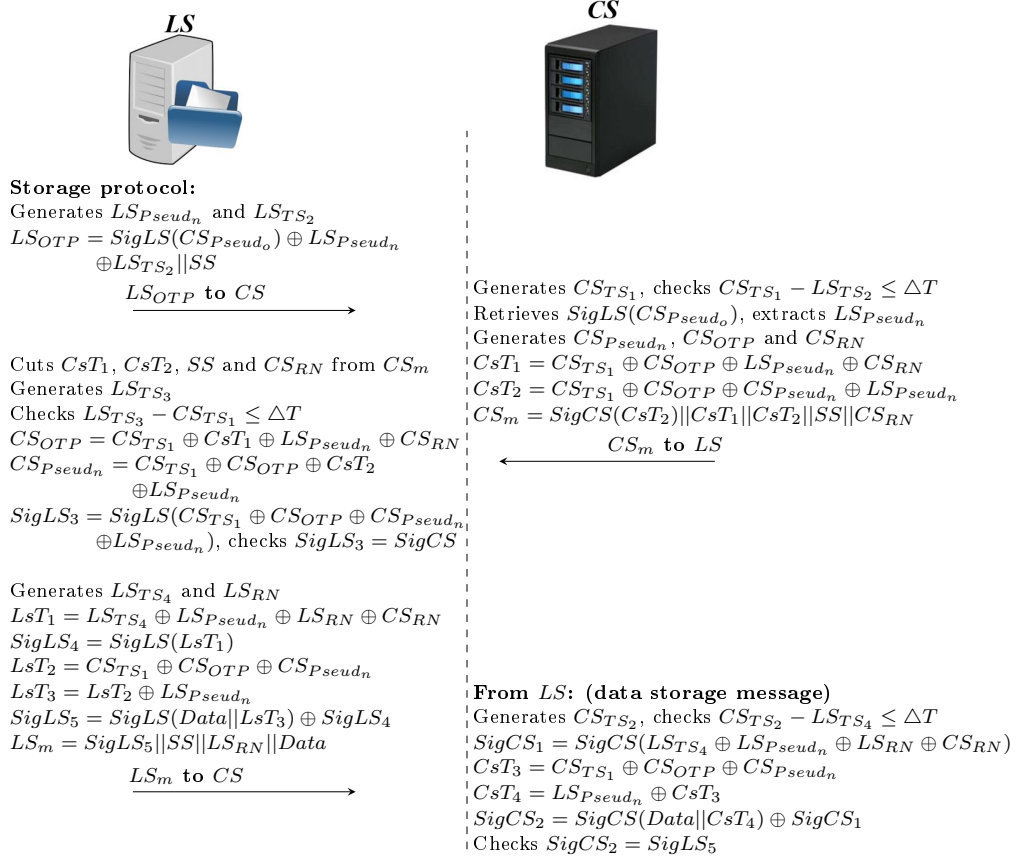


Figure 4.5: Data storage protocol

## 4.4 Summary of the Chapter

In this chapter, we have provided details of the security of data collection and our contributions to build a new data collection scheme. After that, a network model for the data collection scheme explains the general structure for securely storing patient data in the EMR repository. Finally, the data collection scheme methodology has been explained in detail.



# Chapter 5: Robust Security to Authenticate Users Identity to the EHR Repository

In the preceding chapters, we identified the limitations and/necessary improvements to existing HC applications. Chapter 4 proposed a solution integrating WSN technology with EMR repository in a HC application. From this chapter on, we will explore the security strategy developed for the proposed HC application. This chapter describes an authentication scheme developed to protect user/network information.

## 5.1 Information Security in EHR Systems

As we know, user information (personal such as name and network such as password) defines and proves user legitimacy in EHR systems. This information requires a procedure to prevent disclosure of users' secrets while at the same time proving their legitimacy in the network. Authentication is the most critical security requirement that plays a key role in building correct security before the exchange of patient data in EHR (Das et al. 2017, Li et al. 2016, Rajput, Abbas, Wang, Eun & Oh 2016, Al-Zubaidie et al. 2021). First, it reduces malicious or fatal errors caused by penetration attacks on the authentication information. Second, it alleviates errors in specifying drug, dose, timing, or procedure (Yuehong et al. 2016). Therefore, access to these data should be controlled to prevent unauthenticated access. As a result, authentication protocols are a critical requirement to repel various attacks.

Typically, the server application should prevent all fake and illegal authentication requests. It should protect personal information, health records, and physiological

parameters (such as sugar, and heart rate) (Wazid et al. 2016). However, authentication information may be easier to compromise if EHR data and information are stored on a single server. Furthermore, the transfer of authentication information in an insecure environment (WLAN or Internet), may expose patients' data for detection or modification (Li et al. 2016, Shrestha et al. 2016).

Unfortunately, traditional cryptography (such as RSA) and signature (such as SHA1) schemes require complex computations that consume server resources, such as processing power and memory, when used with EHR systems that may deal with large amounts of health data and thus, render them unusable. The electronic signature is an important way to check the integrity of user information in the authentication request (Giri et al. 2015). Many algorithms, especially lightweight algorithms, such as PHOTON, QUARK, and SPONGENT, are used to implement signature algorithms that perform lightweight operations to reduce high overheads on servers. HC applications require high-speed cryptography and signature, and secure algorithms (Liu & Chung 2017). There is a misconception about using a symmetric encryption algorithm instead of public encryption algorithms. Using symmetric encryption instead of asymmetric encryption, where symmetric is faster but sacrifices security. Recent research has proved that using asymmetric encryption is better because it provides strong security and supports applicability in large systems (Farash et al. 2016). In addition, symmetric encryption algorithms have problems with scalability and single secret key detection. To implement an authentication scheme, many algorithms, such as ECC, RSA, hash function, bilinear pairing, fuzzy extractor, and XOR operation (Chandrakar & Om 2017), are used to design HC projects. Many recent HC applications are based on ECC and RSA; both of which provide the same security level, although ECC is more efficient than RSA. The design of an authentication scheme in HC applications should provide mutual authentication, resistance to known attacks such as MITM, eavesdropping, tracing, replay, impersonation, guessing, DoS, protection of information and reduced cost and high-efficiency (Yeh 2016, Shankar et al. 2015).

### **5.1.1 A Robust Model of Authentication for the Proposed HC Application**

We propose a **Robust Authentication Model for Healthcare Users (RAMHU)** that uses lightweight algorithms and security techniques for HC applications that perform massive and continuous authentication processes while simultaneously protecting against various attacks. Our contributions to this scheme are summarised as follows:

- RAMHU uses lightweight algorithms for encryption (ECIES) and signature

(PHOTON). These algorithms provide efficient and secure authentication for users in HC applications compared to other algorithms

- RAMHU applies an OTP mechanism to authenticate users in their first registration in the HC network with timestamp verification and random nonce generation to repel different types of external attacks
- RAMHU uses a multi pseudonyms mechanism to prevent any association between the real information, pseudonyms, and user data. This mechanism prevents attackers from identifying HC users (providers and patients)
- RAMHU integrates the login request with the MAC address in addition to verifying that this address is original and not fake for authentication of legitimate devices. This prevents attackers from using different devices to compromise the network information
- RAMHU improves the mutual authentication between the server and clients to prevent spoofing and impersonation attacks by either fake server or client. This prevents external attacks intended to deceive trusted parties.

## 5.2 The Proposed Authentication Scheme

In this section, we will detail our authentication scheme that provides security and efficiency features in HC applications. This section is divided into the network model, model goals and proposed authentication scheme protocols.

### 5.2.1 Network Model

The RAMHU model consists of four entities as shown in Figure 5.1:

1. Client ( $C_i$ ) or user: This entity includes patients, relatives of patients, and HC providers such as doctors, researchers, emergency practitioners, advisors, and nurses
2. Central server ( $CS$ ): This entity is a gateway to authenticate users with the attributes server and to authorise the data server
3. Attributes server ( $AS$ ): This entity contains real user information as well as multi pseudonyms. The authentication process requires verifying the association of the actual information with the multi pseudonyms in this entity
4. Data server ( $DS$ ): This entity contains user data as well as multi pseudonyms. This entity is not implemented in our authentication scheme. Our scheme focuses only on the process of user authentication in the HC network.

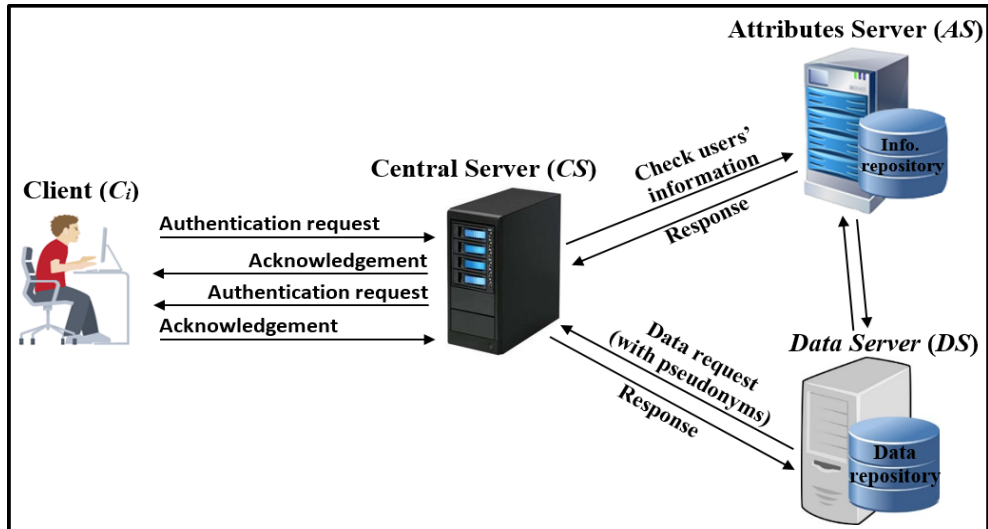


Figure 5.1: General network model

Generally,  $C_i$  creates an authentication request mainly based on ECIES and PHOTON.  $C_i$  sends a request to the  $CS$  to verify encryption, signature, and security parameters (such as MAC address, pseudonyms, and  $OTP_i$ ). Then, the  $CS$  sends a request to the  $AS$  to verify the link between the pseudonyms, the real information, the signatures, and  $PW_i$ . After that, the  $AS$  sends the response to the  $CS$  that verifies the signature and the parameters and then the  $CS$  sends the response (authenticated or not) to the  $C_i$ . If the user is authenticated, the user can then send an authorisation request to access the data in the repository ( $DS$ ) and obtain the authorisation response from the  $CS$ ,  $AS$ , and  $DS$ . Our authorisation protocols will be detailed in Chapter 6.

### 5.2.2 Design Goals of RAMHU

To build a robust authentication scheme, RAMHU must meet the following security requirements:

- **Confidentiality:** This requirement is performed to hide authentication information and to preserve user secrecy from detection by intruders. To fulfil this requirement, a high-security cryptographic algorithm (Al-Janabi et al. 2017) should be used. RAMHU executes ECIES to hide authentication information from intruders
- **Integrity:** This protects the authentication request information from modification by intruders. The authentication request should reach the intended destination without modification to provide a reliable communication channel for legitimate users (Rajput, Abbas & Oh 2016). RAMHU performs



a PHOTON to prevent any process of altering or modifying the user authentication information in HC applications

- **Non-repudiation:** This requirement prevents both clients and server from denying their authentication requests. This is a way to prove that the message is sent by a particular sender in the HC applications network. If a legitimate user in the network performs internal attacks, he/she cannot deny his/her activities while exploiting the privileges granted to him/her. Our scheme uses PHOTON signatures and a MAC address to meet this requirement and detect malicious attacks
- **Anonymity:** This requirement is extremely important in supporting the confidentiality of the authentication request. The purpose of this requirement is to disguise the source and destination of the authentication request. If the authentication scheme applies anonymity with encryption, the attacker finds it exceedingly difficult to analyse authentication requests for a particular user at different times because the authentication request is different each time the user is connected to the network (Rajput, Abbas, Wang, Eun & Oh 2016). RAMHU applies this requirement through the use of random nonces among entities
- **Pseudonym:** This requirement denotes the provision of a mechanism to connect non-real attributes (such as terms and symbols) with the real attributes of the user (such as name, address, and phone number). The use of this mechanism in HC applications is an extremely important way of protecting the personal information of users and prevent the detection of their identities. RAMHU uses a multi pseudonyms mechanism to prevent and separate association with real information
- **Forward secrecy:** This requirement is accomplished when network users use new keys and parameters temporarily without relying on old ones. This requirement prevents attackers from exploiting users' keys and passwords in decrypting authentication requests. Using the temporary random password, private key, and MAC, RAMHU prevents users from accessing previous authentication information
- **Mutual authentication:** This requirement is used in healthcare applications to mitigate the risks of external fraud. With this feature, each party ensures that it deals with a legitimate party. The server authenticates the client by checking encryptions and signatures and vice versa to establish a secure communication channel. In RAMHU,  $CS$  and  $C_i$  authenticate each other to prevent masquerading and impersonating attacks

- **Scalability:** HC applications operate in a scalable environment in terms of data and users. Therefore, these applications require authentication schemes capable of handling and adapting to the ever-increasing number of users of HC applications. This requirement refers to the ability of the authentication scheme to appropriately handle large HC systems. Public key encryption schemes are efficient in supporting this requirement (Kumar et al. 2016)
- **Freshness:** This requirement indicates that the authentication request is new; updated to ensure that the attacker cannot replay the authentication request at a later time. This requirement is achieved through the provision of time checking, a random nonce, and change of signatures in each authentication process to counteract counterfeit attacks, such as MITM, replay, and impersonation (Al-Janabi et al. 2017), which ensures that the authentication request is unaltered or not tampered with.

### 5.2.3 Proposed Protocols for the Authentication Scheme

The RAMHU scheme consists of five protocols: initial setup, registration/login, authentication, password update, and revocation. During these protocols, RAMHU provides reliable authentication processes to protect users' information.

- **Initial Setup Protocol**

In this protocol, all entities are ready to start communicating with each other while configuring all security parameters and ECIES's keys with the following steps:

- Each legitimate user receives a client application from the authorised system provider
- Each legitimate user receives a password (that can be changed later) and a random  $OTP_i$  to be used in the first registration
- All entities ( $C_i$ ,  $CS$ , and  $AS$ ) should create public and private keys ( $C_i$  ( $CK_{pu_i}$ ,  $CK_{pr_i}$ ),  $CS$  ( $CSK_{pu_i}$ ,  $CSK_{pr_i}$ ), and  $AS$  ( $ASK_{pu_i}$ ,  $ASK_{pr_i}$ )) to be used to validate the authentication request. All entities choose an elliptic curve  $Ep(a, b)$  over a prime field  $F_P$  (where,  $P = 256$ ) and base point  $G$  on the curve. Each entity selects a private key  $K_{pr_i}$  randomly and generates the public key  $K_{pu_i}$  during the implementation of scalar multiplication ( $K_{pu_i} = K_{pr_i} * G$ )
- All entities broadcast public key ( $CK_{pu_i}$ ,  $CSK_{pu_i}$ , and  $ASK_{pu_i}$ ) to use in ECIES's encryption operations.

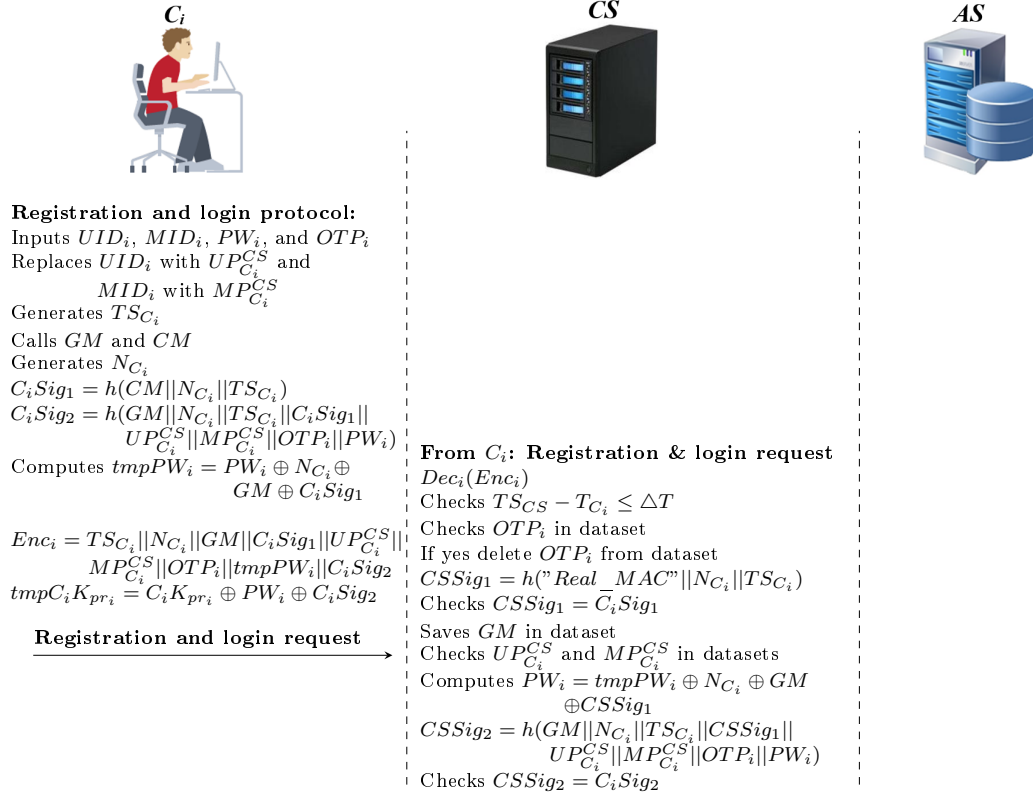


Figure 5.2: Registration and login protocol

### • Registration and Login Protocol

Patients and healthcare providers ( $C_i$ ) should complete the registration and login protocol with  $CS$  to become legitimate users of HC applications. Without this protocol, the user cannot complete the authentication process in RAMHU. User registration is performed once, namely, the user does not need to complete the registration protocol subsequently (only the login protocol), the registration information is kept in the servers until the revocation protocol and deletion of user security parameters, such as pseudonyms, MAC address and  $PW_i$ . This protocol accomplishes the following steps (Figure 5.2 shows registration and login protocol, and Figure 5.3 shows login protocol):

$C_i$  side:

- The user enters  $UID_i$  (such as his/her name),  $MID_i$  (such as medical centre name),  $PW_i$  and  $OTP_i$  for registration and login while only entering  $UID_i$ ,  $MID_i$ , and  $PW_i$  for the login protocol at subsequent logins to the client ( $C_i$ ) application.  $C_i$  replaces  $UID_i$  with user's pseudonym ( $UP_{C_i}^{CS}$ ), and  $MID_i$  with medical centre pseudonym ( $MP_{C_i}^{CS}$ ) to protect the authentication information when moving from  $C_i$  to  $CS$ .  $C_i$  generates timestamp ( $TS_{C_i}$ ) to be used to verify the sending time of the authentication request in the  $CS$

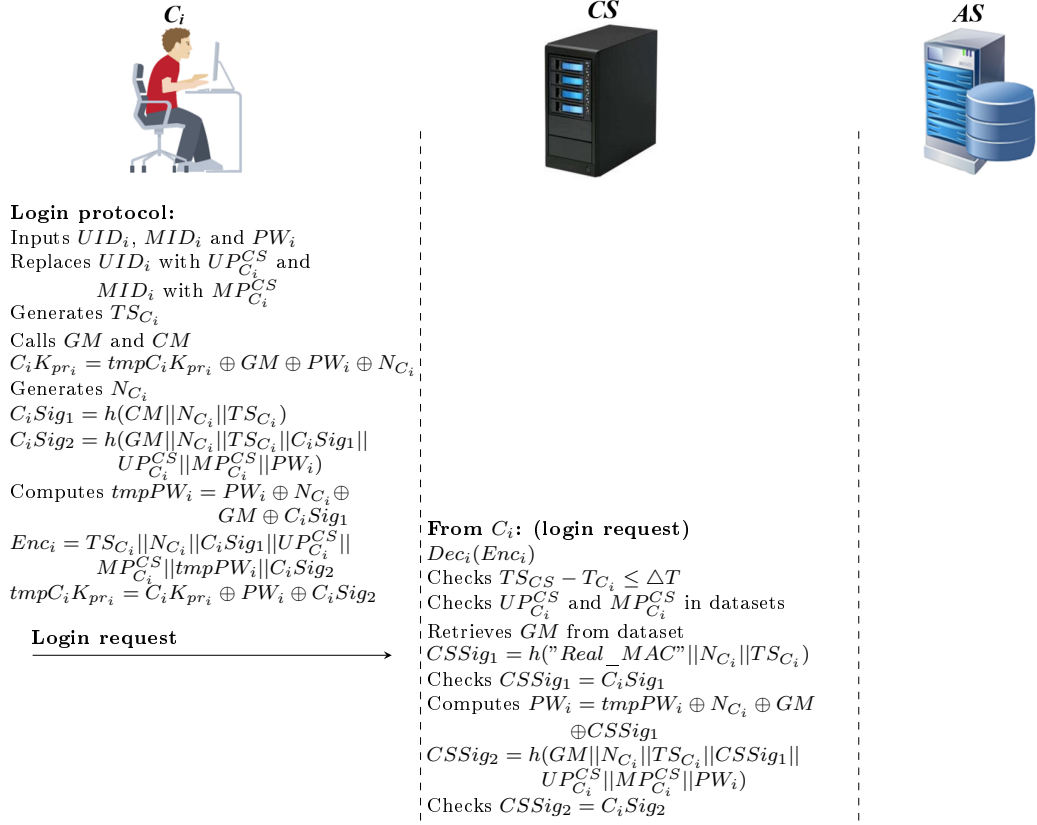


Figure 5.3: Login protocol

- $C_i$  gets a MAC address ( $GM$ ) by entering its IP (Internet protocol) address. The process of checking MAC ( $CM$ ) is performed by  $C_i$  to test the credibility of the MAC address. In the Linux system, we used the command "ethtool -P interface name" (such as "ethtool -P wlo1") in the  $C_i$  application. If the result is identical to  $GM$ , it means that the MAC address is native ( $CM = "Real\_MAC"$ ). In the Windows system,  $C_i$  searches for string value "NetworkAddress" in the path of the system registry " $HKEY\_LOCAL\_MACHINE \setminus SYSTEM \setminus CurrentControlSet \setminus Control \setminus Class \setminus \{4D36E972 - E325 - 11CE - BFC1 - 08002BE10318\}$ " (as shown in Figure 5.4). If NetworkAddress = null,  $CM = "Real\_MAC"$ ; otherwise  $CM = "Fake\_MAC"$ . The  $GM$  sent is encrypted with an authentication request while  $CM$  is implicitly sent with the signature value ( $C_iSig_1$ ). If only login protocol,  $C_i$  needs to extract the private key from the temporary key, MAC address, password, and random nonce through  $tmpC_iK_{pr_i} \oplus GM \oplus PW_i \oplus N_{C_i}$ .  $C_i$  generates a random nonce ( $N_{C_i}$ ) to change signature and encryption data and add anonymity to the authentication request
- $C_i$  performs two signatures using the PHOTON-256 algorithm to protect information from modification. The first signature

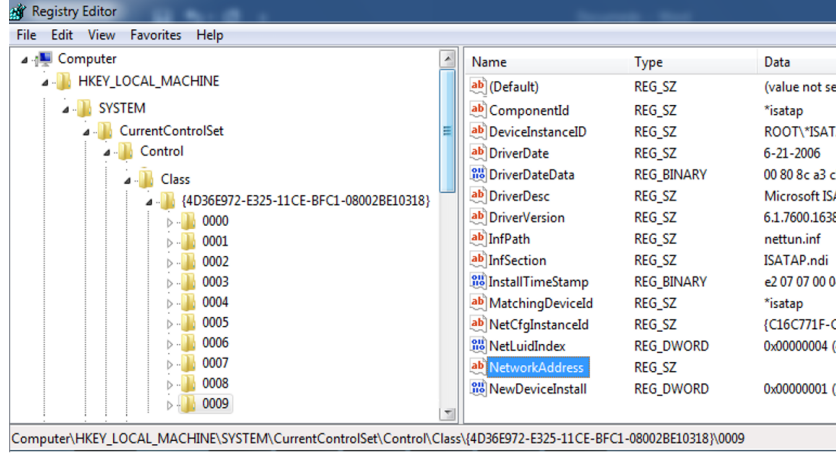


Figure 5.4: NetworkAddress path in system registry

includes the parameters check MAC, nonce, and timestamp ( $CiSig_1 = h(CM\|N_{C_i}\|TS_{C_i})$ ). The second signature includes all the authentication parameters of the get MAC, nonce, timestamp, first signature, pseudonyms, one time password, and password ( $CiSig_2 = h(GM\|N_{C_i}\|TS_{C_i}\|CiSig_1\|UP_{C_i}^{CS}\|MP_{C_i}^{CS}\|OTP\|PW_i)$ ). In the login protocol,  $OTP$  is not added to the signature

- $C_i$  computes a temporary value ( $tmpPW_i = PW_i \oplus N_{C_i} \oplus GM \oplus CiSig_1$ ) of  $PW_i$  when moving from  $C_i$  to  $CS$
- $C_i$  uses ECIES to encrypt and hide all the data of this request ( $Enc_i = TS_{C_i}\|N_{C_i}\|GM\|CiSig_1\|UP_{C_i}^{CS}\|MP_{C_i}^{CS}\|OTP_i\|tmpPW_i\|CiSig_2$ ). In the login protocol,  $OTP_i$  and  $GM$  are not added to the encryption as in Figure 5.3. After that,  $C_i$  sends the registration and login request or login to  $CS$  to complete the authentication protocol. Then  $C_i$  hides the private key by  $tmpC_iK_{pr_i} = C_iK_{pr_i} \oplus PW_i \oplus CiSig_2$ .

$CS$  side:

- Upon receiving a registration and login request or login request,  $CS$  decrypts ( $Enc_i$ ) this request using ECIES's  $C_iK_{pu_i}$  and  $CSK_{pr_i}$ . It checks timestamp ( $TS_{CS} - TS_{C_i} \leq \Delta T$ ) to make sure that this request arrived at an appropriate time and without delay
- In the registration and login protocol, the  $CS$  examines the random  $OTP_i$  in the dataset. If  $OTP_i$  exists, the user is considered legitimate for the registration process. After that, the  $CS$  deletes  $OTP_i$  from the dataset to prevent it from being used at subsequent logins. If  $OTP_i$  is not found, it discards the connection. In the login protocol,  $CS$  examines the  $UP_{C_i}^{CS}$  and  $MP_{C_i}^{CS}$  and then tests their association with the MAC address in the

dataset. If  $GM$  is found, the  $CS$  completes the steps of this protocol; otherwise, it cancels the connection

- The  $CS$  needs to ensure that the user's device is legitimate within the network. The  $CS$  computes the signature value to make sure that the MAC address is native and non-modified ( $CSSig_1 = h("Real\_MAC" \| N_{C_i} \| TS_{C_i})$ ). It examines the result of the computed signature ( $CSSig_1$ ) with the  $C_i$  ( $C_iSig_1$ ) signature. If the result signatures are identical, then the device is legitimate and the MAC address did not change. In the registration and login protocol, the  $CS$  stores this address in dataset for use and checks the next times in the login protocol
- The  $CS$  performs the computation operation the  $tmpPW_i \oplus N_{C_i} \oplus GM \oplus CSSig_1$  to extract the  $PW_i$  value and then uses this value to produce a second signature ( $CSSig_2$ )
- The  $CS$  computes a second signature operation ( $CSSig_2 = h(GM \| N_{C_i} \| TS_{C_i} \| CSSig_1 \| UP_{C_i}^{CS} \| MP_{C_i}^{CS} \| OTP_i \| PW_i)$ ) to guarantee that all the encrypted information is not changed. Then, it compares the computed signature ( $CSSig_2$ ) with the received signature in the request ( $C_iSig_2$ ). If the signatures are identical, then the information for this request is unchanged or not tampered. In the login protocol,  $OTP_i$  and  $GM$  are not added to the signature. At this point, the  $CS$  prepares to send the user's authentication request to the  $AS$ .

- **Authentication Protocol**

In this protocol, RAMHU needs to link pseudonyms and passwords with real information for users in the  $AS$ 's datasets. Note that, the user information (such as name, age, address, mobile number, and passwords) are stored in a separate server ( $AS$ ) and multi pseudonyms are used to prevent detection and tracking of user information. This protocol is illustrated in the following steps (Figure 5.5 shows the authentication protocol in RAMHU):

$CS$  side:

- The  $CS$  computes a new timestamp ( $TS_{CS}$ ) to ensure the fresh authentication request
- The  $CS$  replaces  $C_i$ 's pseudonyms ( $UP_{C_i}^{CS}$  and  $MP_{C_i}^{CS}$ ) with  $CS$ 's pseudonyms ( $UP_{CS}^{AS}$  and  $MP_{CS}^{AS}$ ) to prevent attackers from tracking the authentication request. It generates random nonce ( $N_{CS}$ ) to ensure an anonymous authentication request

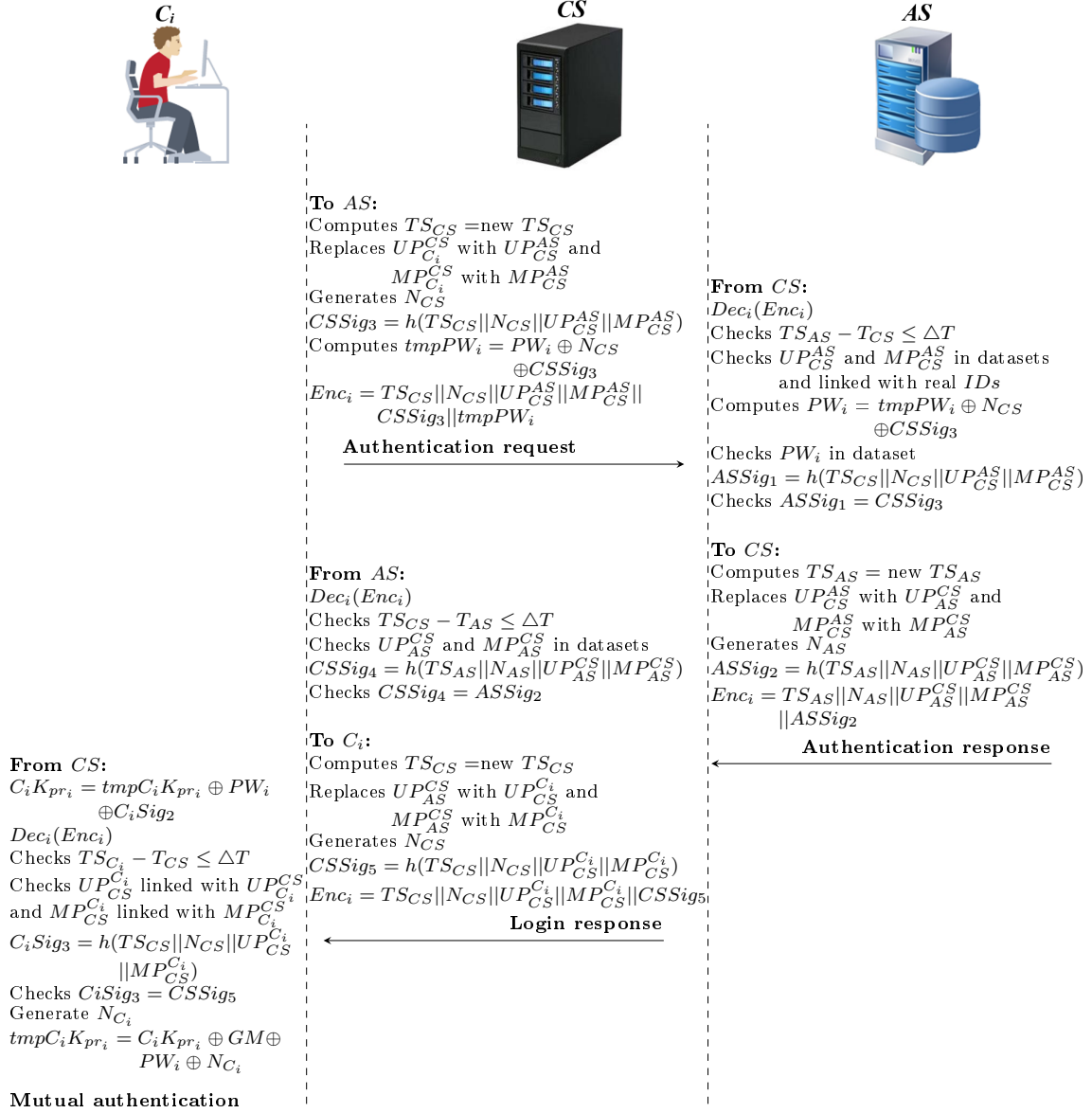


Figure 5.5: Authentication protocol

- The  $CS$  signs security parameters by PHOTON-256 ( $CSSig_3 = h(TS_{CS} || N_{CS} || UP_{CS}^{AS} || MP_{CS}^{AS})$ ) to prevent the modification of authentication request data
- The  $CS$  computes temporary  $PW_i$  by the computation of  $PW_i \oplus N_{CS} \oplus CSSig_3$
- The  $CS$  encrypts the authentication request information ( $Enc_i = TS_{CS} || N_{CS} || UP_{CS}^{AS} || MP_{CS}^{AS} || CSSig_3 || tmpPW_i$ ). It sends an authentication request to verify the user information in the  $AS$ .

$AS$  side:

- Upon receiving the authentication request, the  $AS$  decrypts that request

( $Enc_i$ ) using ECIES's  $ASK_{pr_i}$  and  $CSK_{pu_i}$  to obtain the authentication information clearly

- It checks the timestamp by ( $TS_{AS} - TS_{CS} \leq \Delta T$ ) to ensure that the authentication request is not delayed. The  $AS$  checks the pseudonyms ( $UP_{CS}^{AS}$  and  $MP_{CS}^{AS}$ ) sent from the  $CS$  and correlates it with the user's real identifier ( $UID_i$  and  $MID_i$ ) in the datasets. The  $AS$  extracts the user's password from the equation  $PW_i = tmpPW_i \oplus N_{CS} \oplus CSSig_3$ . After that, it checks matching  $PW_i$  in the dataset. The  $AS$  computes the value of the signature based on the authentication information ( $ASSig_1 = h(TS_{CS} || N_{CS} || UP_{CS}^{AS} || MP_{CS}^{AS})$ ) by PHOTON-256. The  $AS$  compares the computed value of the signature ( $ASSig_1$ ) with the value of the received signature ( $CSSig_3$ ). If the signature values are identical, the user information in the request for the signature is unmodified. At this point, the  $AS$  considers this user to be legitimate and reliable
- The  $AS$  prepares a response to authenticate the request of that user. It computes a new timestamp ( $TS_{AS} = \text{new } TS_{AS}$ ) to prevent delayed or replayed requests at later times. The  $AS$  replaces the  $CS$ 's pseudonyms ( $UP_{CS}^{AS}$  and  $MP_{CS}^{AS}$ ) received with the  $AS$ 's pseudonyms ( $UP_{AS}^{CS}$  and  $MP_{AS}^{CS}$ ) to hide user information. It generates a new random nonce ( $N_{AS}$ ) to add anonymity and prevent attacks from encryption and signature analysis
- The  $AS$  computes a signature ( $ASSig_2 = h(TS_{AS} || N_{AS} || UP_{AS}^{CS} || MP_{AS}^{CS})$ ) to prevent modifications of the authentication response information
- The  $AS$  encrypts the authentication information ( $Enc_i = TS_{AS} || N_{AS} || UP_{AS}^{CS} || MP_{AS}^{CS} || ASSig_2$ ) and sends the authentication response to the  $CS$  to complete the authentication process.

$CS$  side:

- The  $CS$  decrypts the authentication response ( $Enc_i$ ) received from the  $AS$ . It checks the timestamp value ( $TS_{CS} - TS_{AS} \leq \Delta T$ ) to prevent late authentication responses. It examines the  $UP_{CS}^{AS}$  and  $MP_{CS}^{AS}$  in datasets to complete the process of linking multi pseudonyms to the user
- The  $CS$  computes the signature  $CSSig_4 = h(TS_{AS} || N_{AS} || UP_{AS}^{CS} || MP_{AS}^{CS})$  for authentication response information. It compares the computed result of the signature ( $CSSig_4$ ) with the value of the received signature ( $ASSig_2$ ). If the signature values match, then the authentication response information is unchanged



- After this point, the  $CS$  initiates a login response request. It computes the value of the new timestamp ( $TS_{CS} = newTS_{CS}$ ). It replaces the  $AS$ 's pseudonyms ( $UP_{AS}^{CS}$  and  $MP_{AS}^{CS}$ ) received with  $UP_{CS}^{C_i}$  and  $MP_{CS}^{C_i}$ . It generates a new random nonce ( $N_{CS}$ ) to hide the encryption and signature information
- The  $CS$  computes a new signature value ( $CSSig_5 = h(TS_{CS}||N_{CS}||UP_{CS}^{C_i}||MP_{CS}^{C_i}))$  to protect login response information from modification
- The  $CS$  encrypts the login response information ( $Enc_i = TS_{CS}||N_{CS}||UP_{CS}^{C_i}||MP_{CS}^{C_i}||CSSig_5$ ) and sends this response to  $C_i$ .

$C_i$  side:

- $C_i$  extracts the private key ( $C_iK_{pr_i}$ ) from the  $tmpC_iK_{pr_i} \oplus PW_i \oplus C_iSig_2$ , and decrypts the login request ( $Enc_i$ ) received from the  $CS$
- $C_i$  checks timestamp ( $TS_{C_i} - TS_{CS} \leq \Delta T$ ) to ensure that the login response is not late or replayed
- $C_i$  checks that  $CS$ 's pseudonyms ( $UP_{CS}^{C_i}$  and  $MP_{CS}^{C_i}$ ) are received in the dataset and associated with  $UP_{C_i}^{CS}$  and  $MP_{C_i}^{CS}$ . At this point, RAMHU applies multi pseudonyms among model entities ( $C_i$ ,  $CS$ , and  $AS$ ) to prevent traceability in linking the real information of the user with pseudonyms
- $C_i$  calculates the value of the signature  $CiSig_3 = h(TS_{CS}||N_{CS}||UP_{CS}^{C_i}||MP_{CS}^{C_i})$  for login response information. It compares the result of the computed signature ( $CiSig_3$ ) and the value of the received signature ( $CSSig_5$ ). If the signature values are identical, namely, the login response information is unmodified or not tampered,  $C_i$  accepts the login response; otherwise  $C_i$  discards the login response. Then,  $C_i$  hides its private key by  $C_iK_{pr_i} \oplus GM \oplus PW_i \oplus N_{C_i}$  after generating a random nonce to prevent the detection of the private key if the device is hacked. At this point, if all processes are achieved correctly, then all requests are considered legitimate and reliable through the implementation of mutual authentication.

#### • Password Update Protocol

The protocol for changing  $PW_i$  is important in any HC system for two reasons. First, preventing the use of  $PW_i$  fixed for a long time, reducing the guessing attacks. Second, changing  $PW_i$  gives users more flexibility in choosing the appropriate  $PW_i$ . This process requires strict security measures to protect

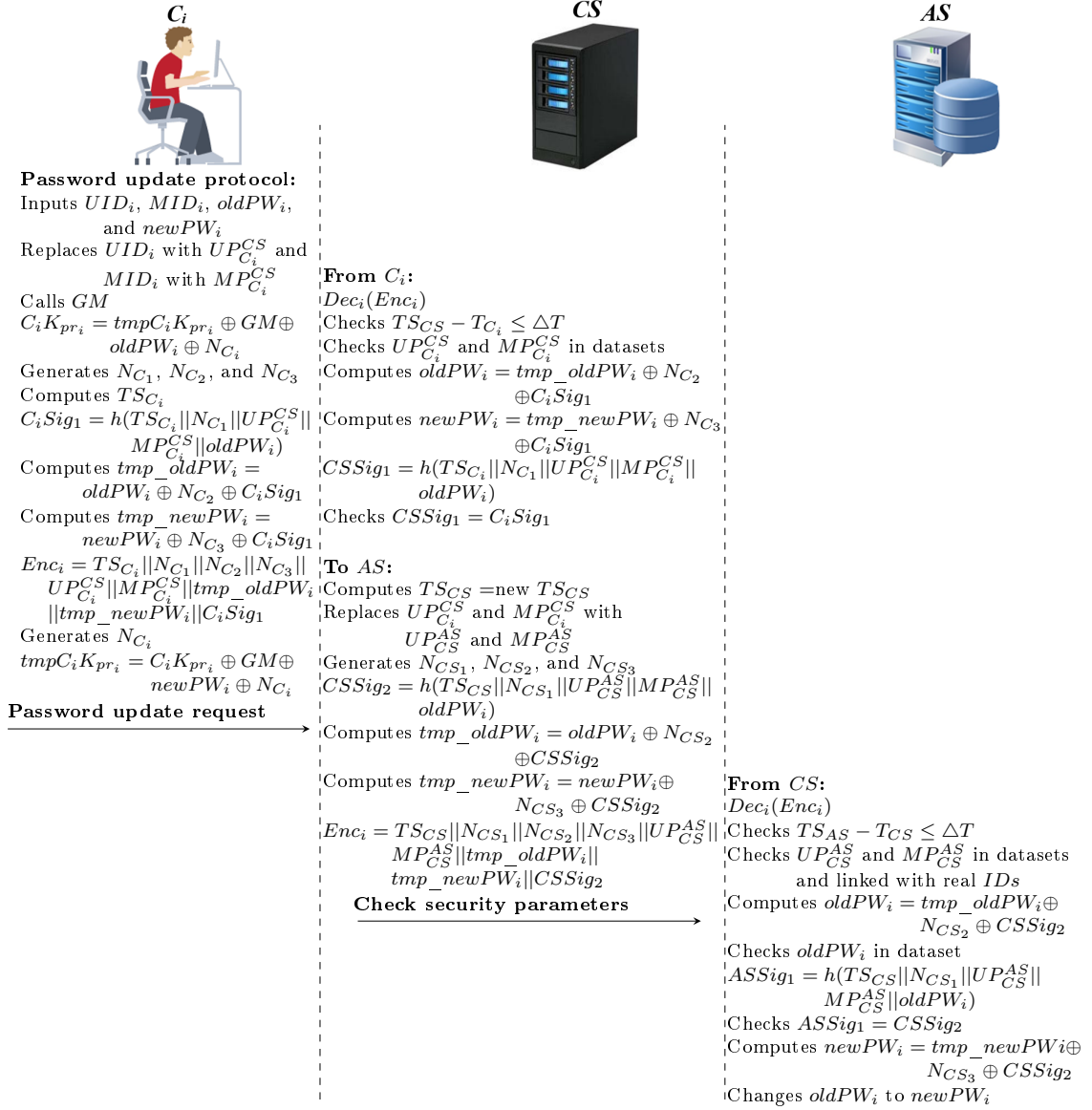


Figure 5.6: Password update protocol

new  $PW_i$ . RAMHU provides the legitimate user with a mechanism to change his/her password at any time. If the user wants to change his/her  $PW_i$ , the following illustration describes the new  $PW_i$  protect procedures in a secure manner (Figure 5.6 shows the password update protocol in RAMHU):

- $C_i$  side:  $C_i$  enters  $UID_i, MID_i,$  old  $PW_i,$  and new  $PW_i$ . It replaces  $UID_i$  and  $MID_i$  with pseudonyms to hide the real user information.  $C_i$  calls MAC address, then extracts the private key from the  $tmpC_i K_{pr_i} \oplus GM \oplus oldPW_i \oplus N_{C_i}$  to use in the encryption process of the password update request.  $C_i$  generates three random nonces ( $N_{C_1}, N_{C_2},$  and  $N_{C_3}$ ) and computes a new timestamp ( $TS_{C_i}$ ).  $C_i$  computes the signature value ( $C_i Sig_1 = h(TS_{C_i} || N_{C_1} || UP_{C_i}^{CS} || MP_{C_i}^{CS} || oldPW_i)$ ) by PHOTON-256

based on the parameters of the password change request. It applies an anonymity mechanism to old  $PW_i$  and new  $PW_i$  ( $tmp\_oldPW_i = oldPW_i \oplus N_{C_2} \oplus CiSig_1$  and  $tmp\_newPW_i = newPW_i \oplus N_{C_3} \oplus CiSig_1$ ) to hide passwords and not explicitly send it in the  $PW_i$  change request. It encrypts the  $PW_i$  change request ( $Enc_i = TS_{C_i} || N_{C_1} || N_{C_2} || N_{C_3} || UP_{C_i}^{CS} || MP_{C_i}^{CS} || tmp\_oldPW_i || tmp\_newPW_i || CiSig_1$ ) and sends it to  $CS$ ,  $C_i$  then hides its private key by  $C_iK_{pr_i} \oplus GM \oplus newPW_i \oplus N_{C_i}$

- $CS$  side: The  $CS$  receives and decrypts a password update request ( $Enc_i$ ). It examines the timestamp to prevent delayed requests, and examines  $UP_{C_i}^{CS}$  and  $MP_{C_i}^{CS}$  in datasets. The  $CS$  extracts old  $PW_i$  and new  $PW_i$  from  $tmp\_oldPW_i \oplus N_{C_2} \oplus CiSig_1$  and  $tmp\_newPW_i \oplus N_{C_3} \oplus CiSig_1$ . Then, it computes signature value ( $CSSig_1$ ) depending on  $TS_{C_i}$ ,  $N_{C_1}$ ,  $UP_{C_i}^{CS}$ ,  $MP_{C_i}^{CS}$ , and  $oldPW_i$  to check the matching between  $CSSig_1$  and  $CiSig_1$ . Similarly, in the authentication protocol, the  $CS$  computes  $TS_{CS}$  and replaces the pseudonyms. The  $CS$  generates three nonces  $N_{CS_1}$ ,  $N_{CS_2}$ , and  $N_{CS_3}$  and then it computes signature value ( $h(TS_{C_i} || N_{C_1} || UP_{C_i}^{CS} || MP_{C_i}^{CS} || oldPW_i)$ ) and hides old  $PW_i$  and new  $PW_i$  by  $oldPW_i \oplus N_{CS_2} \oplus CSSig_2$  and  $newPW_i \oplus N_{CS_3} \oplus CSSig_2$ . It encrypts the password update request with security parameters ( $TS_{CS}$ ,  $N_{CS_1}$ ,  $N_{CS_2}$ ,  $N_{CS_3}$ ,  $UP_{CS}^{AS}$ ,  $MP_{CS}^{AS}$ ,  $tmp\_oldPW_i$ ,  $tmp\_newPW_i$ , and  $CSSig_2$ ) and sends it to the  $AS$
- $AS$  side: The  $AS$  receives the password update request and decrypts ( $Enc_i$ ) this request with  $ASK_{pr_i}$ , and  $CSK_{pu_i}$ . It checks the time delay, and then it checks link pseudonyms with real user information. It extracts old  $PW_i$  from  $tmp\_oldPW_i \oplus N_{CS_2} \oplus CSSig_2$  and then it checks old  $PW_i$  in dataset. It computes the signature value  $ASSig_1 = h(TS_{CS} || N_{CS_1} || UP_{CS}^{AS} || MP_{CS}^{AS} || oldPW_i)$ , and then, it compares the calculated result ( $ASSig_1$ ) with the result of the received signature ( $CSSig_2$ ). If identical, the signature is true; otherwise, the  $AS$  rejects the  $PW_i$  change request. The  $AS$  performs the calculation  $tmp\_newPW_i \oplus N_{CS_3} \oplus CSSig_2$  to obtain the new  $PW_i$  value. If all previous checks are validated, the  $AS$  changes old  $PW_i$  to new  $PW_i$ .

#### • Revocation Protocol

This protocol can be completed by  $C_i$ , or the  $AS$ . If  $C_i$  wants to revoke his account from the HC system after completing his/her duties, such as a research doctor who uses the system for a limited period and then cancels his account after the completion of his duties. Additionally, the  $AS$  can revoke the account of any user who performs suspicious activities (internal attacks)

that are not within his/her privileges, such as a nurse who wants to access the personal information of a particular doctor, or patient. Furthermore, the user can ask the authorities provider (*AS*) to cancel his/her account information that is associated with his/her data (note that the patients' data history remains stored in the *DS* even after the completion of the revocation protocol). The protocol of revocation is extremely important in restricting the malicious activities of any healthcare system. RAMHU includes a revocation protocol to provide strict security procedures in protecting users' authentication information (Figure 5.7 shows revocation protocol in  $C_i$  side in RAMHU):

Revocation from  $C_i$  side:

- $C_i$  enters  $UID_i$ ,  $MID_i$ , and  $PW_i$  and then replaces  $UID_i$  with  $UP_{C_i}^{CS}$  and  $MID_i$  with  $MP_{C_i}^{CS}$ . It chooses the revocation reason ( $RR_i$ ) from the drop-down list (such as ending the researcher's study, ending a satisfactory condition, resigning a professional, changing a health institution, and the unwillingness of a patient to use the system). These reasons have converted to signatures using PHOTON to get MDs with a 256-bit in the dataset.  $C_i$  computes new  $TS_{C_i}$ ,  $N_{C_1}$ ,  $N_{C_2}$ , and  $N_{C_3}$ . Then,  $C_i$  performs the process of  $RR_i \oplus N_{C_1}$  to add randomness for  $RR_i$ . Using this procedure is tremendously useful in tightening security and distinguishing the roles of users (patients or professionals) in the *CS*. It computes the signature  $C_iSig_1 = h(TS_{C_i} || N_{C_1} || UP_{C_i}^{CS} || MP_{C_i}^{CS} || RR_i || PW_i || \text{"delete"})$ .  $C_i$  performs a computation to hide the  $RR_i$  ( $tmpRR_i = RR_i \oplus N_{C_2} \oplus C_iSig_1$ ).  $C_i$  computes the temporary  $PW_i$  value of  $PW_i \oplus N_{C_3} \oplus C_iSig_1$  to hide the  $PW_i$  value. Additionally, it computes encryption ( $Enc_i = TS_{C_i} || N_{C_1} || N_{C_2} || N_{C_3} || UP_{C_i}^{CS} || MP_{C_i}^{CS} || tmpRR_i || tmpPW_i || C_iSig_1$ ) and sends a revocation request to the *CS*. Then, it hides a private key, in the same way, in the password update protocol
- The *CS* decrypts ( $Enc_i$ ) and computes the timestamp and examines  $UP_{C_i}^{CS}$  and  $MP_{C_i}^{CS}$  in the datasets. It obtains the  $RR_i$  from the computation equation  $RR_i = tmpRR_i \oplus N_{C_2} \oplus C_iSig_1$ . It extracts  $PW_i$  from  $tmpPW_i \oplus N_{C_3} \oplus C_iSig_1$  and checks  $PW_i$  matching in the dataset. *CS* computes the signature ( $C_iSig_1 = h(TS_{C_i} || N_{C_1} || UP_{C_i}^{CS} || MP_{C_i}^{CS} || RR_i || PW_i || \text{"delete"})$ ) and then compares the result of the signatures. The *CS* computes operation  $RR_i \oplus N_{C_1}$  to use  $RR_i$ 's signature in order to compare the  $RR_i$  with the user's  $R_i$ . If all operations are achieved and validated correctly, the *CS* sends a request to the *AS* to check the

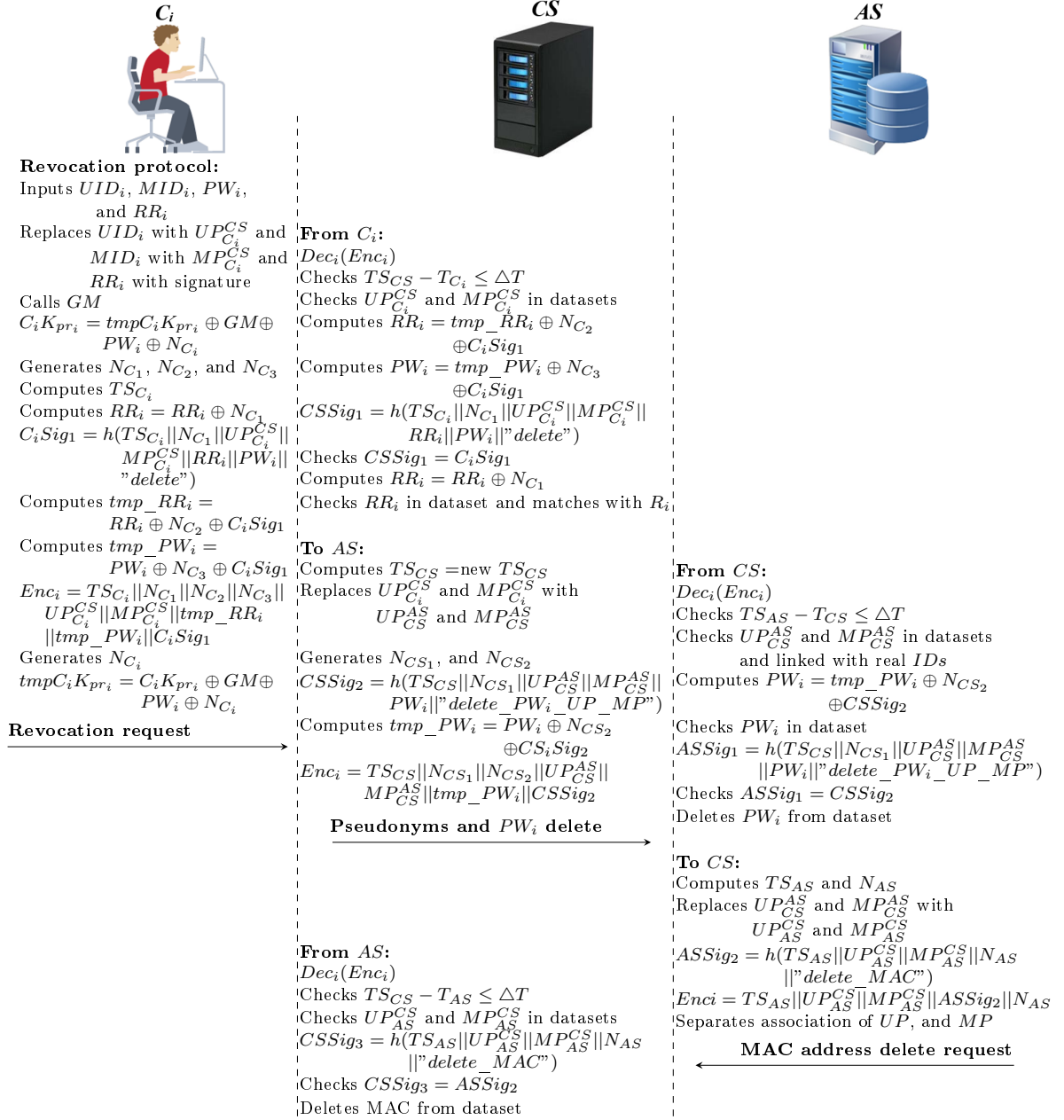


Figure 5.7: Revocation protocol

pseudonym's association with real information and check  $PW_i$ . The  $AS$  deletes association between pseudonyms and information, and deletes the user's  $PW_i$  from dataset. The  $AS$  sends MAC delete request to the  $CS$ . Upon receiving the MAC delete request, the  $CS$  decrypts this request, then checks the security parameters and signature. If all operations are achieved and validated correctly, the  $CS$  deletes the MAC address from the dataset. At this point, this user cannot perform an authentication process in RAMHU.

Revocation from  $AS$  side:

- The *AS* deletes the association between the user information and pseudonyms and  $PW_i$  in the datasets. It sends an encrypted request ( $Enc_i$ ) to the *CS* to delete the device’s MAC address for this user. After the completion of this protocol, the user is considered illegal and cannot access the healthcare services.

### 5.3 Summary of the Chapter

In this chapter, we have provided details of the new authentication scheme and described our network model in the HC application. Additionally, RAMHU’s goals to provide authentication requirements was detailed. Following this, we presented a set of protocols. Finally, the RAMHU scheme methodology was explained in detail.

# Chapter 6: Authorisation of HC Users with Differentiated Access Control

In Chapter 5, we elaborated on a scheme that authenticates HC user identity and the EHR repository. In this chapter, we will explain another integral component of our proposed HC application. This scheme is responsible for authorising various HC users, including patients, with differentiated access control to the EHR repository. The objective of this authorisation method is to provide HC users with more efficient and secure services, as well as preserving patient privacy.

## 6.1 Data Security in EHR Systems

The EHR/EMR technology is a recent advance in the HC industry that digitizes patients' health or medical data and stores these records in a database or repository. In this way, patients' health records and history can be accessed much more accurately and quickly. In emergency, this may save lives. EHR systems include identifications and patients' data that require authorisation privileges to determine access control for authorised users (Calvillo-Arbizu et al. 2014). Accurate medical data is essential for diagnosing diseases and determining the condition of patients (Alhaqbani & Fidge 2008, Riedl et al. 2008). Any unauthorised change to this data causes health problems for patients. In addition, the penetration of medical records of patients with diseases such as HIV infection or dermatological conditions can lead to discrimination, harassment, or even death of the patient if the diagnostic data changes during the transition from client to server (Neubauer & Heurix 2011, Riedl et al. 2008). In a broad sense, a terrorist may cause national instability by disclosing patients' data, changing the data, destroying the data, or impersonating some patients (Quantin et al. 2011). HC systems, in particular EHR

systems, should provide end-to-end privacy for patients' data. Also, data storage and authorisation policies for patients in a central server yield data management gains but are an attractive target for hackers (Quantin et al. 2011). Therefore, there should be security mechanisms to protect the privacy of the patient as well as to prevent the penetration of policies on the server.

Patient data can be used by direct users such as a doctor or nurse who use the data almost daily, or it can be used by indirect users such as emergency or relative who use the data temporarily. The use of patient data for various purposes, such as consultations, access by a relative or caregiver, research, and emergency (secondary or indirect use) are a major challenge for authorisation systems. For example, a researcher should not exceed the limits of privacy granted to him/her (Calvillo-Arbizu et al. 2014). In an emergency, when the patients' doctor is unavailable or the patient does not have the capacity to give consent to another doctor, the patient's privacy is seriously compromised (Sun et al. 2011). Also, if the patient is incapacitated, a relative is responsible for receiving the patient's data (Riedl et al. 2007). Sometimes, the doctor also needs to consult another doctor to treat a patient's condition. All these cases can result in the intrusion and penetration of data. The sharing of medical records among users of the EHR system allows patient data to be misused or abused by malicious breaches (Rezaeibagha et al. 2015). There are many examples of the penetration of patients' medical records for patients by intruders, as mentioned in Section 2.3.2 (Koczkodaj et al. 2018, U.S. Department of Health and Human Services 2018). These penetrations show that the HC system requires a high level of security. Furthermore, an internal attacker penetrates medical records more easily than an external attacker because each practitioner has a privilege that allows him/her to access the server system.

## 6.2 Overview of Requirements of Access Control

Many access control models have been used in EHR, such as mandatory access control (MAC), discretionary access control (DAC), role based access control (RBAC), and attribute based access control (ABAC), and each model has specific authorisation mechanisms for data access (Gajanayake et al. 2014). In this project, we adopted the integration of the RBAC and ABAC to support a security level based on both role and user attributes. Therefore, EHR systems require mechanisms to ensure the privacy of patients' data while protecting authorisation policies and HC provider requests (Fernández-Alemán et al. 2013). In order to develop a successful project, privacy must be provided to the patient via the following measures:

1. Preventing attackers from accessing patient data and making data anonymous



in case attackers do gain access to the data (i.e., external attacks)

2. Preventing legitimate users from exceeding their privileges (i.e., internal attacks)
3. Securing all requests, policies, and data of the change on the server or during the transfer between the clients and server to ensure the accuracy and reliability of patient data
4. Applying anonymity to requests and policies to hide users' identities
5. Applying a random pseudonym to requests, policies, and data to separate data associated with the real attributes of patients.

### 6.2.1 Access Control for the EHR Repository

We developed a **P**seudonymization and **A**nonymization with the **X**ACML (PAX) modular system, which depends on client and server applications. The characteristics of the proposed authorisation scheme can be summarised as follows:

- Combining ABAC and RBAC  
In this scheme, we integrate two existing models (ABAC and RBAC) to develop a system that provides handling of patients' information at the coarse-grained and fine-grained levels. Our model fits the privacy and security requirements for medical records in the EHR by merging a user's ID with the role as a single attribute entered in the signature to identify subjects and objects
- Separating users into two sets  
We have proposed separating users into direct and indirect sets for patients' records to allow the server to distinguish between users' requests. This significantly reduces the penetration rate of internal attacks
- Using ECDSA's signatures with XACML  
The anonymity property has been applied to the requests and policies of subjects. This feature was used during the implementation of the ECDSA signature algorithm with XACML to prevent attackers from determining the identity of HC providers (to prevent knowledge of the relation between a physician with a particular patient)
- Using Shamir scheme with signatures  
We used the Shamir scheme with the ECDSA signatures in the third protocol for authorising indirect users. This procedure is necessary to verify

unauthorised users of patient data who could be conducting serious attacks on the EHR system

- Using random pseudonym with patient data  
The pseudonym property has been applied to the requests and policies of subjects and resources. This feature prevents hackers from knowing that the data belongs to a particular patient (separating data from real attributes).

## 6.3 Our Proposed Authorisation Model

In this section, we provide details of our new authorisation scheme that supports security and privacy mechanisms to ensure legitimate user authorisation in HC applications. This section will be divided into the network model, application of privacy concepts and PAX authorisation protocols for users.

### 6.3.1 Users Access Control Model

As shown in Figure 6.1, Pseudonymization and Anonymization with the XACML (PAX) is an authorisation system that works with EHR. The network model consists of four entities: client ( $C_i$ ), central server ( $CS$ ), attributes server ( $AS$ ) and data server ( $DS$ ). These entities communicate with each other in the PAX framework to accomplish authorisation and privacy preservation of users when accessing datasets. The  $CS$  is the portal that prevents users from directly accessing to both the  $AS$  and  $DS$ . Patients' data are stored on the data server ( $DS$ ) and are fully separated from the attributes of the users (patients and HC providers) that are stored on the attributes server ( $AS$ ). Each  $C_i$  creates an access request and sends it to the  $CS$ . Then, the  $CS$  verifies the authorisation information for the user's request. If this request is valid, the  $CS$  sends the authorisation request to the  $AS$  for an evaluation; otherwise, the  $CS$  sends the "deny" response to  $C_i$ . When the  $AS$  receives the authorisation request from the  $CS$ , the  $AS$  evaluates the access request by PDPs modules, verifies signatures, pseudonyms, and other security parameters. If all evaluates and tests are valid, the  $AS$  sends a request to the  $DS$  to retrieve the patient data; otherwise, the  $AS$  sends the "deny" response to the  $CS$ . After that, the  $DS$  checks for signatures (Sigs) and privacy parameters (PP), if all operations are correctly performed, the  $DS$  sends the required data with pseudonyms and Sigs to  $AS$  which in turn sends the "permit" response to  $C_i$  by the  $CS$  to allow access to the dataset. The authorised user will receive the "permit" response and the copy of the required data.

The PAX system uses two PDPs (PDP1 and PDP2) to implement the user authorisation process, as shown in Figure 6.1. In this scheme, we focus on securing

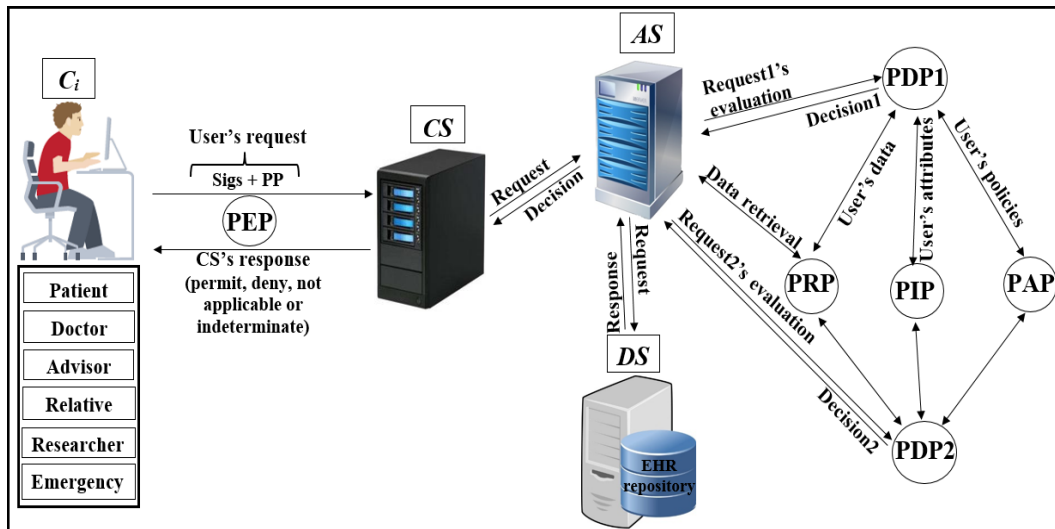


Figure 6.1: PAX model

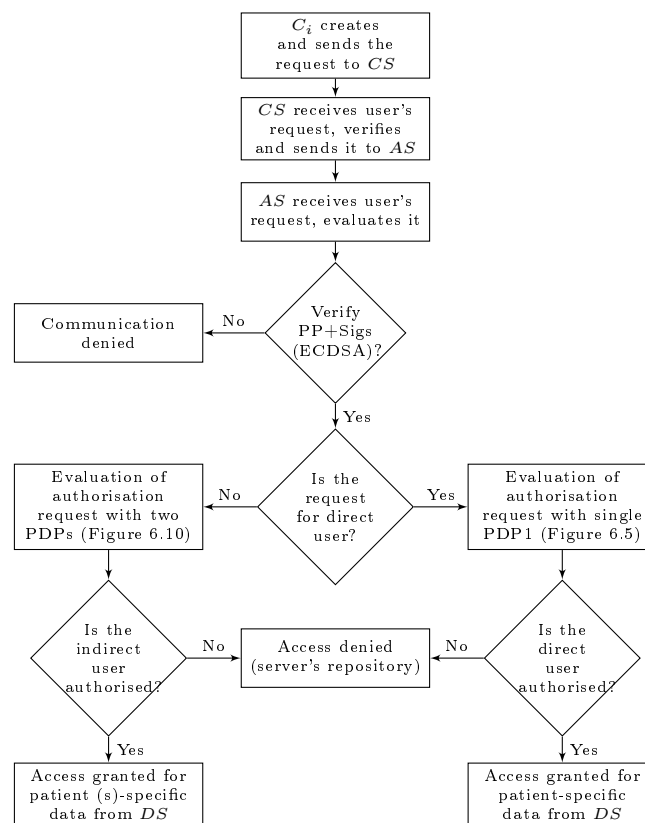


Figure 6.2: Authorisation of direct and indirect users

requests and policies to provide a high level of user privacy. PAX depends on the Balana Project, which is the only open source project that implements XACML v3.0. Privacy and security are essential requirements of EHR. In PAX, we are careful to provide high-level privacy and security mechanisms to authorise users.

### 6.3.2 Design Goals of PAX

There is a set of security features included in PAX:

- **Integrity and non-repudiation of requests:** User requests and policies need protection from change or repudiation. We used the ECDSA algorithm to sign user attributes. Any change in the signatures will be detected in the server because the server checks the user requests before authorising access to the data. In addition, the signatory party cannot deny its signature. These features make the system immune against to internal changing attacks
- **Authentication and authorisation of requests:** Each EHR requires authentication and authorisation properties to protect medical records from unauthorised access. We applied ECDSA to the XACML v3.0 to support these properties in PAX. The use of signatures in XACML between the  $C_i$  and the  $CS$ ,  $AS$  and  $DS$  support user authentication in addition to the use of policies and rules to identify authorised users and the level of access granted to them
- **Confidentiality and anonymization:** One of the security features of hiding information is confidentiality. We applied ECDSA to add confidential requests to subjects and objects, and we added a Shamir scheme (backup or fail-open mechanism) to provide anonymity of  $SS_s$  to users of the EHR system. This process prevents the attacker from seeing explicit attributes and does not allow a hacker to know the user-configured  $SS$  for any healthcare provider. A Shamir scheme ensures the anonymity of the signature. This backup mechanism enables indirect users to access protected health information (PHI) with privacy and security
- **Pseudonymization:** A patient's privacy requires the separation of personal information from their data. Pseudonymization prevents the intruder from knowing the data belonging to any of the patients. PAX supports pseudonym in both subjects' and objects' attributes using pseudonyms for real attributes. This feature supports the privacy of patients' data
- **Audit and activities:** PAX records all user activities (requests and responses) accessing medical records. It monitors user activity, including the number of access times, the result of the decision, and the amount of data required. The audit process is important for any healthcare system in determining users' activities. PAX stores and organizes requests and responses for each user (patient, doctor, advisor, relative, researcher, and emergency doctor) separately to facilitate the management of these activities.

### 6.3.3 Implementation of PAX

In this section, we will introduce the privacy concepts in PAX.

- **EHR's Users in PAX**

Security and privacy address where, when, and why data is available and who can access the data repository. Patients and HC providers require services that are efficient, fast, and continuous and at the same time incorporate strict restrictions to determine data access. Therefore, AC to medical records has several challenges in terms of security and privacy:

1. Legitimate users should not exceed their privileges
2. Users' roles in the EHR system should be defined. For example, a doctor can have several roles, such as an emergency doctor and a researcher doctor
3. Data should be anonymous when it reaches the wrong user due to misuse or attacks
4. Compliance with medical standards for EHR (such as HIPAA) is essential.

In PAX, we divide users into two categories:

- Direct users: These users include those who are directly associated with the data, such as the patient and the doctor
- Indirect users: These users include those who are not directly and continuously associated with the data, such as advisors, patients' relatives, researchers, and emergency doctors.

Although PAX includes both categories of users, this project focuses on indirect users (Figure 6.2 shows a flow chart for authorisation of direct and indirect users in PAX). Any HC system can be exposed to an internal attack by indirect users if there are no security and privacy mechanisms to prevent them.

- **User Pseudonym in PAX**

Authorisation systems require a lightweight mechanism to prevent intruders from distinguishing specific patients' data without the complications of encryption and anonymous mechanisms. To address this problem, we apply random pseudonyms with PAX to separate the association between patients' attributes and their data. The medical records transmitted between the client and server do not contain any patient attributes. This prevents attackers from identifying patients.

Table 6.1: Internal and external pseudonyms of users

Users	$UR$	$CN$	Internal pseudonym	$RN$	$UN$	External pseudonym
patient	$p$		$p_1 \dots p_n$			
doctor	$d$		$d_1 \dots d_n$			
advisor	$a$		$a_1 \dots a_n$			
relative	$pr$	$1 \dots n$	$pr_1 \dots pr_n$	$1 \dots n$	$1 \dots n$	$1 \dots n$
researcher	$r$		$r_1 \dots r_n$			(48-bit)
emergency	$e$		$e_1 \dots e_n$			
Shamir	-		-			

Table 6.2: Parts of  $SP$  and  $OP$ 

$SP$						$OP$					
$RN_{sp}$			$UN_{sp}$			$RN_{op}$			$UN_{op}$		
$RN_{sp_l}$	$RN_{sp_m}$	$RN_{sp_h}$	$UN_{sp_l}$	$UN_{sp_m}$	$UN_{sp_h}$	$RN_{op_l}$	$RN_{op_m}$	$RN_{op_h}$	$UN_{op_l}$	$UN_{op_m}$	$UN_{op_h}$

In PAX, we propose the use of four datasets: the first for user attributes (patients and HC providers), the second for applying pseudonyms to users, the third for user policies (on the  $AS$ ) and the fourth for patient data (on the  $DS$ ).

When the EHR system wants to add a new HC provider or patient, the PAX randomly generates a pseudonym for that user and adds it to the second dataset. Suppose that we have a dataset for random pseudonyms, as in Table 6.1. PAX generates pseudonyms (such as  $p429$  or  $d761$ ) for patients or HC providers during the addition of a letter representing the user’s role ( $UR$ ) such as  $p$  or  $d$  plus a random client’s number ( $CN$ ). Each subject’s pseudonym ( $SP$ ) and object’s pseudonym ( $OP$ ) consists of  $UR$  and  $CN$  (internal pseudonym), which are not transferred between entities and are used for policy verification at the  $AS$ . XACML’s request in PAX depends on the  $SP$  and  $OP$  (external pseudonym), and both  $SP$  and  $OP$  are divided into the role’s number ( $RN$ ) and user’s number ( $UN$ ) (after replacing  $UR$  with  $RN$  and  $CN$  with  $RN$ ) and the latter are segmented into three parts (low (l), medium (m), and high (h)) with length 8 bits per part as in Table 6.2. These pseudonyms are associated with the user IDs. It enables users to access a specific patient’s data without exceeding granted privileges and rights.

- **Using ECDSA’s Signatures**

PAX uses ECDSA (NIST prime-256) with requests and policies to ensure that security requirements apply to the privacy of patients’ data. We have applied ECDSA signatures with subjects’ and objects’ attributes to ensure integrity property to prevent changing attributes in requests and policies, authentication property to prevent external attackers and non-repudiation property to prevent authorised users from denying their requests to receive medical records. The application of security requirements is very important in systems, such as

HC systems, that use sensitive data. In PAX, the  $C_i$  signs the request with pseudonyms ( $RN$  and  $UN$ ), and the servers ( $CS$  and  $AS$ ) verify the request's Sigs. If valid, the  $AS$  assigns the request to the PDPs engines (after replacing Sigs (external pseudonym) with Sigs (internal pseudonym)) in XACML v3.0; otherwise, the request is rejected. PAX uses ECDSA Sigs to hide parts of  $SP$  and  $OP$  when exchanging XACML requests between PAX entities. The high performance and security level make this algorithm suitable for application in large systems (such as EHR).

- **Policies Administration in PAX**

System Administrator is responsible for creating policies for HC providers and patients in the  $AS$  by PAP. Policy in PAX consists of the policy ID, subject, object, and rules for policy implementation. The first process in the PAX system is to create datasets for pseudonyms and attributes for all users. The process of creating policies depends on previous datasets. PAX uses ECDSA to generate a signature of  $SP$  ( $S_{sp}$ ) and a signature of  $OP$  ( $S_{op}$ ) based on the pseudonyms ( $UR$  and  $CN$ ) for both  $SP$  and  $OP$ . Creating signature-based policies and pseudonyms protects policies on the server in a way that is immune to internal and external attacks (policies do not depend on users' real attributes). For example, the system administrator creates a user policy by entering the doctor's name and  $UR$  and patient's name, and PAX creates this policy as shown in Figure 6.3. The policy parameters are highlighted in green: d20 represents the  $SP$  and uses as the policy's ID; the first long 128-bit hexadecimal number represents the  $S_{op}$  and the second long 128-bit hexadecimal number represents the  $S_{sp}$ . This policy can include a set of rules such as determining the date of data access, the time specified on a given day, or the number of access times.

- **Client Requests and Server Responses**

PAX's users must create an authorisation request to access medical records. This request consists of the subjects' and objects' attributes. The  $C_i$  application in PAX uses the parts of  $RN$  and  $UN$  as a single attribute to generate the ECDSA's Sig for the subjects and the objects. Figure 6.4 shows the client's request to access patient data (where the request parameters are highlighted in green;  $C_iS_{2tm} || RN_{optm} || UN_{optm} || N_C || C_iS_{4tm}$  in resource segment represents the object's attributes, and the  $C_iS_{1tm} || RN_{sptm} || UN_{sptm} || N_C || TS_{Ctm} || SN_{Ctm}$  in access-subject segment represents the subject's attributes). Also, the  $C_i$  application uses a part of  $RN_{sp}$  to explain to the  $AS$  the user's role to determine the desired policy after verifying the Sigs. Then, the  $C_i$  sends the request to the  $AS$  by  $CS$  for evaluation. The  $AS$  evaluates the request in

```

<Policy xmlns="urn:oasis:names:tc:xacml:3.0:core:schema:wd-17" PolicyId="permitPolicyFor120"
RuleCombiningAlgId="urn:oasis:names:tc:xacml:3.0:rule-combining-algorithm:first-applicable" Version="1.0">
  <Target>
    <AnyOf>
      <AllOf>
        <Match MatchId="urn:oasis:names:tc:xacml:1.0:function:string-equal">
          <AttributeValue DataType="http://www.w3.org/2001/XMLSchema#string">36b6e95b598c43cae10c6e2369d29a3df8
263e6a75336e20bf8cac2a791ab269bc2664e625636e70389546de67135074c851b6d15751cd29b0a76df47ecc2887
          </AttributeValue>
          <AttributeDesignator AttributeId="urn:oasis:names:tc:xacml:1.0:resource:resource-id"
Category="urn:oasis:names:tc:xacml:3.0:
attribute-category:resource" DataType="http://www.w3.org/2001/XMLSchema#string" MustBePresent="true"/>
        </Match>
        <Match MatchId="urn:oasis:names:tc:xacml:1.0:function:string-equal">
          <AttributeValue DataType="http://www.w3.org/2001/XMLSchema#string">0284894f6327dcca8ebd16a2e8a783ad7
1f911f9d4b8af86b826048eb9c88846075a37b87654ac0ec1f58c35dbc06587d0b6a77d4303de6e19d1bf1fd715ab07
          </AttributeValue>
          <AttributeDesignator AttributeId="urn:oasis:names:tc:xacml:1.0:subject:subject-id" Category="urn:oasis:names:tc:xacml:1.0:
subject-category:access-subject" DataType="http://www.w3.org/2001/XMLSchema#string" MustBePresent="true"/>
        </Match>
      </AllOf>
    </AnyOf>
  </Target>
  <Rule Effect="Permit" RuleId="permit1"/>
</Policy>

```

Figure 6.3: PAX policy

```

<Request xmlns="urn:oasis:names:tc:xacml:3.0:core:schema:wd-17" CombinedDecision="false" ReturnPolicyIdList="false">
  <Attributes Category="urn:oasis:names:tc:xacml:3.0:attribute-category:action">
    <Attribute AttributeId="urn:oasis:names:tc:xacml:1.0:action:action-id" IncludeInResult="false">
      <AttributeValue DataType="http://www.w3.org/2001/XMLSchema#string">access</AttributeValue>
    </Attribute>
  </Attributes>
  <Attributes Category="urn:oasis:names:tc:xacml:1.0:subject-category:access-subject">
    <Attribute AttributeId="urn:oasis:names:tc:xacml:1.0:subject:subject-id" IncludeInResult="false">
      <AttributeValue DataType="http://www.w3.org/2001/
XMLSchema#string">CiS1rm||RNsprrm||UNsprrm||Nc||TScrm||SNcrm
      </AttributeValue>
    </Attribute>
  </Attributes>
  <Attributes Category="urn:oasis:names:tc:xacml:3.0:attribute-category:resource">
    <Attribute AttributeId="urn:oasis:names:tc:xacml:1.0:resource:resource-id" IncludeInResult="false">
      <AttributeValue DataType="http://www.w3.org/2001/XMLSchema#string">CiS2rm||RNoprm||UNoprm||Nc||CiS4rm
      </AttributeValue>
    </Attribute>
  </Attributes>
</Request>

```

Figure 6.4:  $C_i$ 's request

the PDP engines, and the response (permit or deny) returns to the  $C_i$  by  $CS$ .

- **Using Shamir Scheme**

In PAX, we implemented the Shamir scheme to increase the level of security for indirect users (advisors, patients' relatives, researchers, and emergency). Indirect users are legitimate users who can perform an internal attack because of the rights granted to them. PAX uses ECDSA to sign all signatures of HC users to create a master signature ( $MS$ ). Then, PAX uses the Shamir scheme to generate secrets sharing ( $SS_s$ ) from a  $MS$ . Each indirect user receives  $SS$  via a secure communication channel.  $C_i$  needs a set of  $SS_s$  to reproduce the  $MS$ .



PAX uses  $TH = 3$ , which means that the randomly selected  $SS_s$  require at least three  $SS_s$  to generate the  $MS$ . Also, depending on  $RN_{sp}$ , the  $AS$  specifies that the user's role is indirect and uses the Shamir scheme with ECDSA Sig to verify the original  $MS$  and then evaluate the request by PDP2. Using Shamir's scheme with XACML adds the property of authenticity as an indirect user cannot access data with the same  $SS_s$ . This operation enables PAX to secure the privacy of patient data and protect patient data from internal and external attacks. When an indirect user wants access to medical records, he/she does not know whether the  $SS_s$  used to generate the  $MS$  belongs to any specific HC providers.

### 6.3.4 PAX Authorisation Protocols

In this section, we will provide, in detail, PAX's protocols framework to authorise direct and indirect users:

- **Authorisation Protocols for Direct Subjects and Objects**

To run through the authorisation process for direct users of PAX, the security techniques mentioned in Section 3.5 will be the basis for building the PAX authorisation system. In this section, we will explain the protocols for authorising direct users such as doctors and patients to access medical records (EHR).

- **Prerequisite procedures**

There is a set of steps that must be taken before authorisation can begin:

1. Create two datasets (attributes, pseudonym) on the  $AS$ . If datasets are established, the processes are to add new users or delete direct users
2. Create policies (dataset 3) for all direct users based on anonymity and pseudonym
3. Storage of medical records (dataset 4) for patients in the  $DS$ 's repository (after collecting them from patients using wireless medical devices, this process requires security mechanisms, but the process of storing medical records safely detailed in Chapter 4). We assume that patient data is located on the  $DS$ .

- **Authorisation protocols**

The following protocols detail how the direct user is associated with the EHR in  $DS$ . Figure 6.5 depicts the general authorisation process, while Figures 6.6, 6.7, 6.8, and 6.9 show the authorisation protocols of direct users with PAX entities.

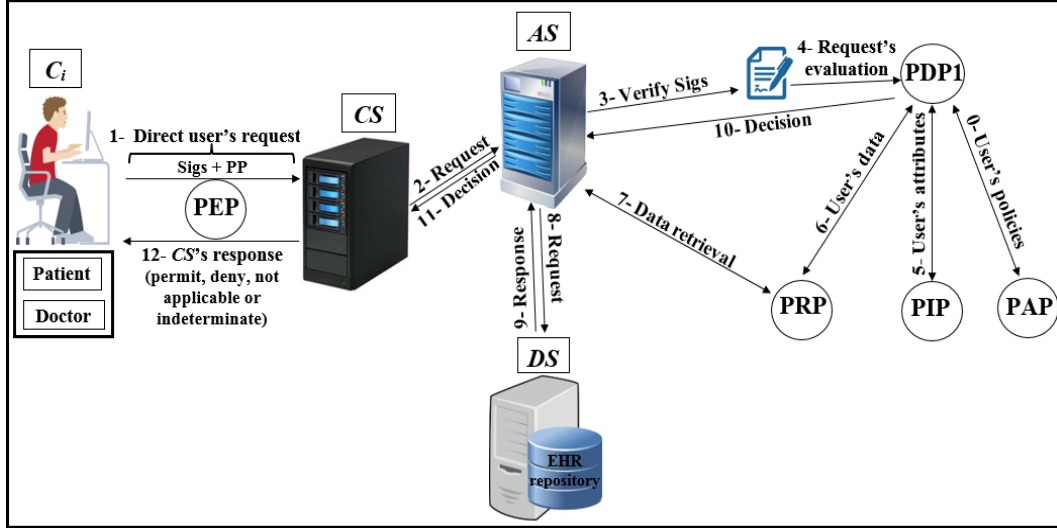


Figure 6.5: Authorisation of direct users

1. First protocol as shown in Figure 6.6:

- \* PAX user enters the subject ID ( $S_{ID}$ ), object ID ( $O_{ID}$ ), subject role ( $S_R$ ) and object role ( $O_R$ ) to the  $C_i$  application.  $C_i$  replaces  $S_{ID}$ ,  $O_{ID}$ ,  $S_R$  and  $O_R$  with  $CN_{sp}$ ,  $CN_{op}$ ,  $UR_{sp}$  and  $UR_{op}$  respectively. Next, internal pseudonyms are replaced with  $UN_{sp}$ ,  $UN_{op}$ ,  $RN_{sp}$  and  $RN_{op}$  respectively. Then,  $C_i$  generates random nonces ( $N_C$  and  $SN_C$ ) and new timestamp ( $TS_{C_i}$ ).  $SN_C$  is a random secret between  $C_i$  and the  $CS$ .  $C_i$  computes 4 Sigs ( $C_iS_1$ ,  $C_iS_2$ ,  $C_iS_3$  and  $C_iS_4$ ).  $C_iS_1$  and  $C_iS_2$  is used to ensure the legitimacy of  $C_i$  in the  $CS$ .  $C_iS_3$  is used to protect  $SN_C$  between  $C_i$  and  $CS$ .  $C_iS_4$  is used to validate  $C_i$  in both the  $AS$  and  $DS$  (depending on  $RN_{op_h}$  and  $UN_{op_h}$ ).  $C_i$  hides all Sigs such as  $C_iS_1$  temporary ( $C_iS_{1tm}$ ) and PP such as  $TS_{Ctm}$  and  $SN_{Ctm}$ . At this point,  $C_i$  sends XACML's request to the  $CS$  including the subject's information ( $C_iS_{1tm} || RN_{sp_{tm}} || UN_{sp_{tm}} || N_C || TS_{Ctm} || SN_{Ctm}$ ) and object's information ( $C_iS_{2tm} || RN_{op_{tm}} || UN_{op_{tm}} || N_C || C_iS_{4tm}$ )
- \*  $CS$  receives XACML's request from  $C_i$ , cuts Sigs and PP from access-subject ( $C_iS_{1tm}$ ,  $RN_{sp_{tm}}$ ,  $UN_{sp_{tm}}$ ,  $N_C$ ,  $TS_{Ctm}$  and  $SN_{Ctm}$ ) and resource ( $C_iS_{2tm}$ ,  $RN_{op_{tm}}$ ,  $UN_{op_{tm}}$ ,  $N_C$  and  $C_iS_{4tm}$ ). Then, the  $CS$  extracts  $RN_{sp_l}$ ,  $UN_{sp_l}$ ,  $RN_{op_l}$  and  $UN_{op_l}$  from receiving parameters (such as  $RN_{sp_{tm}}$ ).  $UN_{sp_l}$  and  $UN_{op_l}$  are used to retrieve  $UN_{sp_m}$  and  $UN_{op_m}$  from the datasets. the  $CS$  extracts  $C_iS_4$ ,  $SN_C$ ,  $TS_{C_i}$  and checks timestamp. Then, the  $CS$  computes Sigs ( $CSS_1$ ,  $CSS_2$  and  $CSS_3$ ), and uses  $CSS_1$  to extract original

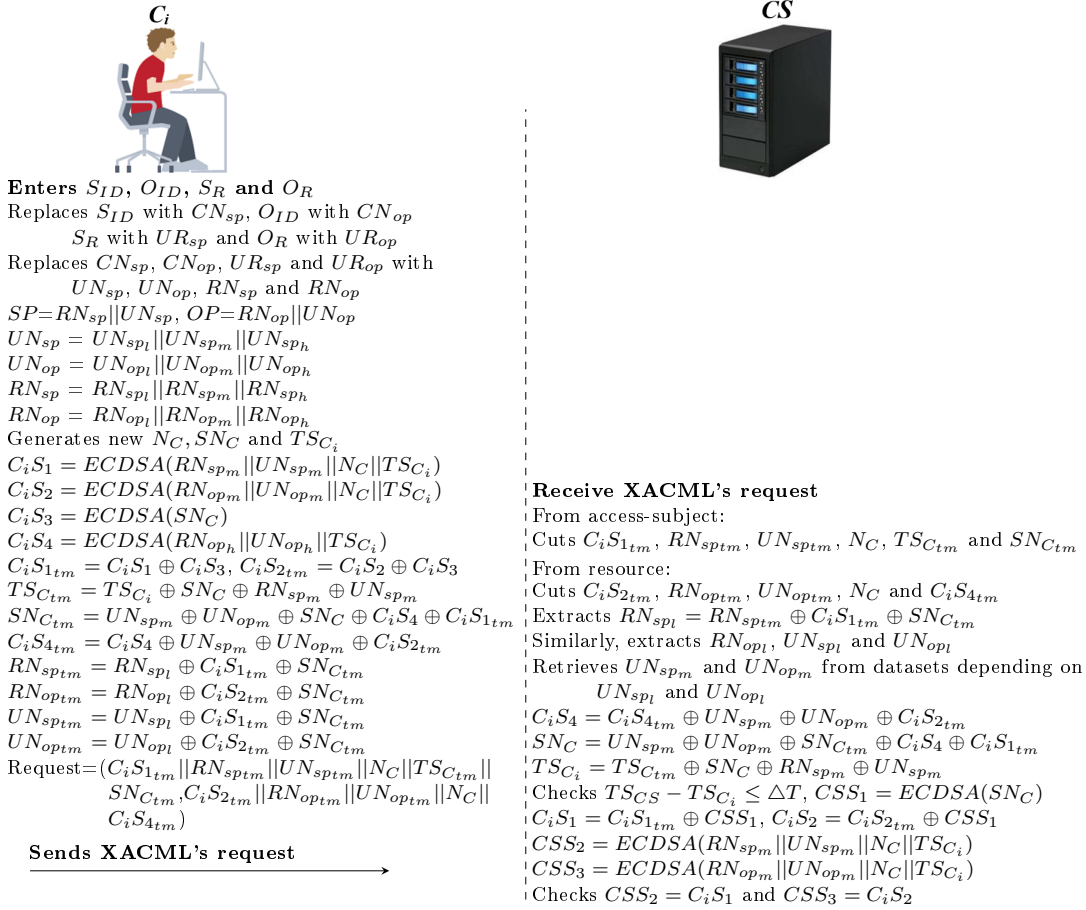


Figure 6.6: Protocol of PAX model between  $C_i$  and  $CS$

$C_i S_1$  and  $C_i S_2$ . After that, the  $CS$  checks  $CSS_2 = C_i S_1$  and  $CSS_3 = C_i S_2$ . If the Sigs are not identical, the  $CS$  cancels the connection; otherwise, it moves to the next protocol.

2. Second protocol as shown in Figure 6.7:

- \* The  $CS$  generates random secret ( $SN_{CS}$ ) and new timestamp ( $TS_{CS}$ ) between the  $CS$  and  $AS$ . Then, the  $CS$  computes the secret signature ( $CSS_4$ ) to protect  $SN_{CS}$ . Also, the  $CS$  hides  $C_i$ 's parameters such as  $N_C$  and  $TS_{C_i}$  to use them with validation operations in the  $AS$  and  $DS$ . In addition, all Sigs (such as  $CSS_{2tm}$ ) and PP (such as  $N_{CS}$  and  $TS_{CS_{tm}}$ ) are anonymously hidden by the  $CS$ . At this point, the  $CS$  sends XACML's request to the  $AS$
- \* The  $AS$  receives the request, cuts Sigs and PP. After that, the  $AS$  extracts the original parameters (such as  $C_i S_4$  and  $TS_{CS}$ ) and checks the timestamp. The  $AS$  computes  $ASS_1$  (to extract  $CSS_2$  and  $CSS_3$ ) and computes  $ASS_2$  and  $ASS_3$  (to check  $ASS_2 = CSS_2$  and  $ASS_3 = CSS_3$ ). The  $AS$  retrieves  $RN_{op_h}$  and  $UN_{op_h}$  from the

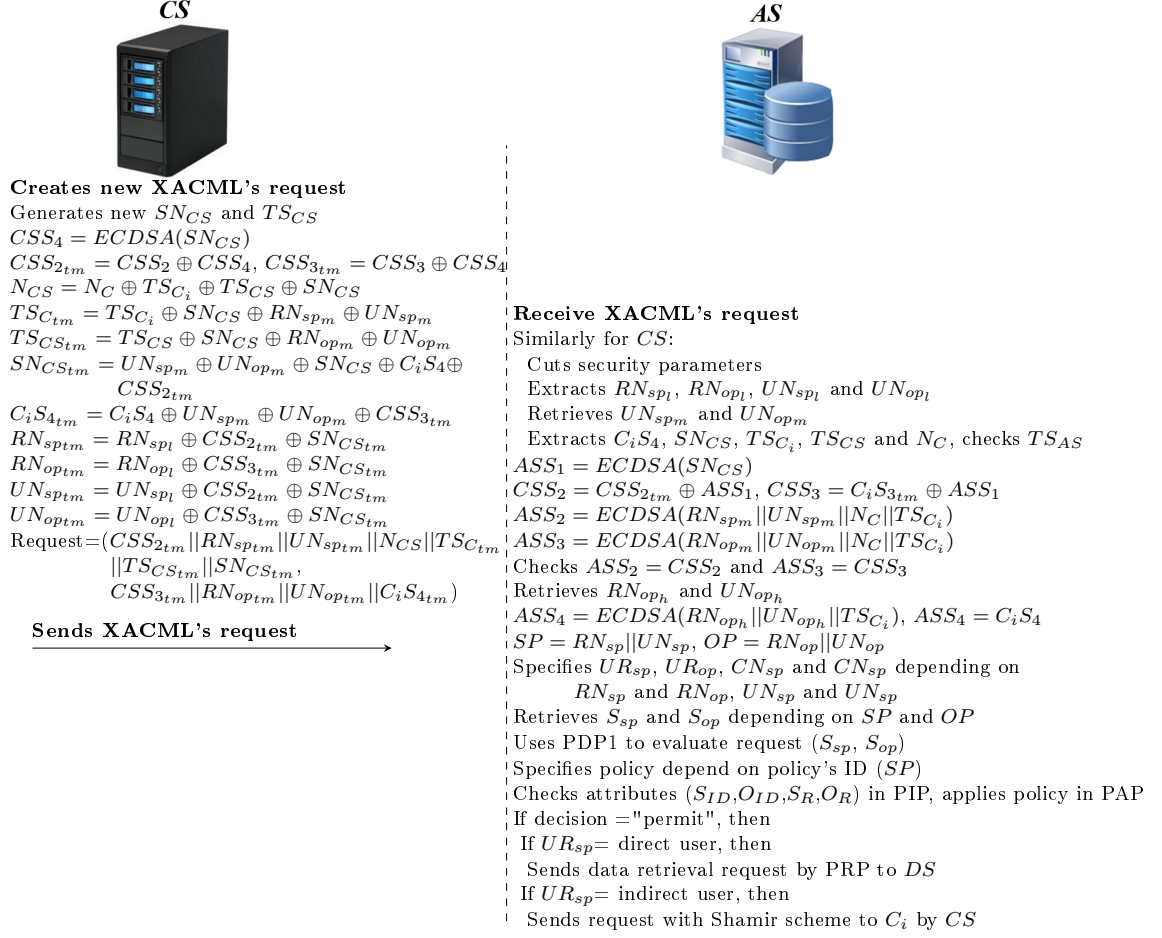


Figure 6.7: Protocol of PAX model between  $CS$  and  $AS$

dataset (depending on  $RN_{opm}$  and  $UN_{opm}$ ) and computes  $ASS_4$  to ensure  $C_i$  request is legitimate after checks  $ASS_4 = C_iS_4$ . The  $AS$  uses the parts of external pseudonyms to specify  $UR_{sp}$ ,  $UR_{op}$ ,  $CN_{sp}$  and  $CN_{op}$ .  $AS$  retrieves Sigs of  $SP$  and  $OP$  ( $S_{sp}$  and  $S_{op}$ ) depending on the internal  $SP$  and  $OP$ . The  $AS$  uses PDP1 engine to evaluate XACML's request after adding  $S_{sp}$  and  $S_{op}$  to that request. The  $AS$  specifies the user's policy in PAP and checks the user's attributes in PIP. PDP1 applies policy to get a decision (permit, deny, not applicable and indeterminate). If decision="permit", the  $AS$  uses  $UR_{sp}$  to specify the user's role (direct/indirect). If  $UR_{sp}$ =direct, the  $AS$  sends the data retrieval request by PRP to the  $DS$ ; if  $UR_{sp}$ =indirect, the  $AS$  sends the Shamir request that contain at least two  $SS_s$  to ensure legitimate indirect users. Otherwise the  $AS$  sends a reject response to  $C_i$  by  $CS$ .

3. Third protocol as shown in Figure 6.8:

\* Similarly, the  $AS$  generates random secret ( $SN_{AS}$ ) and

timestamp ( $TS_{AS}$ ) between the  $AS$  and  $DS$ . The  $AS$  computes  $ASS_5$  to protect secret ( $SN_{AS}$ ) between the  $AS$  and  $DS$ . Additionally, the  $AS$  computes  $ASS_6$  to ensure legitimate PP ( $RN_{op_m}$  and  $UN_{op_m}$ ) in the  $DS$ . All Sigs (such as  $ASS_{6tm}$ ) and PP (such as  $TS_{AS_{tm}}$  and  $SN_{AS_{tm}}$ ) are anonymously hidden by the  $AS$ . Then, the  $AS$  sends XACML's request to the  $DS$

- \* The  $DS$  receives the request, cuts Sigs and PP. After that, the  $DS$  extracts original parameters (such as  $C_iS_4$  and  $SN_{AS}$ ) and checks the timestamp. The  $DS$  computes  $DSS_1$  (to extract  $ASS_6$ ) and retrieves  $RN_{op_h}$  and  $RN_{op_m}$  depending on  $RN_{op_l}$ . Then, the  $DS$  computes  $DSS_2$  and  $DSS_3$  to check  $DSS_2 = ASS_6$  and  $DSS_3 = C_iS_4$ . If the  $AS$ 's parameters are validated in the  $DS$  correctly, the  $DS$  computes a timestamp ( $TS_{DS}$ ) and signs the patient's data ( $DSS_4$ ). All Sigs (such as  $DSS_{4tm}$ ) and PP (such as  $TS_{DS_{tm}}$ ) are anonymously hidden by the  $DS$ . At this point, the  $DS$  sends the response to the  $AS$
- \* The  $AS$  receives the response, extracts PP (such as  $TS_{DS}$ ) and checks timestamp. The  $AS$  tests the Sigs checking (such as  $ASS_6 = DSS_2$ ). Then, the  $AS$  computes data signature ( $ASS_7$ ) to check data integrity by  $ASS_7 = DSS_4$ .

#### 4. Fourth protocol as shown in Figure 6.9:

- \* The  $AS$  prepares the response to the  $CS$  by generating a new timestamp ( $TS_{AS}$ ), hides data signature ( $ASS_7$ ) with  $ASS_2$ ,  $ASS_3$ ,  $C_iS_4$  and secret signature ( $ASS_1$ ). The  $AS$  hides PP and sends the response that contains the decision and patient's data to the  $CS$
- \* The  $CS$  receives the response and extracts Sigs and PP. The  $CS$  computes data signature ( $DSS_5$ ) to check data integrity ( $CSS_5 = ASS_7$ ). Then, the  $CS$  checks other Sigs ( $CSS_2$ ,  $CSS_3$  and  $CSS_4$ ) with received Sigs ( $ASS_2$ ,  $ASS_3$  and  $C_iS_4$ ) to ensure legitimacy of the  $AS$ . The  $CS$  prepares the response to  $C_i$  by generating a new timestamp and hides data signature ( $CSS_5$ ) with  $CSS_2$ ,  $CSS_3$ ,  $C_iS_4$  and secret signature ( $CSS_1$ ). The  $CS$  sends the response to  $C_i$
- \*  $C_i$  receives the response, extracts PP and checks timestamp.  $C_i$  computes data signature ( $C_iS_5$ ) to check data integrity by  $C_iS_5 = CSS_5$ . Then,  $C_i$  extracts signatures ( $CSS_2$ ,  $CSS_3$ ,  $CSS_1$  and  $C_iS_4$ ) and checks them with original signatures ( $C_iS_1$ ,  $C_iS_2$ ,  $C_iS_3$

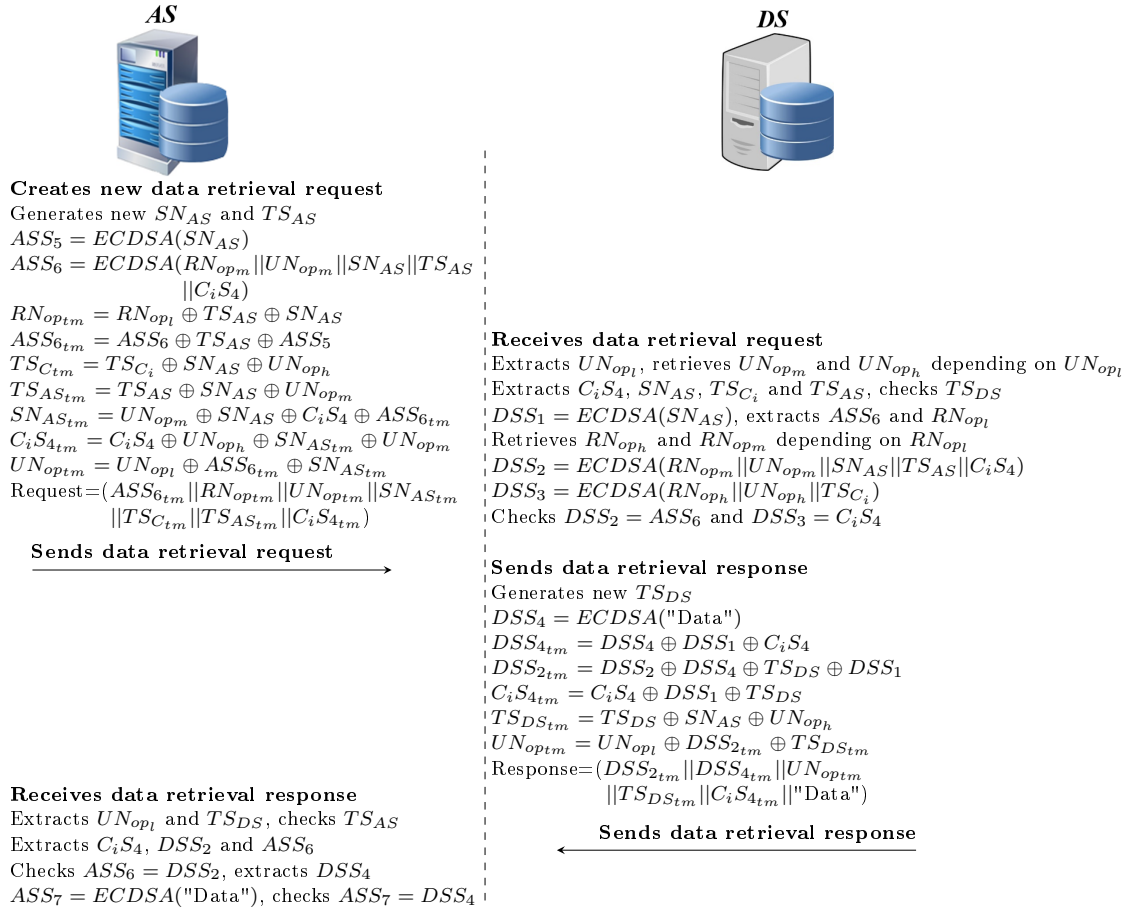


Figure 6.8: Protocol of PAX model between AS and DS

and  $C_i S_4$ ) respectively.  $C_i$  uses  $CSS_2$ ,  $CSS_3$  and  $CSS_1$  (secret signature between  $C_i$  and  $CS$ ) to check legitimacy of the  $CS$  while using  $C_i S_4$  to check legitimacy of the  $AS$  and  $DS$ . If all Sigs are validated, namely, authorised  $C_i$  received securely correct data.

- **Authorisation Protocols for Indirect Subjects and Objects**

Indirect user authorisation is an important process to secure sensitive patient data in the EHR stored in  $DS$ . PAX offers additional procedures to prevent the abuse of indirect user privileges.

- **Prerequisite procedures**

There is a set of steps that must be performed before authorisations are applied:

1. Steps from 1 to 3 are similar to those for direct users
2. The Shamir scheme is used to generate the  $SS_s$  from the  $MS$  for the number of users, each  $C_i$  has unique  $SS$  the same length as the  $MS$ , and authorised with two policies for each indirect user on the

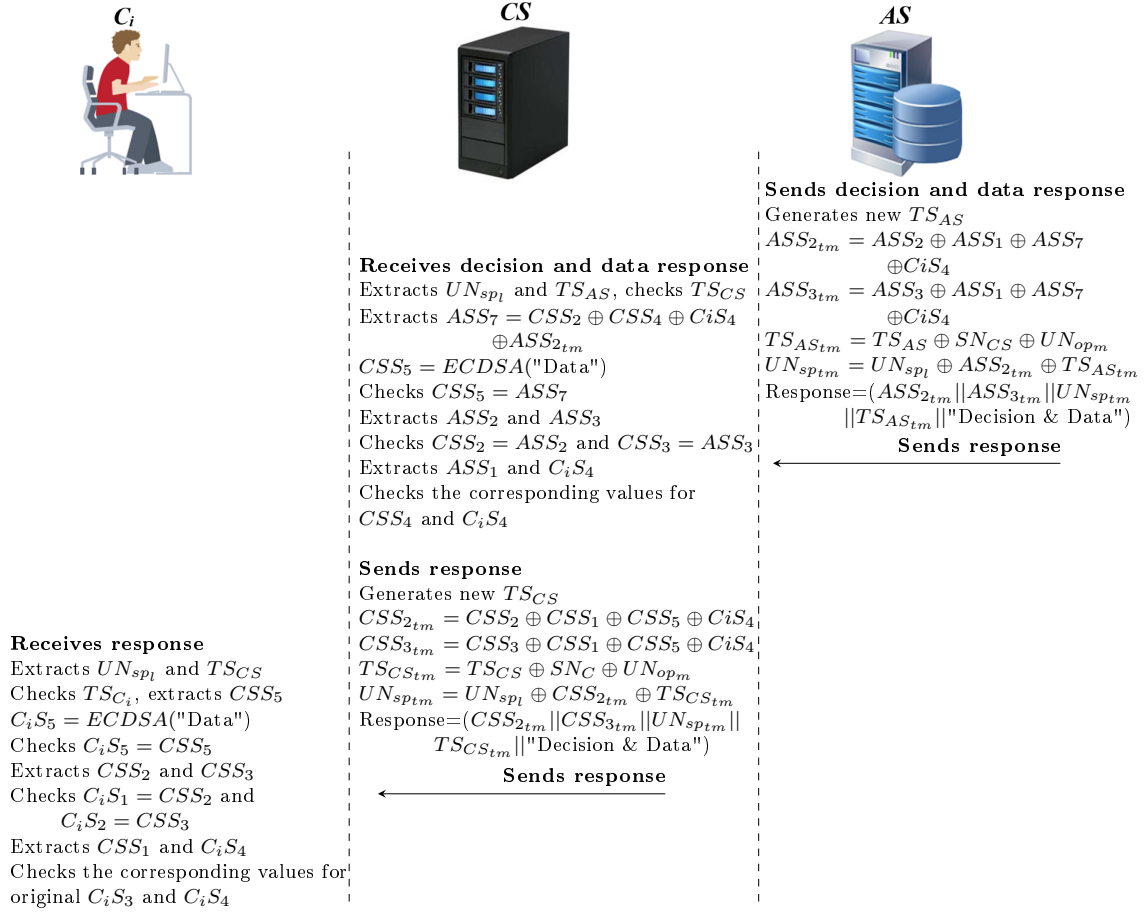


Figure 6.9: Protocol of PAX model between  $AS$ ,  $CS$  and  $C_i$

$AS$ . The policy evaluation process is also done with two, PDP1 and PDP2, evaluation engines. The use of the two evaluation engines is very important in separating direct and indirect users and increasing security in the privacy of medical records

3. The PAX authorisation system identifies certain medical records (the patients' history at a given time such as a year or more ago) for indirect users who can access them, as shown in Figure 7.28 (researcher case).

#### – Authorisation protocols

The following protocols detail how the indirect user obtains medical records in PAX. Figure 6.10 illustrates generally the authorisation of indirect users, while Figures 6.6, 6.7, 6.11, 6.8, and 6.9 show the authorisation protocols of indirect users in PAX:

1. The steps of the first and second protocols are similar to the ones of the direct users authorisation
2. Third protocol as shown in Figure 6.11:

\* The  $AS$  computed the  $MS$  previously by signing all users'

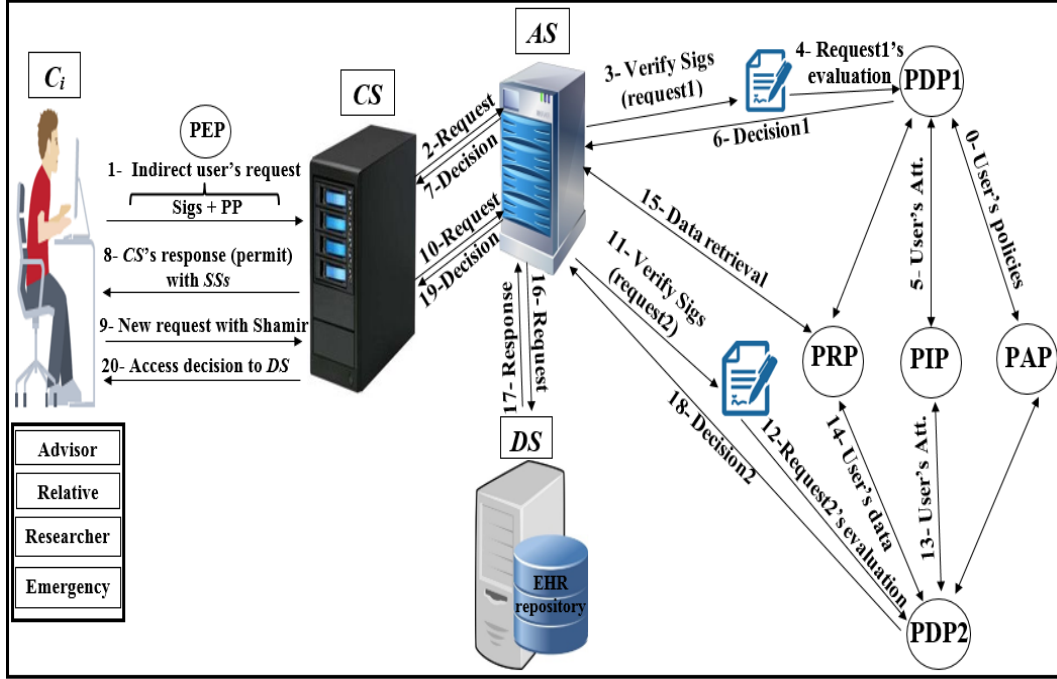


Figure 6.10: Authorisation of indirect users

signatures. Then, the  $AS$  computes the Shamir scheme to generate  $SS_s$  with the same number of users (each  $C_i$  has one unique  $SS$ ). In PAX,  $C_i$  needs at least three  $SS_s$  to generate the original  $MS$ . In this protocol, the  $AS$  generates a new timestamp and retrieves at least two  $SS_s$ . After that, the  $AS$  hides  $SS_s$  with  $ASS_2$ ,  $C_i S_4$ ,  $S_{sp}$  and secret signature ( $ASS_1$ ) as well as parameters (such as  $TS_{AS_{tm}}$  and  $UN_{sp_{tm}}$ ) are anonymously hidden. At this point, the  $AS$  sends request to the  $CS$

- \* The  $CS$  receives the request, extracts PP and checks the timestamp. Then, the  $CS$  removes the secret signature ( $CSS_4$ ) and adds the secret signature ( $CSS_1$ ) in  $CSS_{2tm}$ . The  $CS$  generates a new timestamp ( $TS_{CS}$ ), hides PP and sends the request to  $C_i$
- \*  $C_i$  receives Shamir's request, extracts PP and checks the timestamp. Then,  $C_i$  computes  $C_i S_6$  to extract  $SS_s$  and retrieves his  $SS$ . At the moment,  $C_i$  can generate the  $MS$  from Shamir ( $C_i$ 's  $SS || SS_s$ ), hides the  $MS$  with  $C_i S_6$  and  $C_i S_3$ , generates timestamp and hides PP. At this point,  $C_i$  sends the response to the  $CS$
- \* The  $CS$  receives the response, extracts PP and checks timestamp. Also, the  $CS$  removes  $CSS_1$  and adds  $CSS_4$  in  $C_i S_{6tm}$ . The  $CS$  generates a new timestamp, hides PP and sends the response to



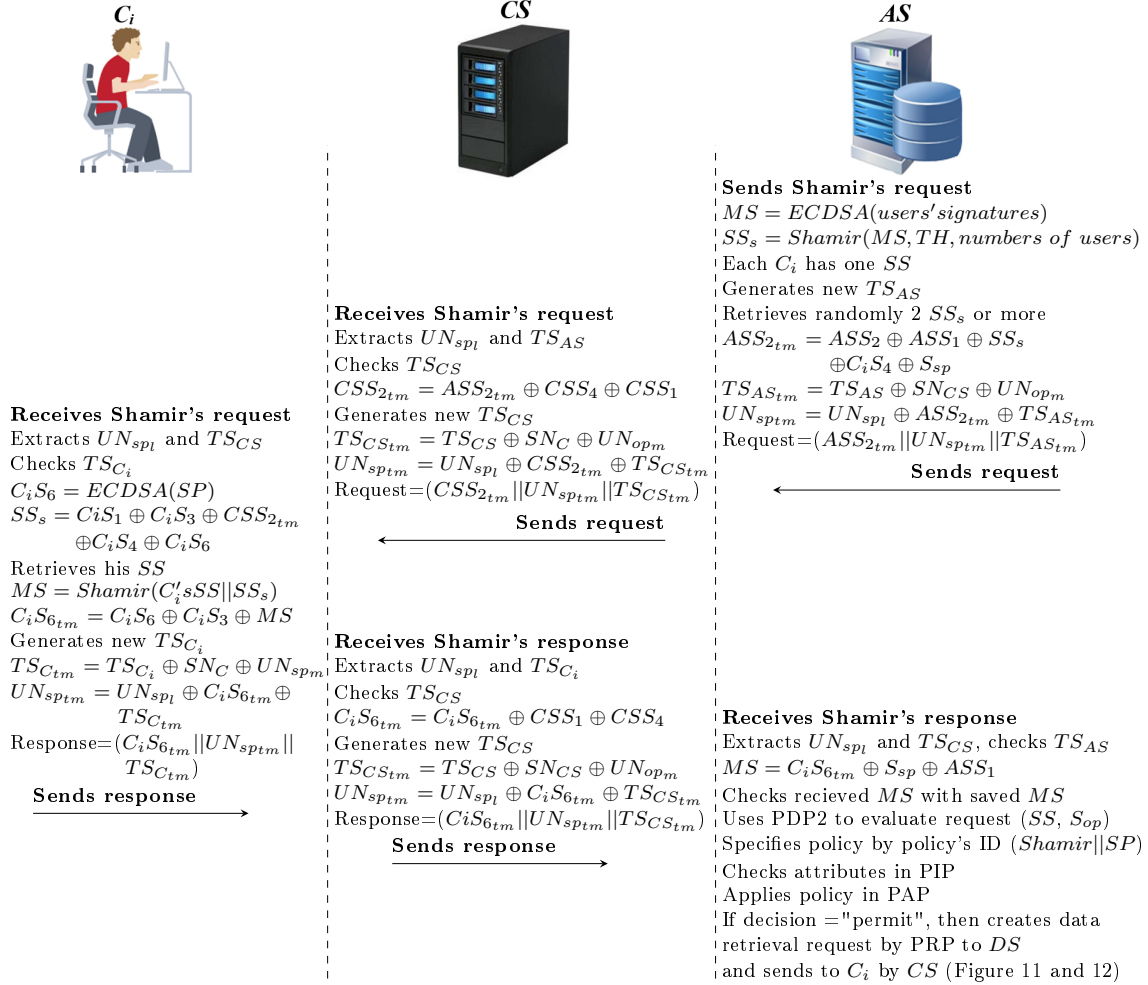


Figure 6.11: Protocol of PAX model for indirect users

the  $AS$

- \* The  $AS$  receives Shamir response, extracts PP and checks timestamp. Then, the  $AS$  extracts the received the  $MS$  and checks it with the saved original the  $MS$ . After that, the  $AS$  retrieves  $C_i$ 's  $SS$  depending on  $S_{sp}(UR_{sp} || CN_{sp})$  and assigns request  $(SS, S_{op})$  to PDP2. The  $AS$  specifies policy depending on policy's ID ( $Shamir || SP$ ), checks attributes in PIP and PDP2 applies policy in PAP to produce the decision. If the decision is "permit", the  $AS$  creates a data retrieval request by PRP to the  $DS$ ; otherwise the  $AS$  sends reject response to  $C_i$  by the  $CS$ .

3. The fourth and fifth protocols are similar to the third and fourth, respectively in the direct user authorisation. The  $DS$  sends the response to the  $C_i$  by the  $AS$  and  $CS$ . If  $C_i$  is advisor, relative, or emergency doctor,  $C_i$  will receive the specific patient's data; otherwise if  $C_i$  is researcher doctor,  $C_i$  will receive a set of medical

records.

## **6.4 Summary of the Chapter**

In this chapter, we have provided details of the requirements and design goals for building a new authorisation scheme. Then, we put forward an AC network model for the proposed HC application. The objective of the AC model is to authorise a differentiated level of access control to the EHR repository, for the purpose of achieving efficiency as well as preserving patient privacy. Finally, the authorisation scheme methodology has been explained in detail to authorise users in the HC application by having given a set of protocols and procedures for authorising HC users with their balanced and deserved authority.

# Chapter 7: Verification of Protocols for the Security and Performance

Having developed an HC application with security features and high efficiency, along with the protocols and algorithms for protecting user authentication and privacy for the patients' health/medical records; as well the HC professionals differentiated access control to the HC patients records, it is time to verify those protocols and prove that the proposed HC application has achieved the objectives. In this chapter, we start with an introduction and description of the protocol testing tool, followed by how to use the tool to verify our developed REISCH, RAMHU and PAX.

## 7.1 Security Testing Tool

In this section, we will provide security testing tool details such as the automated validation of Internet security protocols and applications (AVISPA) used in our project.

### 7.1.1 AVISPA

For all of the protocols designed so far, it is necessary to verify their ability to resist various threats/attacks. In this section, we employ the widely used AVISPA tool, and explain how to use it to check the protocols we have designed. AVISPA is a formal tool for analysing security schemes and is applied by researchers to evaluate recent security protocols (Gupta et al. 2018, Babu & Padmanabhan 2018, Xu et al. 2018, Dong et al. 2018). This tool depends on Dolev-Yao (dy) to verify security protocols. For more details of AVISPA, see Appendix D.

## 7.2 Analysis of Storage Scheme

In this section, we will discuss security and performance analyses for the REISCH scheme and compare it with existing schemes. Analyses demonstrate that REISCH is efficient for use in patient data collection within the HWSN environment in terms of security and performance.

### 7.2.1 Possible Attacks on REISCH Scheme

In this section, we will examine the REISCH scheme theoretically with a set of threats mentioned in the threat model. We will provide a theoretical analysis of REISCH resistance to known attacks as follows:

- **Proposition 1 – MITM and replay attacks**

The intruder ( $I$ ) cannot achieve MITM and replay attacks against the REISCH scheme.

**Proof**

An intruder tries to change or delete part of data/information when transferred between the network's entities. This situation is not possible because REISCH applies the ECDSA algorithm to sign data as well as some information such as  $SN_{Pseud}$ . Additionally, an intruder cannot replay a message late due to the REISCH's entities use of timestamps such as  $SN_{TS}$  and  $CH_{TS}$ . Consequently, REISCH resists MITM and replay attacks successfully.

- **Proposition 2 – DoS attacks**

$I$  will not benefit from using DoS attacks against REISCH servers.

**Proof**

An intruder applies a DoS attack to destroy the availability of service in servers such as the  $LS$  and  $CS$ . The servers in REISCH initially check lightweight parameters such as  $SigLsE_i$  in  $LS$  and  $CS_{Pseud}$  in  $CS$  before completion of the authentication process. Moreover, these parameters change randomly in the communication process between entities. This procedure allows servers to check small parameters and prevent DoS duplicate messages. Therefore, REISCH withstands DoS threats.

- **Proposition 3 – Localisation attacks**

$I$  cannot implement localisation attacks to deceive sensors and servers.

**Proof**

An intruder tries to use the Sybil attack by using many legitimate  $SN$ 's IDs with fake data. Due to  $SN_i$  waits for random  $SigLsE_i$  from the  $LS$  per round, namely, that intruder cannot deceive the  $LS$  with fake data. Also,

an intruder can employ a wormhole attack by using many  $SN_i$  to camouflage communications between network entities. Each  $SN_i$  implicitly sends  $SN_{SL_i}$  to the  $LS$  and  $Dif$  to  $CH_i$  as well as a timestamp. These parameters prevent counterfeit communications. Furthermore, if an intruder aims to apply a sinkhole attack using a node as a sink to attract all patient data from  $SN_i$ , it cannot apply to REISCH because the  $LS$  sends an unique  $LS_{OTP_i}$  including  $SigLS_i(SN_{Pseud_i})$  for all  $SN_i$ . That intruder fails to detect  $SigLS_i$  and  $SN_{Pseud_i}$ . Hence, REISCH strongly overcomes localisation attacks.

- **Proposition 4 – Repository attack**

$I$  does not have the ability to penetrate the EMR repository.

**Proof**

Assume that an intruder can penetrate datasets in  $LS$ . First,  $LS$  does not contain real patient information (real information such as the name is stored in the  $AS$ ). When the intruder gets this data, he/she cannot disclose that it belongs to a particular patient. Second, the  $LS$  'datasets are very difficult to penetrate. Furthermore, the  $LS$  contains partial data for patients because the total data and patients' history are transferred to the  $DS$  by the  $CS$  periodically. Thereupon, REISCH resists the EMR repository attack.

- **Proposition 5 – Eavesdropping attacks**

The external intruder ( $EI$ ) will not get any benefit from eavesdropping in the disclosure of personal information of collected data.

**Proof**

When an intruder eavesdrops and gets some of the messages transferred between  $SN_i$ ,  $CH_i$ ,  $LS$  and  $CS$ . This intruder will not benefit from these messages trapped because these messages contain no real information. Furthermore, the secret parameters are completely hidden. Thus, REISCH prevents eavesdropping attacks from revealing patient information.

- **Proposition 6 – Replication attack**

$I$  cannot perform node replication attacks.

**Proof**

An intruder applies node replication attack by using more than one  $SN_i$  with the same legitimate ID. In REISCH, we suppose that all  $SN_i$  are inside a specific area in the hospital or clinic. Therefore, any  $SN_i$  outside this area extremely finds it difficult to send messages from fake  $SN_i$  with the same legitimate ID. In addition,  $LS$  waits  $SN_m$  by  $CH_i$  at the same number of  $SN_i$  and the  $LS$  remove replicated  $SN_m$  or  $SigSnT_3$ . Also, when  $SN_i$  dies,  $LS$  records this situation in the dataset to prevent replication risks. In a result, REISCH effectively resists replication attacks.

- **Proposition 7 – Collision and preimage attacks**

*I* does not have the ability to perform collision and preimage attacks against REISCH algorithms.

**Proof**

An intruder tries to implement a collision (the generation of two different messages that produce the same MD = $h(m) = h(m')$ ), preimage (the generation of a message that produces the same existing MD value as  $h(m) = MD$ ) and second preimage (the generation of a different message from the received message and produce the same existing MD value) attacks when messages and signatures are transferred between REISCH's entities. These attacks cannot be implemented on REISCH protocols because our protocols use the BLAKE2bp hash instead of SHA1 which resists these attacks. Consequently, REISCH successfully prevents collision and preimage attacks.

1. **Experimental Security Analysis**

Now it is the time to use the AVISPA to conduct a security analysis on the REISCH scheme.

- **REISCH Scheme with AVISPA**

As we have known that REISCH includes four essential roles: localServer (*LS*), sensori (*SN<sub>i</sub>*), clusterHead (*CH<sub>i</sub>*) and centralServer (*CS*), as well as supporting roles: session and environment. Also, there are three sections to complete communication properly and securely: transition, composition and goal specification. The transition section is used in the essential roles to maintain the correct communication sequence. The composition section is used in the supporting roles to connect essential roles in specific sessions. The goal specification section includes security goals such as secrecy and authentication. Secrecy means known secrets only for specific entities while authentication depends on witness (freshness claim) and request (validation) processes to perform strong authentication.

Also, our scheme uses parameters such as RCV (receiving process), SND (sending process), *\_inv* (private key), *dy* (communication channel by Dolev-Yao model) and *intruder\_knowledge* (known information for an intruder). We assume the intruder uses the public key (*k<sub>i</sub>*) and knows the public keys for REISCH's entities (*kSN<sub>pu</sub>*, *kCH<sub>pu</sub>* and *kLS*). Figure 7.1 shows the REISCH's framework in AVISPA.

As shown in Figure 7.4, the *LS* receives the start signal. Then, the *LS* generates and sends new *LSotpi* for all sensors (*SN<sub>i</sub>* and *CH<sub>i</sub>*). *LSotpi*

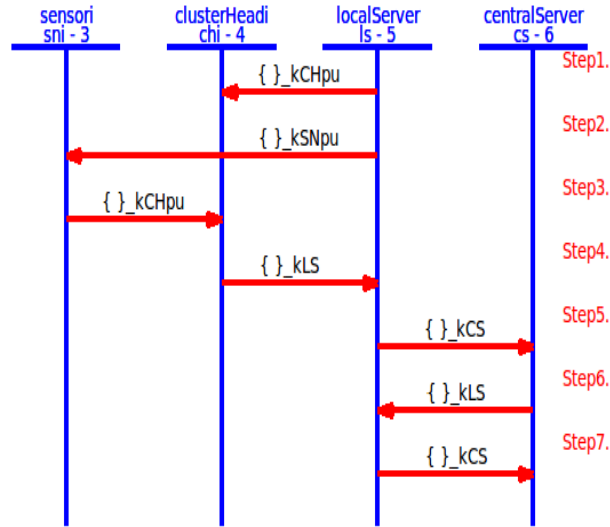


Figure 7.1: REISCH's framework in AVISPA

includes new *SigLsEi* and pseudonym signature. Both Figure 7.2 and Figure 7.3 show that *SNi* and *CHi* receive *LSotp* from the *LS*. Furthermore, *SNi* and *CHi* use freshness nonces, timestamp and signature to support reliable security. For instance, *SNi* uses *SigLsEi*, *SigSnEi*, *SNTs* and *SigSN* to achieve security processes with *CHi* and the *LS*.

*SNi* collects data and uses one ECDSA signature with XoR operations to protect collected data and sends it to *CHi*. At this stage, *CHi* aggregates data and adds security parameters. *CHi* sends aggregation data to the *LS*. After that, the *LS* uses *LSotp*, *SigLS5* and *LSrn* to connect with the *CS* securely as shown in Figure 7.4. Figure 7.5 shows the *CS* with the storage process. The *CS* receives *LSotp* and uses  $ECDSA(CsT2)$ , *CsT1*, *CsT2* and *CSrn* to secure communication with the *LS*. Figure 7.6 shows session and environment roles as well as security goals (secrecy and authentication).

REISCH applies seven secrecy and seven authentication goals. For instance, Sec1 represents secrets between *SNi* and the *LS* such as *SigSN*, *SigLsEi* and *SigSnEi*. Also, the authentication goal, such as auth4 proves freshness between *CHi* and the *LS* such as *CHts2*, *CHotp*, *CHrni* and *SNrni*. Additionally, the environment role includes many attacks (replay, MITM and impersonating) to test the security level in the REISCH scheme.

```

role sensori(SNi,CHi,LS:agent, KSNpu,KCHpu,KLSpu:public_key, ECDSA:hash_func, SNpseud,SNs1,
            Data:text,SND,RCV:channel(dy))
played_by SNi def=
local
    State:nat,
    SNrni,SigLsEi,SigSnEi,SNparity:text,
    MAXv:message,SigSN,SigSnT1,SigSnT2,SigSnT3,SigSnT4,SigLSi:text,
    Dif,SNts,SNtst,SNotp,Date,Time,SS,SNp,LSotpi:text
const
    sec1,sec2,sec3,auth3:protocol_id
init
    State := 0
transition
% SNi receives(LSotpi) from LS
1.State=0
  /\RCV(SNi.LSotpi'.SNrni') => State':=1
  /\SigSnEi':=new() /\SigLSi':={ECDSA(SNpseud)}_inv(KSNpu)
  /\SigLsEi':=xor(LSotpi',SigLSi) /\SigSN':={ECDSA(Data.SNpseud)}_inv(KLSpu)
  /\SNparity':=SigSN' /\SigSnT1':=SNparity' /\SigSnT2':=xor(SigSnT1',SigSnEi')
  /\SNts':=new() /\SNotp':=new() /\SNtst':=xor(Date,xor(Time,xor(SNotp',xor(Dif))))
  /\SNp':={SNtst'.SNotp'.SNrni'.SNpseud.SNs1} /\SigSnT3':=xor(SNp',SigSnT2')
  /\SigSnT4':=xor(SigLsEi',SigSnEi')
  /\secret({SigSN',SigLsEi',SigSnEi'},sec1,{SNi,LS}) /\secret({SNpseud,SNs1},sec2,{SNi,LS})
  /\secret({MAXv,SNts'},sec3,{SNi,CHi})
% SNi sends(SNm) to CHi
/\SND(CHi.SigSnT3'.SigSnT4'.SNrni'.Dif.SNtst'.SS.Data) /\witness(SNi,CHi,auth3,{SNtst',SNrni',Dif})
end role

```

Figure 7.2:  $SN_i$  role of REISCH in HLPsL

```

role clusterHead(CHi,LS,SNi:agent, KCHpu,KLSpu,KSNpu:public_key, ECDSA:hash_func,CHpseud,CHs1:text,
                MAXv:message,SND,RCV:channel(dy))
played_by CHi def=
local
    State:nat,
    SNrns,SNrni,SigLsEi,SNparityi,SNts,LSotpi:text, SigCH,SigChT1,SigChT2,SigSnT3s,SigSnT4s,
    SigSnT3i,SigSnT4i,SigLSi,Difi,SNtst,CHts1,CHts2,SS,SSi,CHp,CHparity,CHotp,CHrni,Datai,
    Datas,CHa:text
const
    sec3,sec4,sec5,auth4:protocol_id
init
    State := 0
transition
% CHi receives(LSotpi) from LS
1.State=0
  /\RCV(CHi.LSotpi'.CHrni')=> State':=1

% CHi receives from SNi
2.State=1/\RCV(CHi.SigSnT3i'.SigSnT4i'.SNrni'.Difi'.SNtst'.SSi'.Datai')=>State':=2
  /\CHts1':=new() /\SigSnT3s':={SigSnT3s'.SigSnT3i'} /\SigSnT4s':={SigSnT4s'.SigSnT4i'}
  /\SNrns':=SNrni' /\Datas':=Datai' /\SigCH':={ECDSA(SigSnT3s')}_inv(KLSpu)
  /\CHparity':=SigCH' /\SigChT1':=xor(CHparity',CHts1')
  /\SigLSi':={ECDSA(CHpseud)}_inv(KCHpu) /\SigLsEi':=xor(LSotpi',SigLSi')
  /\SigChT2':=xor(SigChT1',SigLsEi') /\CHts2':=new() /\CHotp':=new()
  /\secret({MAXv,SNts},sec3,{CHi,SNi}) /\secret({SigCH,SigLsEi,CHpseud,CHs1},sec4,{CHi,LS})
  /\secret({CHotp',CHts2'},sec5,{CHi,LS})
% CHi sends(CHm) to LS
  /\SND(LS.(xor((CHts2'.CHotp'.CHrni.CHpseud.CHs1),SigChT2)).CHrni.SS.(SigSnT3s.SigSnT4s
    .SNrns'.Datas')) /\witness(CHi,LS,auth4,{CHts2',CHotp',CHrni,SNrns'})
end role

```

Figure 7.3:  $CH_i$  role of REISCH in HLPsL

## • Simulation Results

The simulation results described by the AVISPA tool. We have applied AVISPA with OFMC and CL-AtSe backends. Both the



OFMC (Figure 7.7) and CL-AtSe (Figure 7.8) results show that the REISCH scheme is safe against passive and active attacks (as in the SUMMARY section). Furthermore, Figure 7.7 and Figure 7.8 shows analysis details about simulation reports such as the number of sessions, goals and statistical numbers. Also, the goals of authentication and secrecy in Figure 7.6 are applied to prevent the penetration of sensors' data/information in the network. These results prove that REISCH is reliable in combatting known attacks such as replay, MITM, and impersonating.

## 2. Security Comparison

Not only is REISCH secure against the various attacks mentioned in Section 7.2.1, it is also superior over the other schemes in terms of security (Table 7.1 shows a comparison of security features between our scheme and existing schemes).

For example, compared with the scheme in Fan & Gong (2012) that uses a small key ( $F_{2^{163}}$ ) and is extremely vulnerable to attacks, REISCH uses a key with 256-bit that resists attacks (reputable organisation recommendations). REISCH also uses BLAKE2bp to get rid of hash attacks (collision and preimage) while the scheme in Kodali (2013) focused on SHA1 performance without attention to the collision/preimage threats. In addition, all security parameters in REISCH such as  $SN_i$ 's location are completely hidden, while the scheme in Lavanya & Natarajan (2017b) transfers some information explicitly, such as ID (the elliptic curve parameters) in the registration and authentication phases. This allows intruders to distinguish a specific  $SN_i$ . Additionally, this scheme did not address the problem of hiding  $SN_i$  location.

Although the authors in Staudemeyer et al. (2018) addressed privacy to protect the  $SN_i$  parameters, their scheme did not use the signature camouflage or  $SN_{OTP}$  that are used in REISCH to support the privacy of data signing. This makes the privacy parameters in their scheme vulnerable to analysis and easy tracking. Furthermore, REISCH outperforms the scheme in Malathy et al. (2018) which did not use the signature aggregation scheme to support security and hide signatures. The scheme in Sharavanan et al. (2018) uses ECDSA to secure heterogeneous network environments. But their scheme gives medical evaluators privileges to modify the medical parameters in the monitoring environment,  $SN_i$ 's locations and even creates keys that could be the cause of an internal attack. Moreover, some information sent from  $SN_i$  to

the server can clearly leak to intruders. Fortunately, REISCH does not suffer from these problems.

```

role localServer(LS,CHi,SNi,CS:agent, KLSpu,KCHpu,KSNpu,KCSpu:public_key, ECDSA:hash_func,SNpseudi
,SNsli:text,SND,RCV:channel(dy))
played_by LS def=
local
    State:nat,
    SNrni,SNrns,SigLsEi,SigSnEi,SNparityi,SNp:text,
    SigChT2,SigSnT3i,SigSnT4i,SigSnT3s,SigSnT4s,SigLsT1i,SigLsT2i,SigLs1i,SigLs2i,SigLsSi:text,
    CHrni,CHparityi,CHotpi,CHsli,CHts2,SS,Datai,Datas:text,LSpseudo,LSpseudn,CSpseudo,
    CSpseudn:text, LSts2,LSts3,LSts4,LsT1,LsT2,LsT3,Lsotpi,Lsotpii:text,
    CHpseudi,Lsotp,Csotp,CSts1,CsT1,CsT2,CSrn,LSrn,SigLS3,SigLS4,SigLS5:text
const
    sec1,sec2,sec4,sec5,sec6,sec7,auth1,auth2,auth4,auth5,auth6,auth7:protocol_id
init
    State := 0
transition
% Starting signal
1.State=0
    /\ RCV(start) =|>
% LS sends (Lsotpi,Lsotpii)to SNi & CHi
    State':=1/\ SNrni':=new()\SigLsEi':=new()
    /\Lsotpi':=xor({ECDSA(SNpseudi)}_inv(KSNpu),SigLsEi') /\witness(LS,SNi,auth1,{SigLsEi',SNrni'})
    /\SND(SNi.Lsotpi'.SNrni') /\SNrni':=new()\SigLsEi':=new()
    /\Lsotpii':=xor({ECDSA(SNpseudi)}_inv(KCHpu),SigLsEi') /\witness(LS,CHi,auth2,{SigLsEi',SNrni'})
    /\SND(CHi.Lsotpii'.SNrni')
2.State=1
% LS receives(CHm) from CHi
    /\RCV(LS.(xor((CHts2'.CHotpi'.CHrni'.CHpseudi'.CHsli'),SigChT2')).CHrni'.SS'.(SigSnT3s'.SigSnT4s'
.SNrns'.Datas')) =|>State':=2
    /\SigLs1i':={ECDSA(SigSnT3s')}_inv(KLSpu) /\CHparityi':=SigLs1i'
    /\SigLsT1i':=xor(SigLs1i',SigLsEi)
    /\SigChT2':=xor((CHts2'.CHotpi'.CHrni'.CHpseudi'.CHsli'),SigLsT1i')
    /\SNrni':=SNpseudi/\Datai':=Datas' /\SigLs2i':={ECDSA(Datai.SNpseudi)}_inv(KLSpu)
    /\SNparityi':=SigLs2i' /\SigSnT3i':=SigSnT3s' /\SigSnT4i':=SigSnT4s'
    /\SigSnEi':=xor(SigSnT4i',SigLsEi) /\SigLsT2i':=xor(SNparityi',SigSnEi')
    /\SNp':=xor(SigLsT2i',SigSnT3i') /\request(LS,CHi,auth4,{CHts2,CHotpi',CHrni',SNrns'})
    /\secret({SigLs2i',SigLsEi,SigSnEi},sec1,{LS,SNi}) /\secret({SNpseudi,SNsli},sec2,{LS,SNi})
    /\secret({CHparityi',SigLsEi,CHpseudi,CHsli},sec4,{LS,CHi})
    /\secret({CHotpi',CHts2'},sec5,{LS,CHi}) /\LSpseudn':=new()\LSts2':=new()
    /\Lsotp':=xor(SigLsSi,xor(LSpseudn',LSts2'))
% LS sends(Lsotp) to CS
    /\SND(CS.Lsotp'.SS) /\secret({LSpseudn,CSpseudn},sec6,{LS,CS})
    /\witness(LS,CS,auth5,{CSpseudo,LSpseudn',LSts2'})
3.State=2
% LS receives(CSm) from CS
    /\ RCV(LS.{ECDSA(CsT2')}_inv(KLSpu).CsT1'.CsT2'.SS'.CSrn') =|>
    State':=3/\LSts3':=new() /\Csotp':=xor(CSts1,xor(CsT1',xor(LSpseudn,CSrn')))
    /\CSpseudn':=xor(CSts1,xor(Csotp',xor(CsT2',LSpseudn)))
    /\SigLS3':={ECDSA(xor(CSts1,xor(Csotp',xor(CSpseudn',LSpseudn))))}_inv(KLSpu)
    /\secret({SigLsSi,Csotp'},sec7,{LS,CS}) /\request(LS,CS,auth6,{CSpseudn',LSpseudn,CSts1})
% Prepares message to send data with mutual authentication
    /\LSts4':=new()\LSrn':=new() /\LsT1':=xor(LSts4',xor(LSpseudn,xor(LSrn',CSrn')))
    /\SigLS4':={ECDSA(LsT1')}_inv(KCSpu) /\LsT2':=xor(CSts1,xor(Csotp',CSpseudn'))
    /\LsT3':=xor(LsT2',LSpseudn) /\SigLS5':=xor({ECDSA(Datas.LsT3')}_inv(KCSpu),SigLS4')
% LS sends(LSm) to CS
    /\SND(CS.SigLS5'.SS.LSrn'.Datas) /\witness(LS,CS,auth7,{SigLS5',LSts4',LSrn'})
end role

```

Figure 7.4: *LS* role of REISCH in HLPSP

```

role centralServer(CS,LS:agent, KCSpu,KLSpu:public_key, ECDSA:hash_func,SND,RCV:channel(dy))
played_by CS def=
local
  State:nat,
  SigCS1,SigCS2,LSts4:text, LSpseudo,LSpseudn,CSpseudo,CSpseudn:text,
  CsT1,CsT2,CsT3,CsT4,LSts2,CSts1,CSts2,CSotp,CSrn,LSrn,SS,Datas,LSotp,SigLSi,SigLS5:text
const
  sec6,sec7,auth5,auth6,auth7:protocol_id
init
  State := 0
transition
% CS receives from LS
1.State=0
  /\RCV(CS.LSotp'.SS)=|> State':=1 /\CSts1':=new()/\CSpseudn':=new()
  /\CSotp':=new()/\CSrn':=new() /\CsT1':=xor(CSts1',xor(CSotp',xor(LSpseudn,CSrn')))
  /\CsT2':=xor(CSts1',xor(CSotp',xor(CSpseudn,LSpseudn)))
  /\request(CS,LS,auth5,{CSpseudo,LSpseudn,LSts2'})
  /\secret({LSpseudn,CSpseudn},sec6,{CS,LS}) /\secret({SigLSi,CSotp'},sec7,{CS,LS})
% CS sends to LS
  /\SND(LS.{ECDSA(CsT2')}_inv(KLSpu).CsT1'.CsT2'.SS.CSrn')
  /\witness(CS,LS,auth6,{CSpseudn,LSpseudn,CSts1'})

% CS receives from LS
2.State=1
  /\RCV(CS.SigLS5'.SS'.LSrn'.Datas')=|> State':=2/\CSts2':=new()
  /\SigCS1':={ECDSA(xor(LSts4,xor(LSpseudn,xor(LSrn,CSrn))))}_inv(KCSpu)
  /\CsT3':=xor(CSts1',xor(CSotp,CSpseudn)) /\CsT4':=xor(LSpseudn,CsT3')
  /\SigCS2':=xor({ECDSA(Datas.CsT4')}_inv(KCSpu),SigCS1')
  /\request(CS,LS,auth7,{SigLS5,LSts4,LSrn'})
end role

```

Figure 7.5: *CS* role of REISCH in HLPSP

REISCH adds sufficient randomization to hide security parameters, and patient records are protected even after *LS* is penetrated, while the scheme in Sui & de Meer (2019) needs to support randomization and protect user information when a demand-response management unit is penetrated by an intruder. Besides, an intruder can send messages from a forged unit and deceive users after penetrating this module and revealing information.

REISCH is robust against information leakage, while the scheme in Hathaliya et al. (2019) uses a 160-bit key that is vulnerable to attacks. It explicitly sends patient identities within the encrypted message in the login and authentication phases. If an intruder can break the encryption, he/she uses this information in data disclosure. REISCH uses ECDSA-BLAKE2bp and random pseudonyms to secure data signing. The scheme in Furtak et al. (2019) is based on SHA1 and HMAC, which are vulnerable to attacks in signing and authenticating collected data. It also does not include a pseudonym mechanism to protect  $SN_i$  parameters from misbehaving.

```

role session(SNi,CHi,LS,CS:agent, KSNpu,KCHpu,KLSpu,KCSpu:public_key, ECDSA:hash_func ,MAXv:
message, SNpseudi,SNsli,Datai:text)
def=
local
  SND1,RCV1,SND2,RCV2,SND3,RCV3,SND4,RCV4: channel(dy)
composition
  sensori(SNi,CHi,LS,KSNpu,KCHpu,KLSpu,ECDSA,SNpseudi,SNsli,Datai,SND3,RCV3)
  /\clusterHeadi(CHi,LS,SNi,KCHpu,KLSpu,KSNpu,ECDSA,SNpseudi,SNsli,MAXv,SND2,RCV2)
  /\localServer(LS,CHi,SNi,CS,KLSpu,KCHpu,KSNpu,KCSpu,ECDSA,SNpseudi,SNsli,SND1,RCV1)
  /\centralServer(CS,LS,KCSpu,KLSpu,ECDSA,SND4,RCV4)
end role

role environment()
def=
const
  kSNpu,kCHpu,kLS,kCS,ki:public_key, ecdsa:hash_func,datai,snpseudi,snsli:text,
  sni,chi,ls,cs,i:agent,maxv:message,
  sec1,sec2,sec3,sec4,sec5,sec6,sec7,auth1,auth2,auth3,auth4,auth5,auth6,auth7:protocol_id
  intruder_knowledge = {sni,chi,ls,i,kSNpu,kCHpu,kLS,ki}
composition
  session(sni,chi,ls,cs,kSNpu,kCHpu,kLS,kCS,ecdsa,maxv,datai,snpseudi,snsli)
  % Check replay attack
  %/\ session(sni,chi,ls,cs,kSNpu,kCHpu,kLS,kCS,ecdsa,maxv,datai,snpseudi,snsli)
  % Check MITM attack
  %/\ session(chi,sni,ls,cs,kSNpu,kCHpu,kLS,kCS,ecdsa,maxv,datai,snpseudi,snsli)
  % Check impersonate SNi
  /\ session(i,chi,ls,cs,kSNpu,kCHpu,kLS,kCS,ecdsa,maxv,datai,snpseudi,snsli)
  % Chekc impersonate CHi
  %/\ session(sni,i,ls,cs,kSNpu,kCHpu,kLS,kCS,ecdsa,maxv,datai,snpseudi,snsli)
  % Check impersonate LS
  %/\ session(sni,chi,i,cs,kSNpu,kCHpu,kLS,kCS,ecdsa,maxv,datai,snpseudi,snsli)
end role

goal
  secrecy_of sec1,sec2,sec3,sec4,sec5,sec6,sec7
  authentication_on auth1,auth2,auth3,auth4,auth5,auth6,auth7
end goal
environment()

```

Figure 7.6: Session, environment and goal roles of REISCH in HLPSL

```

% OFMC
% Version of 2006/02/13
SUMMARY
  SAFE
DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
PROTOCOL
  /home/span/span/testsuite/results/REIESCH.if
GOAL
  as_specified
BACKEND
  OFMC
COMMENTS
STATISTICS
  parseTime: 0.00s
  searchTime: 532.61s
  visitedNodes: 1899 nodes
  depth: 7 plies

```

Figure 7.7: Simulation result of REISCH using OFMC backend

```

SUMMARY
  SAFE
DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
  TYPED_MODEL
PROTOCOL
  /home/span/span/testsuite/results/REIESCH.if
GOAL
  As Specified
BACKEND
  CL-AtSe
STATISTICS
  Analysed : 325 states
  Reachable : 325 states
  Translation: 0.12 seconds
  Computation: 0.01 seconds

```

Figure 7.8: Simulation result of REISCH using CL-AtSe backend

Table 7.1: Comparison of security features between REISCH and other data collection schemes

Security feature	Fan & Gong (2012)	Lavanya & Natarajan (2017b)	Staudemeyer et al. (2018)	Malathy et al. (2018)	Sharavanan et al. (2018)	Sui & de Meer (2019)	Hathaliya et al. (2019)	Furtak et al. (2019)	<b>REISCH scheme</b>
Anti MITM		✓				✓	✓	✓	✓
Anti replay	✓	✓	✓			✓	✓	✓	✓
Availability	✓	✓					✓	✓	✓
Anti Sybil	✓						✓	✓	✓
Anti Wormhole							✓	✓	✓
Anti fake sink							✓	✓	✓
Anti repository attack					✓			✓	✓
Anti eavesdropping		✓	✓	✓	✓	✓	✓	✓	✓
Anti node replication							✓	✓	✓
Anti collision/preimage		✓						✓	✓
Pseudonym						✓	✓		✓
Homomorphic						✓			✓
Mutual authentication		✓					✓		✓

## 7.2.2 Performance Analysis

Analysis of performance is an important factor when designing data/records collection protocols for HWSNs. In this section, we analyse REISCH performance theoretically and experimentally, and compare it with existing schemes.

- **Theoretical Performance Analysis**

Theoretically, REISCH uses several features that qualify it to be efficient in HWSN performance. First, it relies on the ECDSA algorithm that integrates data collected by small keys compared to public key cryptography algorithms (RSA, DSA and Elgamal). For instance, ECDSA produces 256-bit equivalent keys in security for 3072-bit keys produced by RSA, DSA, and Elgamal. Second, REISCH implicitly uses BLAKE2bp with ECDSA which is dramatically efficient in the operation of a hash function instead of SHA1. Third, REISCH uses the homomorphic property to combine signatures in *CHs* and significantly reduces energy dissipation. Fourth, REISCH relies on the LEACH routing protocol, which is the most efficient energy-saving protocol in WSN. Fifth, REISCH relies on rapid random pseudonyms to protect medical records rather than complex and costly processes of data encryption and k-anonymity. Finally, REISCH uses XML to support efficient patient data management. Therefore, these features allow REISCH to maintain the energy of the *SNs* as long as possible.

- **Experimental Performance Analysis**

More importantly, we will evaluate the performance of REISCH in the execution of security operations in conjunction with the saved and collected data. As noted in previous sections, *SNs* requires performance-efficient signatures to perform services for as long as possible in patients' monitoring

Table 7.2: REISCH’s simulation parameters

Parameters	Value
Area of WSN	1000m×1000m
Number of <i>SNs</i>	200
Number of <i>CHs</i>	5%
Number of hops	2
Node type	Homogeneous
Node distribution	Random
<i>LS</i> location	(500,500)
<i>Dif</i>	Maximum value (707.1068)
Initial energy	25J
Size of packet	200K, 400K, 800K and 1M
Control packet size	50B
Rounds	1000
Routing protocol	LEACH
Propagation energy	10 nJ/bit/ $m^2$
Multi-hop propagation energy	0.0013 pJ/bit/ $m^4$
Aggregation energy	5 nJ/bit/signal
Number of runs	100
Simulation time	300s
Simulator	Octave

Table 7.3: REISCH computational processes

Process type	Number of process			Running time	Storage	Energy
	<i>SN</i>	<i>CH</i>	<i>LS</i>			
SHA1 hash	1	1	Many	0.05529	160-bit	0.008464
BLAKE2bp hash	1	1	Many	0.040606	512-bit	0.006216
Keys generation	2	2	2	0.000859	256-bit	0.000132
Point multiplication	2	2	Many	0.000543	-	0.000083
ECDSA-SHA1 signature	1	1	-	0.072838	256-bit	0.011151
ECDSA-SHA1 verification	-	-	Many	0.073103	-	0.011191
ECDSA-BLAKE2bp signature	1	1	-	0.050046	256-bit	0.007662
ECDSA-BLAKE2bp verification	-	-	Many	0.052076	-	0.007972

and care. We will provide tests on hash algorithms (SHA and BLAKE) and the signature algorithm (ECDSA). Additionally, we apply these algorithms to HWSN to analyse performance properties such as time, storage and energy. Table 7.2 shows all the simulation parameters used in HWSN, while Table 7.3 shows computational operations in the REISCH scheme. All hash and signature algorithms are implemented by C language while WSN is designed in Octave under Ubuntu 16.04 LTS, processor Intel Core i5 2.6GHz, OS type 64-bit, Memory 4 GiB and disk 32.0 GB.

The computation of energy in our scheme is based on the Micaz sensor specification. This process uses parameters such as current (0.0567), voltage (2.7) and time to extract both power and energy using  $power = current * voltage$  and  $energy = time * power$ . We relied on real data provided by the City of Melbourne that is licensed under CC 4.0 (City of Melbourne Open Data Team October 19, 2018). This data was generated by sensors to monitor environmental parameters such as humidity, temperature and light, as well as include some information such as timestamp and ID. We divided this data into different sizes (200K, 400K, 800K and 1M) and then converted it into an XML context. Furthermore, there are no communication

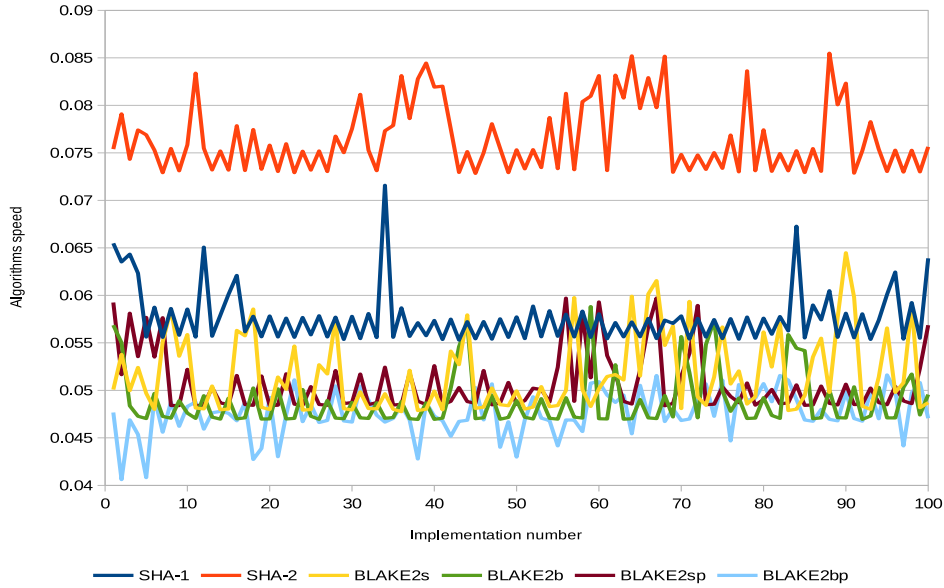


Figure 7.9: Comparison of SHA and BLAKE2 with 1MB data

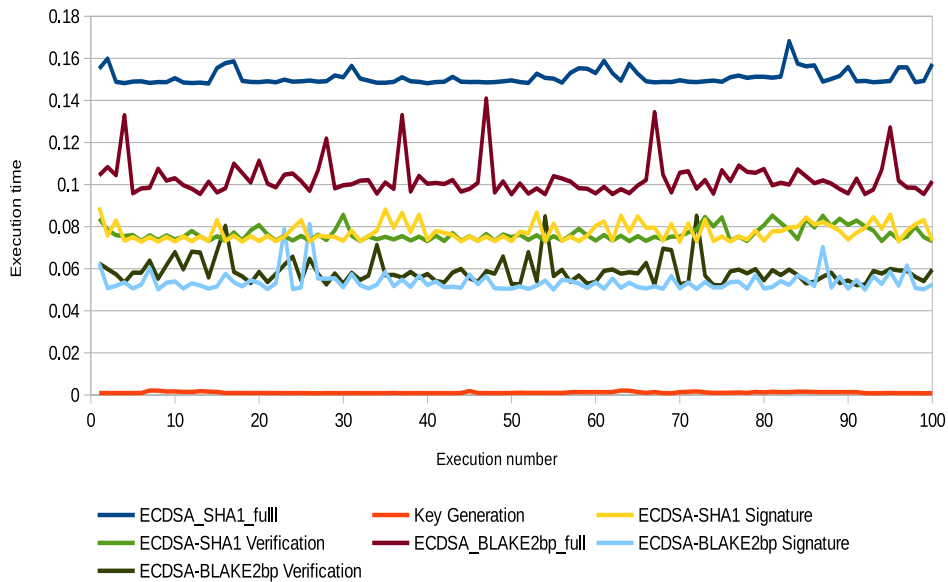


Figure 7.10: Execution time of ECDSA-SHA1 and ECDSA-BLAKE2bp with 1MB data

channels between patients and *SNs*. To check performance, we implemented the SHA1-160, SHA2-256, BLAKE2s-256, BLAKE2b-512, BLAKE2sp-256, and BLAKE2bp-512 algorithms with 1MB data size as shown in Figure 7.9. Also, Figures 7.11, 7.12 and 7.13 show execution time (minimum, maximum and average) for hash functions when using 200K, 400K, 800K and 1M data. We noticed that BLAKE2bp is the best performance in terms of execution time in all figures. In addition, Figure 7.10 shows that ECDSA-BLAKE2bp gives the best execution time of ECDSA-SHA1. Also, Figures 7.14, 7.15 and

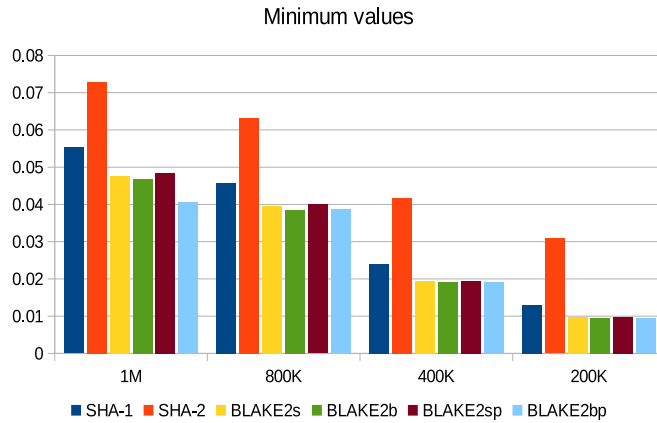


Figure 7.11: Minimum execution time of hash functions with 1MB data

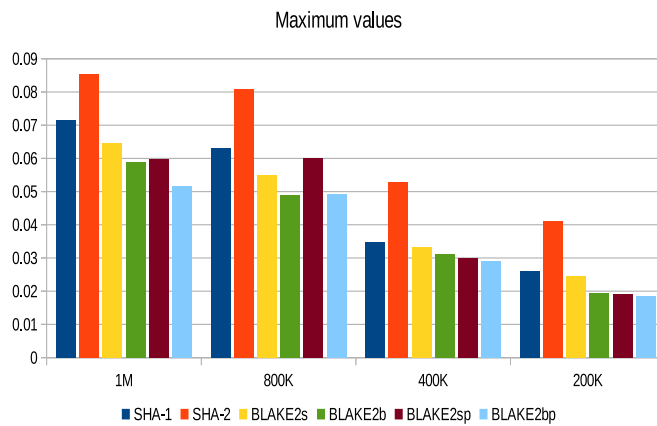


Figure 7.12: Maximum execution time of hash functions with 1MB data

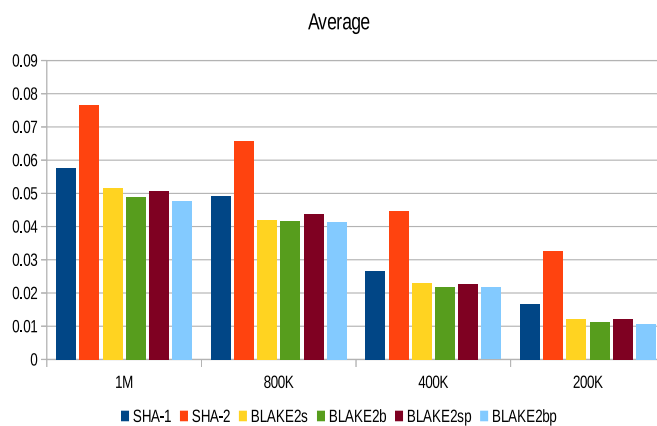


Figure 7.13: Average execution time of hash functions with 1MB data

7.16 show the execution time (minimum, maximum and average) for the ECDSA algorithms when using 200K, 400K, 800K and 1M data. Thus, the amendment to the ECDSA algorithm is entirely appropriate for the use of security measures with the longest life of the  $SNs$  from the original algorithm.



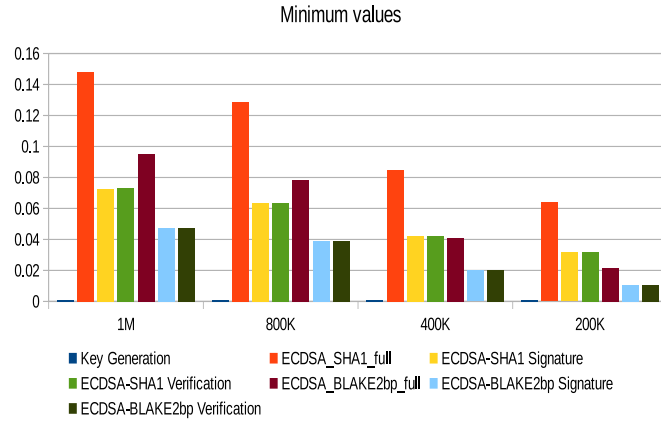


Figure 7.14: Minimum execution time of ECDSA algorithms with 1MB data

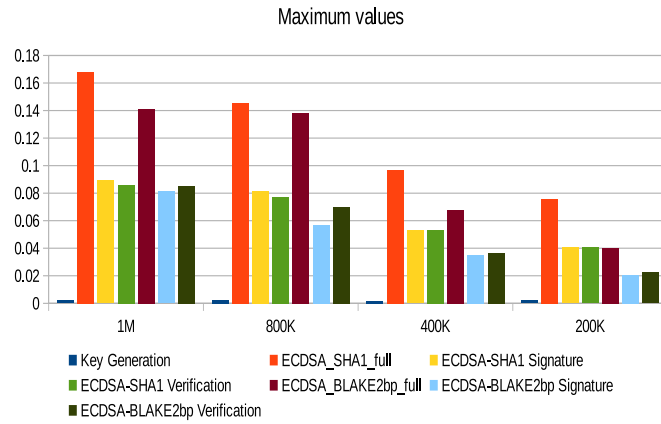


Figure 7.15: Maximum execution time of ECDSA algorithms with 1MB data

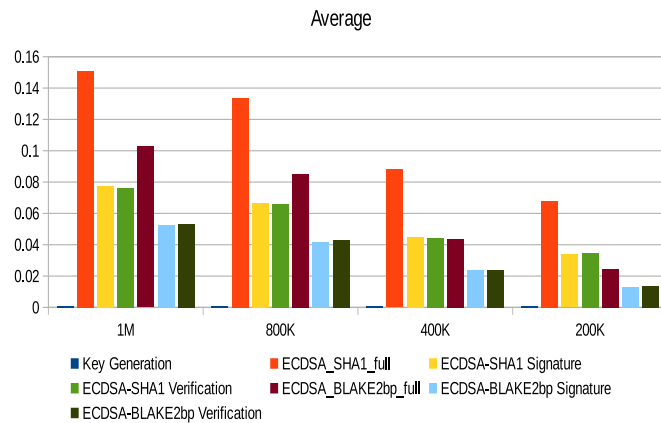


Figure 7.16: Average execution time of ECDSA algorithms with 1MB data

We have computed message complexity which is the number of messages transmitted between network entities. For each round,  $SN$  and  $CH$  send one message while  $CH$  and  $LS$  receive a set of aggregated messages. Thus,

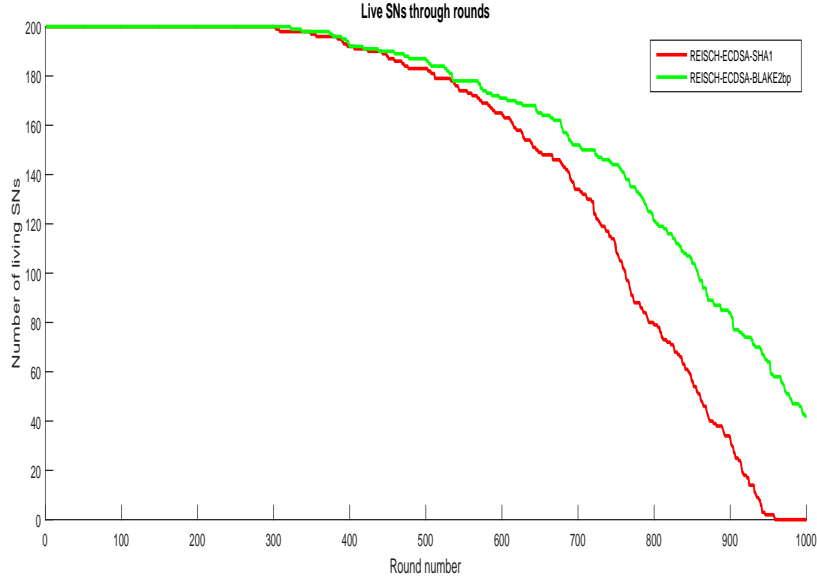


Figure 7.17: Comparison of alive  $SNs$

the message complexity with modified algorithms for  $SNs$  is (156972),  $CHs$  is (8313) and  $LS$  is (165285) while with original algorithms for  $SNs$  is (142541),  $CHs$  is (7572) and  $LS$  is (150113). Message overhead is to calculate the message size between network entities. In each round, the message overhead of  $SN$  is  $(1024 + 32)$  bytes while  $CH$  is  $(15360 + 32)$  bytes. Figure 7.17 shows that REISCH-ECDSA-BLAKE2bp is better than REISCH-ECDSA-SHA1 in terms of alive  $SNs$ , namely, HWSN will have a longer life span to collect patients' data when it uses REISCH-ECDSA-BLAKE2bp. It also contributes to the energy balance of  $SN_s$  which improves the continuity of electing  $CH_s$  and collecting the most patient data in each round. We noticed that REISCH with the modified algorithm (ECDSA-BLAKE2bp) has more alive  $SNs$  by 24% than the original algorithm (ECDSA-SHA1). Furthermore, the first  $SN$  dies when using the modified algorithm in round 322, while in the original algorithm is in round 295.

- **Performance Comparison**

Finally, we will make a comparison on performance with the existing schemes (Table 7.4 shows a comparison of the ECDSA's signature and verification (running time) between our scheme and existing schemes). Due to different environments, security parameters and network parameters such as key length, number of  $SNs$ , etc., it is very difficult to compare schemes' performance. However, we have made some comparisons to illustrate the superiority of REISCH on the existing schemes in terms of performance.

The scheme in Fan & Gong (2012) focused on accelerating ECDSA's verification based on computation results for neighbouring  $SNs$ . These computations consume additional energy. In addition, this scheme is very expensive if applied to a cluster scheme because  $CH$  needs to accomplish one PM in each signature for each  $SN_i$  and thus will consume energy in the intermediate  $SNs$ . REISCH does not need these computations because signatures' verification is performed in  $LS$ . Schemes in Kodali (2013), Lavanya & Natarajan (2017b), Malathy et al. (2018) used ECDSA to sign data without using homomorphic. Consequently, the performance of the  $SNs$  would be very low due to signature and verification processes in each round. The scheme in Kodali (2013) addressed the bits (8 and 32) of data processing in SHA1 but did not address the cost of energy consumption by SHA1. Also, the scheme in Lavanya & Natarajan (2017b) did not support the clustering environment to reduce energy consumption and the computation time to generate and verify the signature was not clearly indicated. Furthermore, the scheme in Sharavanan et al. (2018) used SHA2, which is more secure than SHA1 but performs heavy processes that significantly affect the energy of  $SNs$ . It also addresses only computations in transport while REISCH addresses computations in transport and processing using BLAKE2bp and homomorphic.

Schemes in Staudemeyer et al. (2018), Hathaliya et al. (2019), Furtak et al. (2019) rely on the use of encryption to protect data without a homomorphic property, since encryption processes extremely consume  $SNs$  resources (as mentioned in Section 3.3.4, point 4). While REISCH uses signatures and homomorphic to improve HWSN network performance. Although the scheme in Sui & de Meer (2019) uses encryption and signature of data with homomorphic, encryption can particularly affect network performance, especially through a burden on the servers.

Moreover, the scheme in Furtak et al. (2019) has implemented RSA 2048-bit algorithm which is significantly expensive in encryption operations. In addition, it uses several parameters such as many keys, 2048-bit key length and  $SN_i$  addresses (master, replica and gateway) that cause storage problems in the pre-deployment and registration phases (consumption of  $SNs$  resources). It has used a random routing of the sensor network without relying on a specific routing protocol such as LEACH. This scheme has considered the structure of the data in the  $SN_i$  memory and did not pay attention to the structure of the data as it was transferred to the servers. REISCH uses XML to support performance of the  $LS$  and  $CS$  without having to convert data

Table 7.4: Comparison of ECDSA’s procedures

Running time (second)	Fan & Gong (2012)	Kodali (2013)	Malathy et al. (2018)	Kittur & Pais (2019)	Kuang et al. (2019)	Marino et al. (2019)	Zhao et al. (2019)	Liu et al. (2019)	<b>REISCH scheme</b>
Signature	0.38	0.941	0.59	0.078	0.3472	0.434	0.084	0.051	0.050
Verification	0.65	-	-	0.079	-	0.429	0.088	0.105	0.052

formats between network devices. In terms of alive  $SNs$ , REISCH provides more than 24% while in Elhoseny, Yuan, El-Minir & Riad (2016b) 17.5%, Elhoseny, Elminir, Riad & Yuan (2016) 18.26% (100 nodes), Prithi & Sumathi (2020) 16% (100-700 nodes) and Vinitha et al. (2019) 7.14% (100 nodes) and 4% (50 nodes). Thus, REISCH provides longer network lifetime than schemes Elhoseny, Yuan, El-Minir & Riad (2016b), Elhoseny, Elminir, Riad & Yuan (2016), Prithi & Sumathi (2020) and Vinitha et al. (2019). Recent research Kittur & Pais (2019), Kuang et al. (2019), Marino et al. (2019), Zhao et al. (2019), Liu et al. (2019) have used different ways to improve ECDSA’s procedures. However, REISCH provides better performance in terms of ECDSA’s signature and verification than existing schemes (as shown in Table 7.4).

## 7.3 Analysis of RAMHU Scheme

In this section, we will analyse RAMHU’s security and performance in both theoretical and experiential aspects.

### 7.3.1 Possible Attacks on the RAMHU Scheme

In this section, theoretical and experimental security analyses are presented. We describe how our scheme (RAMHU) applies security requirements to protect user authentication information in the healthcare system. In this section, we also show how RAMHU provides a high-security level against these attacks meanwhile providing propositions and proofs.

- **Proposition 1 – Privileged-insider attack**

The internal intruder ( $II$ ) cannot detect the private key or password (privileged-insider attack) for another legitimate user in the healthcare network.

**Proof**

$II$  needs to eavesdrop on authentication requests between  $C_i$  and  $CS$ . After that, he/she tries to perform an analysis of these requests based on his/her access privileges to the network. First, the analysis of these requests to

obtain the private key or password is infeasible because the authentication request is encrypted by the ECIES 256-bit algorithm;  $II$  cannot decrypt these requests with his private key. Second, if  $II$  breaks the encryption (which is impossible), he/she is unable to extract the  $PW_i$  value ( $tmpPW_i = PW_i \oplus N_{C_i} \oplus GM \oplus C_iSig_1$ ) in the login phase because it is hidden and depends on the values of  $GM$ ,  $C_iSig_1$ , and  $N_{C_i}$  where  $II$  does not know the  $GM$  value of the legitimate user's device, and the  $C_iSig_1$  value depends on the  $CM$  value that is also not known to  $II$ . Therefore, RAMHU prevents a privileged insider attack.

- **Proposition 2 – Stolen device/application attack**

$I$  will not gain any benefit from device or client application theft (stolen device/application attack) for use in authentication as a legitimate user.

**Proof**

In the first case,  $I$  stole a legitimate user device (such as a laptop) that contains a client application. In our scheme, user's  $PW_i$ , and  $IDs$  are not stored on the user's device, or in the client application. In addition, the private key is hidden and random for each authentication process by  $C_iK_{pr_i} \oplus GM \oplus PW_i \oplus N_{C_i}$ . Additionally, the proof in Proposition 1 shows that the  $PW_i$  value cannot be extracted from the  $tmpPW_i$ . If  $I$  is  $II$ , he/she also cannot use his/her  $IDs$  and  $PW_i$  to access information or other user data because both  $CS$  and  $AS$  perform matching  $IDs$ , and  $PW_i$  to determine user-related information and data. In the second case, the attacker steals only the client application.  $I$  cannot use the application on another device because it does not have  $OTP_i$  or original MAC, which prevents the application from being used on another device even if  $I$  knows the  $IDs$  and  $PW_i$ . The original MAC mechanism ( $C_iSig_1 = h(CM || N_{C_i} || TS_{C_i})$ ) prevents the fake authentication request from being verified in the server because  $I$  cannot generate an original MAC address ( $CM$ ) in  $C_iSig_1$ . Thus, RAMHU is resistant to stolen attacks.

- **Proposition 3 – Replay attack**

$I$  cannot use the login/registration/authentication request later (replay attack).

**Proof**

$I$  tries to get a login/registration/authentication request for a legitimate user to send it later, and thus gains access to the network. This case is infeasible in our scheme because all entities ( $C_i$ ,  $CS$ , and  $AS$ ) use a timestamp (such as  $TS_{CS} - TS_{C_i} \leq \Delta T$ , where  $\Delta T$  is the maximum transfer delay rate) that prevents the attacker from sending the authentication request at a later time. Furthermore, signatures and random nonces are not usable in subsequent

times. Hence, RAMHU successfully resists replay attacks.

- **Proposition 4 – Man-in-the-Middle attack**

$I$  does not have the ability to intercept, modify, and replace authentication requests (man-in-the-middle (MITM) attack) between RAMHU's entities.

**Proof**

Assume that an  $I$  attempts to intercept encrypted login/authentication requests (such as  $Enc_i = TS_{C_i} || N_{C_i} || CiSig_1 || UP_{C_i}^{CS} || MP_{C_i}^{CS} || tmpPW_i || CiSig_2$ ) among network entities, and then modifies or replaces these requests with his/her messages to send to network entities. However, the attacker cannot replace exchanged requests between  $C_i$ ,  $CS$ , and  $AS$  because, first, he/she does not know the private keys ( $C_iK_{pr_i}$ ,  $CSK_{pr_i}$ ,  $ASK_{pr_i}$ ) and therefore, the decryption process is computationally infeasible with 256 bits key length and difficulty in solving ECDLP. Second, mutual authentication with PHOTON-256 signatures prevents the modification of requests between RAMHU's entities. As a result, RAMHU gracefully overcomes the MITM attack.

- **Proposition 5 – ID or Password Guessing Attack**

$EI$  cannot guess  $ID_s$  and  $PW_i$  (guessing attack) for legitimate users of the RAMHU protocol.

**Proof**

Assume that an  $EI$  was able to penetrate the encryption ( $Enc_i$ ) between  $C_i$  and the  $CS$  (from Proposition 4, this assumption is infeasible). This  $EI$  tries to guess  $PW_i$  in a login request to use it to access the network as a legitimate user.  $EI$  cannot detect  $PW_i$  for any authorised user (either on-line or off-line) because he/she does not know the configured process to protect  $PW_i$  ( $tmpPW_i = PW_i \oplus N_{C_i} \oplus GM \oplus CiSig_1$ ) and does not know the MAC address for that user, and thus the process of deriving  $PW_i$  is infeasible (Proposition 1). It is an extremely difficult process to guess  $PW_i$  from the  $tmpPW_i$ , which is 64 hex (256 bits). In addition,  $EI$  cannot detect  $UID_i$  and  $MID_i$  for any legitimate user because of the use of multi pseudonyms mechanism for users and medical centres instead of sending real information to legitimate users. As a result, RAMHU is safe against guessing attacks.

- **Proposition 6 – Client impersonation attack**

$I$  cannot impersonate a legitimate user or device in the network (client impersonation attack).

**Proof**

Assume that an attacker tries to impersonate a login request (such as  $Enc_i = TS_{C_i} || N_{C_i} || CiSig_1 || UP_{C_i}^{CS} || MP_{C_i}^{CS} || tmpPW_i || CiSig_2$ ) for a legitimate user.

This  $I$  can create  $TS_{C_i}$  and  $N_{C_i}$  but does not know  $PW_i$  and  $C_iK_{pr_i}$  (Proposition 1, and 4) for the legitimate user, namely,  $I$  cannot impersonate the user identity.  $I$  also tries to impersonate the legitimate user's device by programmatically changing the MAC address to a legitimate one to gain access to the network. This case is infeasible because the original MAC check ( $CM$ ) in  $C_iSig_1 = h(CM\|N_{C_i}\|TS_{C_i})$  detects the attacker's attempt to mimic the legitimate user's device (as proved in Proposition 2). Therefore, RAMHU withstands instances of impersonating the user's identity and device.

- **Proposition 7 – Server impersonation attack**

$I$  cannot impersonate (server impersonation attack) the central server ( $CS$ ) and cheat the client ( $C_i$ ).

**Proof**

Assume that an  $I$  traps login requests from  $C_i$  to  $CS$ . The attacker tries to deceive  $C_i$  by sending fake requests to  $C_i$  in order to inform them that he is a legitimate server.  $I$  needs the private key for  $CS$  to decrypt and to accomplish the attack. Mutual authentication prevents  $I$  from impersonating  $CS$ 's requests (such as  $Enc_i = TS_{CS}\|N_{CS}\|UP_{CS}^{C_i}\|MP_{CS}^{C_i}\|CSSig_5$ ) and sending them to  $C_i$ . This mechanism ensures that  $C_i$  deals with legitimate  $CS$ . Consequently, our protocol effectively resists server impersonation attack.

- **Proposition 8 – DoS attack**

$I$  cannot effectively perform a DoS attack against our scheme.

**Proof**

In order for  $I$  to execute a DoS attack against  $CS$  and  $AS$ , he/she needs to decrypt the login request and change its data or send the same request multiple times to destroy the servers. However, in the first case, decryption and change of signatures are infeasible as proved in Propositions 2 and 4.  $CS$  checks signature validity and rejects login requests containing fake signatures, and  $I$  cannot execute a collision or preimage attack because PHOTON-256 supplies FPR, SPR, and CR. In the second case, the attacker sends the same request multiple times. This status is infeasible because the  $CS$  or  $AS$  checks the timestamp ( $TS_{C_i}$ ,  $TS_{CS}$ ,  $TS_{AS}$ ) for each login/authentication request and eliminates all late requests (Proposition 3) without checking the other security parameters such as  $PW_i$ ,  $CM$ , and multi pseudonyms. In case  $I$  can break the encryption, he/she can change the timestamp and nonce, but cannot tamper with the signatures. RAMHU prevents this condition during  $C_iSig_1$  and does not need to check the remaining security parameters. Therefore, RAMHU successfully resists DoS attacks.

- **Proposition 9 – Password change attack**

$I$  cannot detect new  $PW_i$  or change old  $PW_i$  (password change attack) to prevent legitimate users from accessing the network.

**Proof**

Assume that an  $I$  intercepts a request to change  $PW_i$  between  $C_i$  and  $CS$ .  $I$  obtains an encrypted request (such as  $Enc_i = TS_{C_i} || NC_1 || NC_2 || NC_3 || UP_{C_i}^{CS} || MP_{C_i}^{CS} || tmp\_oldPW_i || tmp\_newPW_i || C_iSig_1$ ). If  $I$  can decrypt (this process is infeasible as proved in Propositions 1, and 4), he/she will find a temporary password and cannot derive new  $PW_i$  because it depends on the  $C_iSig_1 = h(TS_{C_i} || NC_1 || UP_{C_i}^{CS} || MP_{C_i}^{CS} || oldPW_i)$ . The signature operation ( $C_iSig_1$ ) is based on the old  $PW_i$  which is not explicitly sent to  $CS$  in this phase.  $I$  does not know old  $PW_i$  and therefore, he/she cannot create a signature to complete the  $PW_i$  change process. As a result, RAMHU provides a reliable solution against password change attacks.

- **Proposition 10 – Eavesdropping attack**

$I$  does not gain plaintext and useful information when an eavesdropping attack has applied to our scheme.

**Proof**

Assume that an  $I$  eavesdrops on login/authentication requests to gain information about user authentication and access to the network. However, in our scheme,  $I$  will not benefit from requests that are intercepted because RAMHU uses ECIES algorithm with key 256 bits to encrypt authentication information. The attacker can only decrypt requests by deriving private keys and this operation is infeasible (as proved in Propositions 1, and 2) due to key length, and random encryption with nonces (anonymity). Therefore, our protocol is resistant to eavesdropping attack.

- **Proposition 11 – Traceability attack**

$I$  cannot track exchanged login/authentication requests (traceability attack) between all entities in the RAMHU scheme.

**Proof**

$I$  attempts to collect as many login/authentication requests as possible and then performs an analysis of those requests that helps him/her to perform user identity tracing. When an  $I$  succeeds in tracking user requests, he/she can detect and distinguish patient data. All exchanged requests among RAMHU's entities do not contain direct user information (such as username). RAMHU replaces the real user  $ID_s$  ( $UID_i$  and  $MID_i$ ) with pseudonyms. Our protocol uses multi pseudonyms ( $UP_{C_i}^{CS}$ ,  $UP_{CS}^{AS}$ ,  $UP_{AS}^{CS}$ , and  $UP_{CS}^{C_i}$  for users and  $MP_{C_i}^{CS}$ ,  $MP_{CS}^{AS}$ ,  $MP_{AS}^{CS}$ , and  $MP_{CS}^{C_i}$  for medical centres) to prevent attackers from



tracking user requests and revealing their identities when transferred between RAMHU entities ( $C_i$ ,  $CS$ , and  $AS$ ). Hence, RAMHU resists traceability attacks.

- **Proposition 12 – Revocation attack**

$I$  cannot penetrate or send a revocation request to delete or remove user account information (revocation attack) in the RAMHU protocol.

**Proof**

Assume that an  $I$  tries to penetrate a revocation request. The attacker tries to analyse the request and use it to prevent users from accessing the network’s services. Depending on Propositions 1, 5, and 11, the attacker cannot extract or distinguish  $UID_i$ ,  $MID_i$  and  $PW_i$  from the revocation request. The attacker does not know and cannot extract a reason from the  $tmpRR_i$ , which is based on the values of  $RR_i$ ,  $N_{C_2}$ , and  $C_iSig_1$ . In Propositions 2 and 8,  $I$  cannot perform collision, preimage, and second preimage attacks against the PHOTON-256 algorithm. Thus, our protocol prevents penetration of revocation request.

- **Proposition 13 – Verifier attack**

$I$  cannot extract users’ passwords from datasets in  $CS$  (verifier attack).

**Proof**

Assume that  $I$  tries to penetrate the datasets in  $CS$ . If the attacker is  $EI$ , he/she cannot penetrate datasets because he/she does not have a  $K_{pr}$ ,  $UID$ ,  $MID$ ,  $OTP$ , and  $PW_i$ . If the attacker is  $II$ , when he penetrates datasets in  $CS$  and wants to impersonate another user’s identity. First, he/she cannot distinguish this information for a particular user because the real information for users is stored in the  $AS$ . Second, since the  $CS$  does not contain the passwords’ dataset,  $II$  will not benefit from hacking datasets such as pseudonyms and cannot create a request and send it to  $AS$  because it does not know users’ passwords. Therefore, RAMHU resists verifier attacks meritoriously.

- **Proposition 14 – Leakage attack**

The attacker does not get any information leaked from requests and responses exchanged (leakage attack) between RAMHU entities.

**Proof**

Suppose that  $I$  listens to some exchanged requests among  $C_i$ ,  $CS$ , and  $AS$  and tries to find any information that helps him/her to penetrate network authentication such as sending an ID explicitly, or sending a password with weak encryption. Exchanged requests between RAMHU entities such as a password update request ( $Enc_i = TS_{C_i} || N_{C_1} || N_{C_2} || N_{C_3} || UP_{C_i}^{CS} || MP_{C_i}^{CS} ||$

$tmp\_oldPW_i || tmp\_newPW_i || C_i Sig_1$ ) show that  $I$  does not receive any leaked real information for users during transmission, such as  $IDs$  and  $PW_i$  (all information is anonymous and hidden) that could be useful in penetrating the healthcare network. Therefore, RAMHU resists leakage attacks.

## 1. Experimental Security Analysis

In the previous subsection, we have listed various possible attacks on the RAMHU scheme. In this section, we provide the proposed scheme simulation using the AVISPA tool to verify our scheme; whether safe or unsafe. This tool has been accepted by researchers in recent years and is widely used (Amin, Kumar, Biswas, Iqbal & Chang 2018, Amin, Islam, Biswas, Khan & Kumar 2018). It has been used to check security problems in authentication procedures and to ensure that known attacks are not able to penetrate user authentication information.

### • RAMHU Scheme with AVISPA

In this section, we illustrate the implementation and simulation of RAMHU with the AVISPA tool using HLP language. Our scheme depends on three core roles: *clienti*, *centralServer*, and *attributesServer* played by  $C_i$ ,  $CS$  and  $AS$  respectively, in addition to the supporting roles of *session*, and *environment*, goal specification section. Each role contains parameters, variables, and local constants. Each basic role contains a transition section that indicates the sequence of communication between entities. Each supporting role contains a composition section that indicates the binding of roles and sessions.

Asymmetric encryption has been implemented between scheme entities ( $C_i$ ,  $CS$ , and  $AS$ ) during public key exchange ( $KC_{pu}$ ,  $KCS_{pu}$ , and  $KAS_{pu}$ ) to perform confidentiality as well as mutual authentication to ensure the legitimacy of related parties in the phases of the proposed scheme (initial setup, registration, login, and authentication). Moreover, it uses nonces ( $N_c$ ,  $N_{cs}$ , and  $N_{as}$ ) and timestamps ( $TS_c$ ,  $TS_{cs}$ ,  $TS_{as}$ ) to support the features of anonymity and freshness. Our scheme accomplishes 10 secrecy goals and six authentication goals as noted in the goal section in Figure 7.22. Figure 7.18 shows RAMHU's framework in AVISPA.

$C_i$  receives the start signal and changes the state flag (State variable) from 0 to 1. It replaces  $UID$  and  $MID$  with  $UP_c$  and  $MP_c$  and calculates the timestamp ( $TS'_c$ ) and new nonce ( $N'_c$ ) by the `new()` operation, and

computes the signatures ( $C_iSig_1$  and  $C_iSig_2$ ). The password hiding process is also calculated in the operation of the  $TmpPW$  parameter. It encrypts the registration and login request ( $TS'_c$ ,  $N'_c$ ,  $GM'$ ,  $C_iSig'_1$ ,  $UP'_c$ ,  $MP'_c$ ,  $OTP_i$ ,  $Temporary\_PW'$ , and  $C_iSig'_2$ ) by the public key ( $KCS_{pu}$ ) to establish a reliable communication with  $CS$ .

$C_i$  sends the request to  $CS$  where the transmission process is performed by the  $SND()$  operation. It achieves a set of secret goals ( $sec1$  to  $sec6$ ) with both  $CS$  and  $AS$ ; these secrets are known only to and kept only by the intended parties. For example in  $sec1$ ,  $UID$ ,  $MID$ , and  $PW$  are known only to, and kept only by  $C_i$ , and  $AS$ , while in  $sec3$   $GM$ , and  $CM$  have been known and kept only to  $C_i$  and  $CS$ , since these parameters are not transmitted directly during the transition of information between network parties such as  $PW$  implicitly is in the calculation of  $TmpPW$  and  $CM$  implicitly is in  $C_iSig_1$ .

$C_i$  also achieves the goal of authentication using a statement (witness) with the parameters ( $C_i$ ,  $CS$ ,  $ci\_cs\_auth2$ ,  $N_{cs}$ ,  $TS_c$ ), which means that  $C_i$  is a witness that the security parameters ( $N_{cs}$ ,  $TS_c$ ) are fresh and correct, and  $CS$  uses a statement (request) to validate parameters with the strong authentication goal ( $ci\_cs\_auth2$ ) specified in the goal section (Figure 7.22).  $C_i$  receives the authentication response via the  $RCV()$  operation and sent from  $AS$  by  $CS$ . Then,  $C_i$  decrypts the response using its private key to verify the security parameters. If all security parameters are verified correctly,  $C_i$  performs the mutual authentication process securely.

As shown in Figure 7.20,  $CS$  receives a registration and login request by  $RCV()$  operation in state 0 and decrypts it with its private key and then checks the parameters and signatures to accomplish the secrecy and authentication goals. The  $CS$  changes the state signal from 0 to 1 and constructs an authentication request based on the security parameters ( $TS'_{cs}$ ,  $N'_{cs}$ ,  $UP_{cs}$ ,  $MP_{cs}$ ,  $CSSig_3$ , and  $TmpPW$ ) and encrypts it by the public key of  $AS$ .  $CS$  performs strong authentication with  $AS$  during witness ( $CS$ ,  $AS$ ,  $as\_cs\_auth4$ ,  $TS'_{cs}$ ,  $N'_{cs}$ ) to accomplish the authentication goal ( $as\_cs\_auth4$ ) based on the timestamp and fresh nonce and is validated in the  $AS$  by statement (request).

In state 1,  $CS$  receives an authentication response from  $AS$  and checks

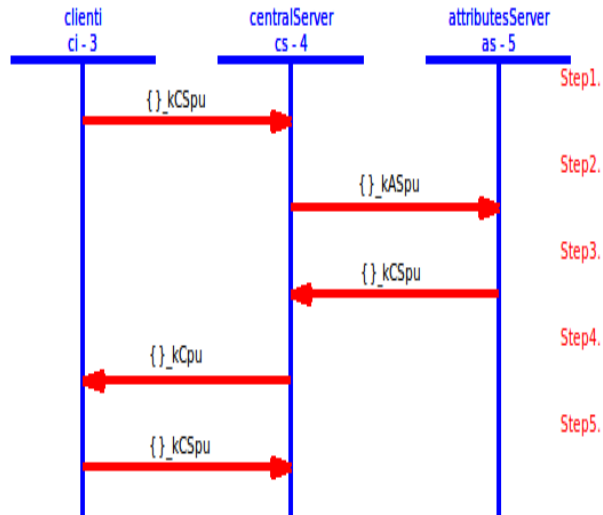


Figure 7.18: RAMHU’s framework in AVISPA

the security parameters after decryption with its private key. It changes the state signal to 2 and then constructs and sends the authentication response to  $C_i$  with two strong authentication goals ( $cs\_ci\_auth1$  and  $cs\_ci\_auth5$ ) based on the security parameters ( $N_c$ ,  $TS_{cs}$ ,  $TempPW$ , and  $OTP_i$ ).

$AS$  receives the authentication request and decrypts it with the private key as shown in Figure 7.21. It accomplishes five secret goals, and accomplishes two authentication goals ( $as\_cs\_auth4$  and  $as\_cs\_auth6$ ) based on  $TS'_{cs}$ ,  $N'_{cs}$ , and  $PW'$ . It constructs the authentication response and establishes a strong authentication when validating parameters ( $TS_{as}$ ,  $N'_{cs}$ , and  $PW'$ ) in  $CS$ .

Figure 7.22 displays the roles of session, environment, and goal section. In the session role, a composition process has been performed for the three roles ( $clienti$ ,  $centralServer$ , and  $attributeServer$ ) and specifies the sending and receiving channels in the Dolev Yao model.

In the environment role, the security parameters, the goals specified in the goal section, and the known information for the intruder ( $intruder\_knowledge$ ) have been defined. In this role, one or more sessions are composed, and we tested our scheme with sessions for replay, MITM, and impersonating attacks. We assume that an intruder ( $I$ ) creates a public key ( $ki$ ) and has knowledge of the public keys ( $kCpu$ ,  $kCSpu$ , and  $kASpu$ ) of legitimate entities in the network.

The authentication process begins by sending requests from clients to

the server. Therefore, the  $client_i$  role includes the start signal as shown in Figure 7.19.

```

role clienti(Ci,CS,AS:agent, KCpu,KCSpu:public_key, H:hash_func, UID,MID,OTPi,PW,GM,CM:message
, SND,RCV:channel(dy))
played_by Ci def=
local
    State:nat,
    TSc,TScs,Nc,Ncs:text, CiSig1,CiSig2:text, UPc,MPc,UPcs,MPcs,TmpPW:message
const
    sec1,sec2,sec3,sec4,sec5,sec6, cs_ci_auth1,ci_cs_auth2:protocol_id
init
    State := 0
transition
1. State = 0
    /\RCV(start)=|> State' := 1 /\UPc' := UID /\MPc' := MID /\GM' := Ci /\Nc' := new() /\TSc' := new()
    /\CiSig1' := H(CM.Nc'.TSc') /\CiSig2' := H(GM'.Nc'.TSc'.CiSig1'.UPc'.MPc'.OTPi.PW)
    /\TmpPW' := xor(PW,xor(Nc',xor(GM',CiSig1')))

% Registration and login phase
% Ci sends security parameters to CS
    /\SND({TSc'.Nc'.GM'.CiSig1'.UPc'.MPc'.OTPi.TmpPW'.CiSig2'}_KCSpu)
    /\secret({UID,MID,PW},sec1,{Ci,AS}) /\secret(PW,sec2,{Ci,CS}) /\secret({GM,CM},sec3,{Ci,CS})
    /\secret({CiSig1',CiSig2'},sec4,{Ci,CS}) /\secret({TmpPW',OTPi},sec5,{Ci,CS})
    /\secret({UPc,MPc,UPcs,MPcs},sec6,{Ci,CS})

2. State = 1
% Ci receives authentication response from CS
    /\RCV({TScs'.Ncs'.Nc.UPcs'.MPcs'. H(TScs'.Ncs'.UPcs'.MPcs')}_KCPU)=|>
    State' := 2 /\SND({Ncs'}_KCSpu)

% Clienti checks that the received security parameters
    /\request(Ci,CS,cs_ci_auth1,{Nc,TScs}) /\request(Ci,CS,cs_ci_auth5,{TmpPW,OTPi})
% Clienti sends Ncs to prove her identity
    /\witness(Ci,CS,ci_cs_auth2,{Ncs,TSc})
end role

```

Figure 7.19:  $C_i$  role of RAMHU in HLPsL

The intruder attempts to resend the registration/login or authentication requests later, intercepts/modifies these requests, or impersonates the participating entities using  $i\_ci$ ,  $i\_cs$ , and  $i\_as$  constants rather than  $ci$ ,  $cs$ , and  $as$ . The results section shows that these attacks cannot penetrate the security goals in our scheme.

### • Simulation Results

In this section, the simulation results in the AVISPA tool are based on two backends (OFMC, and CL-AtSe). Figure 7.23 shows the simulation result with the OFMC backend and Figure 7.24 displays the simulation result with the CL-AtSe backend. From the results shown in Figures 7.23 and 7.24, our scheme clearly and accurately shows the SAFE result in the SUMMARY section, bounded number of sessions in the DETAILS section, the goals of the scheme achieved ( $as\_specified$ ) in the GOAL section as well as statistical numbers such as time, number of nodes, and analysed states in the STATISTICS section for both figures. Based on these results, we note that our scheme is capable of preventing passive and

active attacks such as replay, MITM, and impersonating, and that the goals of the scheme in Figure 7.22 prevented the violation of legitimate user information in the network authentication.

## 2. Security Comparison

In this section, we compare RAMHU with existing authentication schemes in terms of security. We explain RAMHU superiority to solve the deficiencies in existing authentication schemes.

The authentication schemes in He & Zeadally (2015), Giri et al. (2015) suffer from a leak of authentication information when transferring user requests between network entities. Compared with RAMHU, all real user information is not transmitted through the network exchanges and therefore does not leak information. Farash et al. (2016) and Jiang et al. (2016) designed authentication schemes but these schemes lacked the management and protection of user information/data on the server. RAMHU stores information on the *AS* and uses signatures and multi-pseudonyms to disguise user information on the *AS*. It also uses *CS* as a gateway to check requests before sending them to the *AS*. In Kumar et al. (2016), the authentication scheme suffers from internal attacks. If the intruder uses a sniffing program to steal user information such as MAC addresses, he/she becomes authenticated in the network as a legitimate user. In comparison, RAMHU uses *CM* and *GM* to prevent internal attacks.

Li et al. (2016) and Das et al. (2017) used a symmetric algorithm that relies on a single key and therefore runs the risk of key detection. In contrast, RAMHU relies on an asymmetric algorithm that supports scalability. Rajput, Abbas, Wang, Eun & Oh (2016) proposed an authentication scheme that suffered greatly from impersonation attacks. An intruder can use his/her device as a server and deceive users. RAMHU uses robust mutual authentication to prevent impersonation attacks. In Chandrakar & Om (2017), the authentication scheme suffers from collision and preimage attacks, and it handles real user information when requests are transferred to the network. Compared to RAMHU, it uses PHOTON to prevent collision and preimage attacks as well as using multi-pseudonyms to prevent the exchange of real information between network entities.

```

role centralServer(Ci,CS,AS:agent, KCpu,KCSpu,KASpu:public_key, H:hash_func, SND,RCV:channel(dy))
played_by CS def=
local
  State:nat,
  UPc,MPc,UPcs,MPcs,UPas,MPas,TmpPW:message, CSSig1,CSSig2,CSSig3:text,
  TSc,TScs,TSas,Nc,Ncs,Nas:text, PW,OTPi:message, GM,CM:message
const
  sec1,sec2,sec3,sec4,sec5,sec6,sec7,sec8,sec9,sec10,
  ci_cs_auth2,cs_ci_auth1,cs_ci_auth5,cs_as_auth3,as_cs_auth4,as_cs_auth6:protocol_id
init
  State := 0
transition
% Registration and login request from Ci
1. State = 0
  /\RCV({TSc'.Nc'.GM'.H(CM'.Nc'.TSc').UPc'.MPc'.OTPi'.TmpPW'.
    H(GM'.Nc'.TSc'.H(CM'.Nc'.TSc').UPc'.MPc'.OTPi'.PW')}_KCSpu) =|>
  CSSig1' := H(CM'.Nc'.TSc') /\CSSig2' := H(GM'.Nc'.TSc'.CSSig1'.UPc'.MPc'.OTPi'.PW)
  /\PW' := xor(TmpPW,xor(Nc',xor(GM',CSSig1))) /\secret(PW',sec2,{CS,Ci})
  /\secret({GM,CM},sec3,{CS,Ci}) /\secret({CSSig1,CSSig2},sec4,{CS,Ci})
  /\secret({TmpPW',OTPi},sec5,{CS,Ci}) /\secret({UPc,MPc,UPcs,MPcs},sec6,{CS,Ci})

% Authentication request from CS to AS
  /\State' := 1 /\Ncs' := new() /\TScs' := new() /\CSSig3' := H(TScs'.Ncs'.UPcs.MPcs)
  /\TmpPW' := xor(PW,xor(Ncs',CSSig3')) /\SND({TScs'.Ncs'.UPcs.MPcs.CSSig3'.TmpPW'}_KASpu)
  /\secret(PW,sec7,{CS,AS}) /\secret({CSSig3},sec8,{CS,AS})
  /\secret({TmpPW'},sec9,{CS,AS}) /\secret({UPcs,MPcs,UPas,MPas},sec10,{CS,AS})

% Authentication response from AS to CS
2. State = 1
  /\RCV({TSas'.Nas'.Ncs.UPas'.MPas'.H(TSas'.Nas'.UPas'.MPas')}_KCSpu)=|>
% Authentication response to Ci
  State' := 2 /\Ncs' := new() /\TScs' := new()
  /\SND({TScs'.Ncs'.Nc.UPcs.MPcs.H(TSas'.Ncs'.UPcs.MPcs)}_KCPU)
  % CS prove his identity
  /\witness(CS,Ci,cs_ci_auth1,{Nc,TScs'}) /\witness(CS,Ci,cs_ci_auth5,{TmpPW,OTPi})
  /\witness(CS,AS,cs_as_auth3,{Nas',TScs'})
  /\request(CS,AS,as_cs_auth4,{Ncs',TSas'}) /\request(CS,AS,as_cs_auth6,{PW})

3. State = 2
  /\RCV({Ncs}_KCSpu) =|>
% CS checks that the received nonce and timestamp correct
  State' := 3 /\request(CS,Ci,ci_cs_auth2,{Ncs,TSc})
end role

```

Figure 7.20: *CS* role of RAMHU in HLPSL

```

role attributesServer(AS,Ci,CS:agent, KASpu,KCSpu:public_key, H:hash_func, SND,RCV:channel(dy))
played_by AS def=
local
  State:nat,
  UID,MID,PW:message, TmpPW:message, ASSig1,ASSig2:text,TScs,Ncs,TSas,Nas:text,
  UPcs,MPcs,UPas,MPas:message, GM,CM:message
const
  sec1,sec7,sec8,sec9,sec10,cs_as_auth3,as_cs_auth4,as_cs_auth6:protocol_id
init
  State:= 0
transition
1. State = 0
  /\RCV({TScs'.Ncs'.UPcs'.MPcs'.H(TSas'.Ncs'.UPcs'.MPcs').
    TmpPW'}_KCSpu)=|>ASSig1' := H(TSas'.Ncs'.UPcs.MPcs)
  /\PW' := xor(TmpPW,xor(Ncs',ASSig1)) /\secret({UID,MID,PW},sec1,{AS,Ci}) /\secret(PW,sec7,{AS,CS})
  /\secret({ASSig1},sec8,{AS,CS}) /\secret({TmpPW'},sec9,{AS,CS})
  /\secret({UPcs,MPcs,UPas,MPas},sec10,{AS,CS}) /\State' := 1 /\Nas' := new() /\TSas' := new()
  /\ASSig2' := H(TSas'.Nas'.UPas.MPas) /\SND({TSas'.Nas'.Ncs.UPas.MPas.ASSig2'}_KCSpu)
  /\witness(AS,CS,as_cs_auth4,{Ncs',TSas'}) /\witness(AS,CS,as_cs_auth6,{PW'})
  /\request(AS,CS,cs_as_auth3,{Nas',TScs'})
end role

```

Figure 7.21: *AS* role of RAMHU in HLPSL

```

role session(Ci,CS,AS:agent, KCpu,KCSpu,KASpu:public_key, H:hash_func, UID,MID,OTPi,PW,GM,
             CM:message)
def=
local
    SndC,RcvC,SndCS,RcvCS,SndAS,RcvAS:channel(dy)
composition
    clienti(Ci,CS,AS,KCpu,KCSpu,H,UID,MID,OTPi,PW,GM,CM,SndC,RcvC)
    /\centralServer(Ci,CS,AS,KCpu,KCSpu,KASpu,H,SndCS,RcvCS)
    /\attributesServer(AS,Ci,CS,KASpu,KCSpu,H,SndAS,RcvAS)
end role

role environment()
def=
const
    ci,cs,as,i_ci,i_cs,i_as:agent, kCpu,kCSpu,kASpu,ki:public_key, uid,mid,otp,pw,gm,cm:message,
    h:hash_func, sec1,sec2,sec3,sec4,sec5,sec6,sec7,sec8,sec9,sec10,
    ci_cs_auth2,cs_ci_auth1,cs_ci_auth5,cs_as_auth3,as_cs_auth4,as_cs_auth6:protocol_id
    intruder_knowledge={ci,cs,as,i_ci,i_cs,i_as,kCpu,kCSpu,kASpu,ki}
composition
    session(ci,cs,as,kCpu,kCSpu,kASpu,h,uid,mid,otp,pw,gm,cm)
    % Check replay attack
    /\session(ci,cs,as,kCpu,kCSpu,kASpu,h,uid,mid,otp,pw,gm,cm)
    % Check MITM attack
    /\session(cs,ci,as,kCSpu,kCpu,kASpu,h,uid,mid,otp,pw,gm,cm)
    % Check impersonate Ci
    /\session(i,cs,as,ki,kCSpu,kASpu,h,uid,mid,otp,pw,gm,cm)
    % Check impersonate CS
    /\session(ci,i,as,kCpu,ki,kASpu,h,uid,mid,otp,pw,gm,cm)
    % Check impersonate AS
    /\session(ci,cs,i,kCpu,kCSpu,ki,h,uid,mid,otp,pw,gm,cm)
end role

goal
    secrecy_of sec1,sec2,sec3,sec4,sec5,sec6,sec7,sec8,sec9,sec10
    authentication_on cs_ci_auth1,ci_cs_auth2,cs_as_auth3,as_cs_auth4,cs_ci_auth5,as_cs_auth6
end goal

environment()

```

Figure 7.22: Session, environment, and goal roles of RAMHU in HLPSP

```

% OFMC
% Version of 2006/02/13
SUMMARY
SAFE
DETAILS
BOUNDED_NUMBER_OF_SESSIONS
PROTOCOL
/home/span/span/testsuite/results/RAMHU.if
GOAL
as_specified
BACKEND
OFMC
COMMENTS
STATISTICS
parseTime: 0.00s
searchTime: 54.60s
visitedNodes: 3636 nodes
depth: 11 plies

```

Figure 7.23: Simulation result of RAMHU using OFMC backend

```

SUMMARY
SAFE
DETAILS
BOUNDED_NUMBER_OF_SESSIONS
TYPED_MODEL
PROTOCOL
/home/span/span/testsuite/results/RAMHU.if
GOAL
As Specified
BACKEND
CL-AtSe
STATISTICS
Analysed : 324 states
Reachable : 64 states
Translation: 0.52 seconds
Computation: 0.42 seconds

```

Figure 7.24: Simulation result of RAMHU using CL-AtSe backend

The schemes in Nizzi et al. (2019) and (El-Tawab et al. 2019) suffered



from several problems, such as spoofing the coordinator/server by shuffle (AShA)/randomisation of fake addresses sent from intruders, key detection, breaking the integration process/vulnerability to preimage/second preimage attacks, and a single technique that does not provide security for online devices. RAMHU does not suffer from these problems because it uses *CM* to prevent MACs change, the public key algorithm to prevent key breaking, PHOTON to provide signature principles, and it uses a set of techniques to protect authentication processes. Table 7.5 shows a comparison between RAMHU and existing authentication schemes in various attacks resistance.

### 7.3.2 Performance Analysis

In this section, the theoretical and experimental performance analysis and performance comparison with existing related works are presented to examine the computation and communication processes of RAMHU in improving the performance of the authentication processes.

- **Theoretical Performance Analysis**

The authentication scheme should perform lightweight processes to support the reliable communication of users in healthcare applications. Authentication is the first process that allows users to be recognised as legitimate users of the network services. If the authentication process is vulnerable for attacks, network performance will be greatly affected by the fact that the servers will perform additional complex computations.

RAMHU uses algorithms and techniques to support performance-efficient authentication. RAMHU uses the ECIES algorithm to encrypt user information only. This algorithm performs lightweight operations and produces small keys compared to public key cryptographic algorithms as described in Chapter 2, Table 2.2. In addition, RAMHU uses the hash function (PHOTON) that performs hash operations compared to lightweight hash functions as described in Appendix B, Table B.1. The use of robust security algorithms against attacks such as ECIES and PHOTON is a major cause of performance stability. In RAMHU, new users use OTP only once at the registration phase. They do not need to use this technique in subsequent times. This technique reduces the burden on the server processor to perform complex computations. If the attacker tries to connect to the network with a fake or previously used OTP, the server would reject this request early without having to test other authentication techniques. This contributes

Table 7.5: Comparison of resistance in repelling the various threats between RAMHU and other authentication schemes

Attack	He & Zeadally (2015)	Giri (2015)	Li et al. (2016)	Farash et al. (2016)	Kumar et al. (2016)	Jiang et al. (2016)	Rajput, Abbas, Eun & Oh (2016)	Das et al. (2017)	Chandrakar & Om (2017)	Nizzi et al. (2019)	El-Tawab et al. (2019)	RAMHU scheme
Privileged-insider	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Stolen device/application	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Replay	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
MITM	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Guessing	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Client impersonation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Server impersonation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
DoS	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Change password	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Eavesdropping	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Traceability	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Revocation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Verifier	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Leakage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

significantly to reducing the depletion of server capabilities.

Furthermore, RAMHU relies on multi-pseudonyms that perform lightweight operations in protecting user information rather than using k-anonymity, which consumes the server's time and power needed to search and explore real information for legitimate users. Moreover, RAMHU supports the authentication process via the MAC address technique. This technique is extremely efficient in verifying legitimate devices connected to the network. The other solutions also rely on IP to authenticate users' devices. IP does not prove the identity of the legitimate device when connected to the network because it is the address of software and not hardware. Also, if the attacker uses a legitimate IP, he/she can perform malicious threats on the EHR repository that will significantly affect network performance. RAMHU uses lightweight operations ( $GM$  and  $CM$ ) as part of the authentication processes in the examination of legitimate devices. Therefore, the aforementioned RAMHU features enable it to perform lightweight and efficient authentication.

- **Experimental Performance Analysis**

In this section, we show RAMHU's performance in healthcare applications. We provide tests on the hash function (PHOTON 256-bit) and encryption algorithm (ECIES 256-bit). In addition, communication costs (storage overheads) and computation (execution time) are calculated to extract RAMHU's performance. Applications codes ( $C_i$ ,  $CS$  and  $AS$ ) are written in Java Programming Language. Also, RAMHU's results are implemented on Ubuntu 16.04 LTS, processor Intel Core i5 2.6GHz, OS type 32-bit, Memory 4 GiB and disk 32.0 GB.

To compute the cost of communication, we compute the bits of all security parameters. Hash's MD (PHOTON) is 256-bit and the ECIES encryption key is 256-bit. The number of messages transmitted through the authentication and login protocol is 4, the password update protocol is 2 and the revocation protocol is 3. On the  $C_i$  side, it produces a 6-line file ( $TS_{C_i}=8$ ,  $GM=17$ ,  $C_iSig_1=64$ ,  $UP_{C_i}^{CS}||MP_{C_i}^{CS}=5$ ,  $N_{C_i}=8$ ,  $tmpPW_i=64$  and  $C_iSig_2=64$ ). The total size of the parameters is 230 bytes. Then  $C_i$  converts the plaintext file to an encrypt file with a size from 210 bytes to 255 bytes (the minimum value is 1680 bits) and the number of bits inside the encryption file is 253 bits. When  $C_i$  receives the authentication response from  $CS$ , the size of the decryption file is from 93 bytes to 99 bytes (the minimum value is 744 bits). The total size of encryption and decryption files in  $C_i$  is 2424 bits.

On the *CS* side, it produces a 4-line file ( $TS_{CS}=8$ ,  $UP_{CS}^{AS}||MP_{CS}^{AS}=11$ ,  $N_{CS}=8$ ,  $tmpPW_i=64$  and  $CSSig_3=64$ ). The total size of the parameters is 155 bytes. Then *CS* converts the plaintext file to an encrypt file with a size of 133 bytes to 178 bytes (the minimum value is 1064 bits) and the number of bits within the encryption file is 176 bits. When *CS* receives the authentication response from *AS*, the size of the decryption file is from 99 bytes to 125 bytes (the minimum value is 792 bits). The total size of encryption and decryption files in *CS* is 1856 bits.

On the *AS* side, it produces a 3-line file ( $TS_{AS}=8$ ,  $UP_{AS}^{CS}||MP_{AS}^{CS}=17$ ,  $N_{AS}=8$  and  $ASSig_2=64$ ). The total size of the parameters is 97 bytes. Then *AS* converts the plaintext file to an encrypted file with a size of 119 bytes to 125 bytes (the minimum value is 952 bits) and the number of bits within the encryption file is 212 bits. When *AS* receives the authentication response from *CS*, the decryption file size is from 158 bytes to 164 bytes (the minimum value is 1264 bits). The total size of encryption and decryption files in *AS* is 2216 bits. Also, storage complexity in RAMHU is 8352 bits.

To compute the cost of computation, we obtained preliminary results about the running time for PHOTON-256, ECIES-256 encryption and ECIES-256 decryption (100 times, information size of 93 bytes) as shown in Figure 7.25. We noted that the execution time of PHOTON is faster than hash algorithms such as SHA-1 and SHA-256 depending on the results in Latinov (2018). The minimum execution time for the PHOTON 256-bit hash function is 0.002358 ms, ECIES 256-bit encryption is 0.133672 ms, ECIES 256-bit decryption is 0.110136 ms, ECIES 256-bit encryption and PHOTON 256-bit is 0.136186 ms and ECIES 256-bit decryption and PHOTON 256-bit is 0.112521 ms. Also, time complexity in RAMHU is 0.994828 ms.

- **Performance Comparison**

In this section, we compare the superiority of RAMHU over the authentication schemes in the performance side. Although the implementation environment for authentication schemes varies, we make some comparisons that demonstrate the superiority of RAMHU's performance over existing schemes.

The authentication scheme in He & Zeadally (2015) relies on ECC 512-bit plus AES to generate session key, while RAMHU relies on ECC 256-bit which is NIST certified and sufficient to encrypt and secure the authentication request. As a result, RAMHU uses ECC with the best performance and has no need to use symmetric encryption that increases computation expenses.

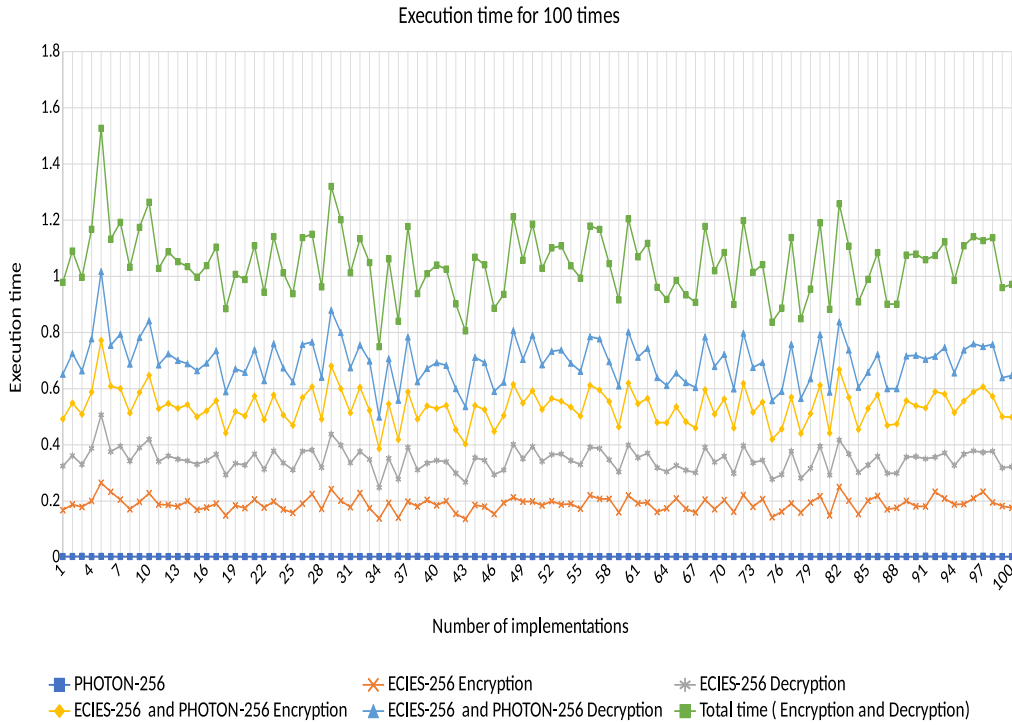


Figure 7.25: Implementations of PHOTON 256-bit and ECIES 256-bit

Schemes in Farash et al. (2016) and Jiang et al. (2016) are based on a single server performing all complex operations with users' devices. These processes consume server resources while RAMHU divides computations on servers  $CS$  and  $AS$  which dramatically improves performance. In addition, RAMHU performs the lowest number of hashes compared to these schemes as shown in Table 7.6 ( $T_h$  is the time complexity for hash function,  $T_s$  is the time complexity for symmetric encryption and  $T_H$  is the time complexity for bio-hash function). This makes RAMHU's performance suitable for the healthcare application environment.

Compared to RAMHU, both schemes in Jiang et al. (2016) and Das et al. (2017) use a fuzzy extractor that requires additional operations to consume an execution time of 0.442s, while RAMHU does not need these additional operations. Furthermore, the scheme in Giri et al. (2015) is based on RSA 1024-bit which is expensive in encryption and decryption while RAMHU relies on ECIES 256-bit which uses small keys and is suitable for high-performance security. The CACPPA scheme in Rajput, Abbas, Wang, Eun & Oh (2016) suffers from storage overheads. It requires 76 bytes per pseudonym as well as other storage requirements such as keys, encryption by ECIES 256-bit and signature by ECDSA 256-bit. With increasing numbers of users, this

Table 7.6: Comparison of computation cost between RAMHU and existing authentication schemes

Scheme	Hashes number on user side	Hashes number on server side	Total	Hash type	Running time in ms	No. of messages	No. of bits
He & Zeadally (2015)	$2T_h + 2T_s$	$1T_h + 4T_s$	$3T_h + 6T_s$	Standard	0.4 +0.4	6	-
Giri et al. (2015)	$5T_h$	$4T_h$	$9T_h$	Standard	-	4	1600
Jiang et al. (2016)	$7T_h$	$7T_h$	$14T_h$	Standard	-	4	-
Kumar et al. (2016)	$5T_h$	$5T_h$	$10T_h$	Standard	-	3	-
Li et al. (2016)	$6T_h + 2T_s$	$7T_h + 6T_s$	$13T_h + 8T_s$	Standard	0.0001+0.442	4	768
Das et al. (2017)	$3T_h$	$7T_h$	$10T_h$	Standard	0.0001+0.442	4	768
Chandrakar & Om (2017)	$12T_h+1T_H$	$7T_h$	$19T_h+1T_H$	Standard	0.0005+0.02102	9	2240
<b>RAMHU</b>	$3T_h$	$5T_h$	$8T_h$	Lightweight	0.002358	4	253

scheme will be extremely costly for server memory (communication and computational overheads). RAMHU uses only 5-17 bytes per pseudonym which saves significant memory storage. Moreover, the scheme in Chandrakar & Om (2017) stores the same user information on multiple servers which consumes storage resources as well as the computation cost to store this information. RAMHU does not deplete storage sources by repeating the same information on servers.

The scheme in El-Tawab et al. (2019) suffers from costly processes due to the use of SHA-256, while RAMHU uses PHOTON which has lightweight processes. Additionally, impersonation attacks of legitimate MACs on schemes in Nizzi et al. (2019) and El-Tawab et al. (2019) cause low network performance due to increased network-connected fake devices. RAMHU prevents the use of legitimate MACs addresses in more than one device by using the *CM* technique and thus maintains network performance.

## 7.4 Analysis of PAX Scheme

In this section, we discuss user scenarios, security and performance analysis and compare PAX with existing search and demonstrate PAX's ability to protect patient data during security and privacy implementation.

### 7.4.1 Direct and Indirect Users Scenarios in PAX

There are four case scenarios in PAX that involve obtaining access to patients' medical and/or health records in the EHR/EMR repository. Here we present how the user can access patient data while securing their privacy. To provide user scenarios, we introduce a number of EHR users to the PAX system, as shown in Figure 7.26.

Assume we have three patients, Sara, John, and Rose, who suffer from cancer, dementia, and diabetes respectively. Each disease requires a different level of care. For instance, a patient suffering from dementia needs a family member who assists with all of the patient's tasks and is able to access all of the patient's data. We assume that Julia is one of John's relatives. Also, there is a group of healthcare providers, including Simon, Adam, Hawa, and Abraham, who want access to the patients' medical records. These users can have different roles; for example, Adam may have the roles of advisor and doctor, and Abraham may be a doctor and an emergency doctor. Different user roles can be a major reason for breaching the privacy of medical records. Users such as patients (Sara and Rose) and the physician (Simon) need direct authorisation to EHR data because of regular and ongoing requests to access the repository. For example, Simon is the general practitioner (GP) for Sara and needs to access her data every day or even more than once a day. Under the PAX system, only Sara and Simon can access Sara's data, as shown in Figure 7.27.

1. The first scenario use (advisor): Simon needs a consultant (such as Adam) to diagnose Sara's disease or to submit treatment suggestions (after receiving Sara's consent to seek specialist advice). Adam is not associated with Sara permanently and continuously and does not need Sara's personal information; he only needs certain details of the patient data and medical reports. Therefore, in PAX, Adam needs to enter his name (Adam), the name of the doctor (Simon), and Sara's pseudonym to access Sara's data; he does not need to know Sara's real attributes. Figure 7.27 shows Sara's data, which can be obtained by Simon and Adam. We note, from Figure 7.27, that the data received does not contain any of Sara's attributes, and Adam does not use any real attributes for Sara, which means that PAX provides a high level of security and privacy that can prevent external and internal attacks
2. The second scenario use (relative of a patient): Because the patient (John) suffers from dementia, he is unable to perform his duties. John needs a family helper (such as Julia) to access his medical data without misuse or to bypass these privileges to other medical records. Julia needs a request that contains her Sigs and John's pseudonym to be considered a legitimate user in the system but is not authorised to access John's data until the *CS* and *AS* complete the third authorisation protocol with the Shamir scheme
3. The third scenario use (researcher): Hawa is a researcher and tries to access the server's repository to use EHR in evaluating a medical study to develop a disease treatment. The researcher needs access to medical records sporadically

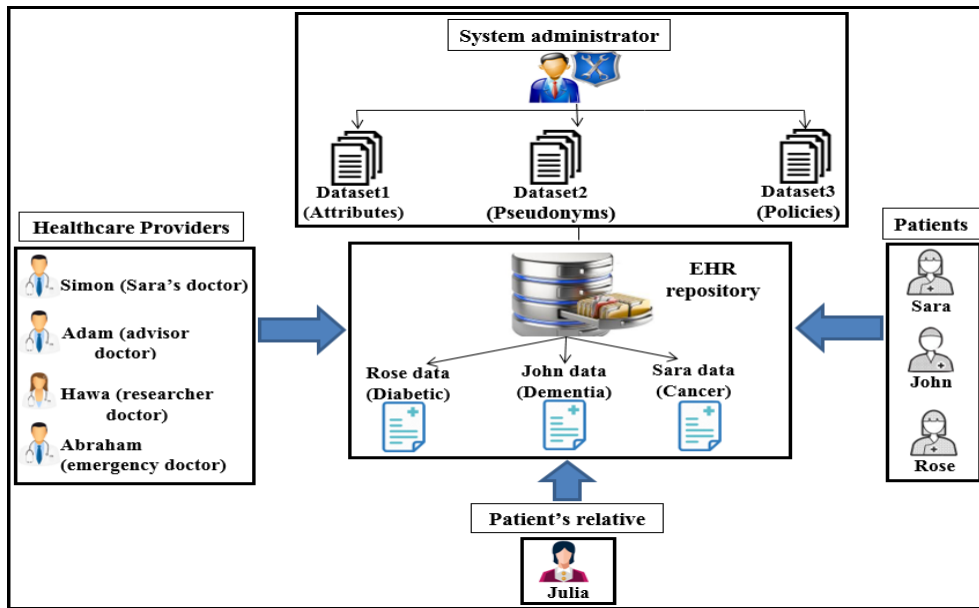


Figure 7.26: Users' scenarios in PAX

and temporarily. The researcher is not associated with a particular patient and needs access to a set of patients data. Also, this indirect user does not need access to patient attributes. Figure 7.28 shows a set of medical records obtained by Hawa in the case of authorisation without using any of the patients' real attributes

4. The fourth scenario and the last use (emergency doctor): When Rose's health deteriorates significantly and suddenly, her doctor is not available for some reason. Rose needs an emergency doctor to assess and treat her condition quickly (e.g., Abraham). The emergency doctor needs to access Rose's data without accessing personal information. In an emergency, access to a patient's data does not require the patient's consent. Abraham should not know any secrets healthcare providers have used to authorise access to Rose's data.

PAX provides security and privacy for all previous scenarios; indirect users cannot access the patient's personal information because it is separate and completely hidden from the data. As a result, the user can retrieve this data to improve healthcare without penetrating the repository in *DS*.

## 7.4.2 Possible Attacks on PAX Scheme

Applying privacy to medical records (EHR) requires the use of access models in the authorisation of users. Integrating RBAC and ABAC gives more powerful features to PAX users. The result is an access control model based on roles and attributes that handle user requests at coarse-grained and fine-grained levels. To increase



```

*****
*      Patient's Data      *
*****

Pseudonym:  $RN_{optm}$  &  $UN_{optm}$ 

check1:  report:  status:  date:
check2:  report:  status:  date:
check3:  report:  status:  date:
check4:  report:  status:  date:
check5:  report:  status:  date:
.        .        .        .
.        .        .        .
.        .        .        .

```

Figure 7.27: Part of Sarah's data

```

*****
*      Patients' DataSet   *
*****
-----
No Check  Report  Status  time      date
-----
1  check3  Report3  still    23:21:33  2017-09-05
2  check1  Report1  ok       14:36:45  2017-09-08
3  check2  Report2  normal   17:09:57  2017-09-08
5  check3  Report3  still    17:10:09  2017-09-10
6  check2  Report2  normal   12:28:20  2017-09-11
.        .        .        .        .
.        .        .        .        .
.        .        .        .        .

```

Figure 7.28: Part of a group of patients' medical records

security and privacy in the authorisation model, we have added a set of mechanisms to hide and separate personal information about data. The PAX system ensures that legitimate users access their specific data and, on the other hand, the privacy of medical records is maintained. Any healthcare system should support the basic security features of confidentiality, integrity, and availability (C.I.A.) (Neubauer & Heurix 2011). There are a range of attacks that pose a serious risk to any healthcare system. PAX's security mechanisms act as countermeasures against known attacks.

- **Proposition 1 – Availability attack**

$I$  cannot efficiently destroy PAX scheme by availability attacks.

**Proof**

The server is vulnerable to denial of service (DOS) attacks that are intended to disable the service. In PAX, the indirect user creates a random Sig based on  $SS_s$  provided by healthcare providers. The attacker cannot use the same  $SS_s$  because the  $CS$  and  $AS$  will ignore the request. The abundance of medical records is critical to healthcare providers' flexible access. Therefore, supporting robustness in any healthcare system depends on preventing DOS attacks. Although the PAX system limits the risk of DOS attacks, it does not do so fully because the attacker can still send requests without penetrating

the patient's personal information and data.

- **Proposition 2 – Data and policies datasets attacks**

*II* or *EI* cannot penetrate data and policies datasets in EHR repository.

**Proof**

The data in the single server is considered an attractive target for attackers. Also, policies contain the attributes and roles of users, which can assist attackers in carrying out an attack to recognise and access patient data. In PAX, even if the attacker obtains a patient's data, the data would not be useful because both the stored and movable data would have pseudonym. In addition, the data is stored (on *DS*) separately from policies (on *AS*). Furthermore, PAX policies are associated with pseudonyms and anonymity (both *CS* and *DS* do not have real attributes datasets for users), attackers are prevented from revealing subjects' and objects' attributes.

- **Proposition 3 – MITM attack**

*I* cannot apply modification attacks to change authorisation requests for users.

**Proof**

User requests from clients to the server in PAX are fully protected from modification. PAX uses random nonces and Sigs to detect a changing operation (MITM) by intruders.

- **Proposition 4 – Replay attack**

*I* cannot resend authorisation requests later (replay attacks) to gain access to the network.

**Proof**

The intruder cannot resend authorisation requests to the network later because PAX produces a new timestamp ( $TS_C$ ,  $TS_{CS}$ ,  $TS_{AS}$ , and  $TS_{DS}$ ) between PAX's entities.

- **Proposition 5 – Unauthorised access attack**

*I* cannot perform unauthorised access attacks against PAX scheme.

**Proof**

User access to a repository depends on authorisation policies. We use XACML v3.0 to create user policies. Integrating RBAC and ABAC into XACML prevents unauthorised users from accessing patient data.

- **Proposition 6 – Traffic analysis attack**

*EI* cannot use traffic analysis attacks to detect user information.

**Proof**

To perform this attack, the hacker must analyse either the requests or the

data moving between the source and the target. In PAX, if we assume that the attacker has some attributes (such as the name) and expects a specific patient, the attacker cannot use a keyword (name) and analyse it with multiple requests or medical records, even if it is the same user, to reveal its real attributes; the attacker cannot identify this data for a particular patient. Using pseudonym and anonymity prevents attackers from tracking traffic. For example, if advisor1 and advisor2 want patient1 data, the generated requests will be different. This prevents the parsing of requests.

- **Proposition 7 – Impersonation attack**

*I* cannot impersonate PAX’s entities (impersonation attacks).

**Proof**

The intruder cannot impersonate PAX’s entities ( $C_i$ ,  $CS$ ,  $AS$  and  $DS$ ) because PAX uses secret nonces ( $SN_C$ ,  $SN_{CS}$  and  $SN_{AS}$ ) and secret Sigs among entities to support mutual authentication and prevent impersonation attacks.

- **Proposition 8 – Timing attack**

*EI* cannot use timing attacks to penetrate security parameters in signatures.

**Proof**

This attack exploits the security procedure while calculating the time period for security operations (such as encryption and signing). PAX prevents these attacks because when the attacker gets multiple requests for the same user, the attacker will find that these requests contain different Sigs, and the attacker does not have the parameters to generate the Sig. In addition, ECDSA’s Sigs with 256-bit is resistant to timing attacks.

## 1. Experimental Security Analysis

In this section, we will use the AVISPA tool to analyse PAX authorisation procedures. Then we will present the results of PAX analysis in repelling known attacks.

- **PAX Scheme with AVISPA**

As we have described the AVISPA in Section 7.1.1, PAX consists of four core (essential) roles: client ( $C_i$ ), centralServer ( $CS$ ), attributesServer ( $AS$ ) and dataServer ( $DS$ ). Also, there are the supporting roles such as session, and environment, goal specification section. Essential roles include a transition section (to specify the sequence of communication operations in network framework). Supporting roles include a composition section (to specify the linking of sessions and roles).

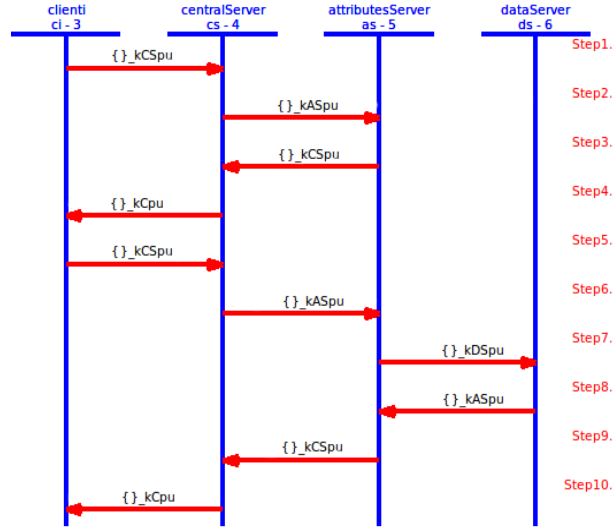


Figure 7.29: PAX's framework in AVISPA

PAX depends on asymmetric cryptography using ECDSA with public keys ( $KC_{pu}$ ,  $KCS_{pu}$ ,  $KAS_{pu}$  and  $KDS_{pu}$ ) to perform security requirements (integrity, authentication and non-repudiation). Moreover, PAX applies nonces ( $SN_C$ ,  $SN_{CS}$ ,  $SN_{AS}$  and  $SN_{DS}$ ) to support anonymity and timestamps ( $TS_C$ ,  $TS_{CS}$ ,  $TS_{AS}$  and  $TS_{DS}$ ) to support freshness. The authorisation process for indirect users is illustrated by the HLPSL scripts in Figures 7.30, 7.31, 7.32 and 7.33. Each role consists of the number of transitions, the receiving process (RCV), the sending process (SND), the sender's claim process of fresh value and correct (witness), the validation process in receiver for the sender's claim (request), the process of creating a fresh value for the nonce and timestamp (new) and the use of the private key ( $\_inv$ ) in PAX's entities. At first,  $C_i$  receives the start signal as in Figure 7.30, then the SND and RCV operations continue until the authorisation process is completed as in Figure 7.29.

Figure 7.34 shows the roles of session, environment, and goal section. In the session role, a composition process has been performed for the four roles (*clienti*, *centralServer*, *attributeServer* and *dataServer*) and specifies the send and receive channels in the Dolev-Yao model. In the environment role, the PP, the goals specified in the goal section, and the known information for the intruder (*intruder\_knowledge*) have been defined. In this role, one or more sessions are composed, and we tested our scheme with sessions for replay, MITM, and impersonating entity attacks. We assumed that an intruder ( $I$ ) creates a public key ( $ki$ ) and has knowledge of the public keys ( $kCpu$ ,  $kCSpu$ , and  $kASpu$ ) of PAX's

entities in the network. Intruder attempts to resend legitimate user requests later, intercepts/modifies these requests, or impersonates the connecting entities using  $i$  constant rather than  $ci$ ,  $cs$ ,  $as$  and  $ds$ .

The results display that these attacks cannot penetrate the security goals in our scheme. Goal section describes verified goals in PAX, and provides 10 goals of secrecy (such as  $S\_ID$ ,  $O\_ID$ ,  $S\_R$  and  $O\_R$  representing the first secret (sec1) and known only for both  $ci$  and  $cs$ ) and eight goals of authentication (such as  $UNspm$ ,  $UNopm$  and  $TScs$  representing the first authentication between  $ci$  and  $cs$ ).

```

role clienti(Ci,CS:agent, KCpu,KCSpu:public_key,H:hash_func, S_ID,O_ID,S_R,O_R:message,SND,
RCV:channel(dy))
played_by Ci def=
local
    State:nat,
    TSc,TScs,TSctm,TScstm,Nc,SNc,SNctm:text,
    CiS1,CiS2,CiS3,CiS4,CiS5,CiS6,CiS1tm,CiS2tm,CiS4tm,CiS6tm,CSS2tm,CSS3tm,CSS5:text,
    SP,OP,UNspl,UNspm,UNsph,UNopl,UNopm,UNoph,RNspl,RNspm,RNsph,RNopl,RNopm
    ,RNoph:text, RNspn,RNopn,UNspn,UNopn:text,AS,DS:agent, MS,SS,SSs,Decision,Data:text
const
    sec1,sec2,sec3,sec4,sec5,sec6,auth1,auth2:protocol_id
init
    State := 0
transition
1.State=0
  /\RCV(start) =|> State':=1 /\Nc':=new() /\SNc':=new() /\TSc':=new()
  /\CiS1':={H(RNspm.UNspm.Nc'.TSc')} _inv(KCpu) /\CiS2':={H(RNopm.UNopm.Nc'.TSc')} _inv(KCpu)
  /\CiS3':={H(SNc')} _inv(KCpu) /\ CiS4':={H(RNoph.UNoph.TSc')} _inv(KCpu)
  /\CiS1tm':=xor(CiS1',CiS3') /\CiS2tm':=xor(CiS2',CiS3')
  /\TSctm':=xor(TSc',xor(SNc',xor(RNspm,UNspm)))
  /\SNctm':=xor(UNspm,xor(UNopm,xor(SNc',xor(CiS4',CiS1tm'))))
  /\CiS4tm':=xor(CiS4',xor(UNspm,xor(UNopm,CiS2tm'))
  /\RNspn':=xor(RNspl,xor(CiS1tm',SNctm')) /\RNopn':=xor(RNopl,xor(CiS2tm',SNctm'))
  /\UNspn':=xor(UNspl,xor(CiS1tm',SNctm')) /\UNopn':=xor(UNopl,xor(CiS2tm',SNctm'))
% Ci sends XACML's request to CS
  /\SND(CS.CiS1tm'.RNspn'.UNspn'.Nc'.TSctm'.SNctm'
.CiS2tm'.RNopn'.UNopn'.Nc'.CiS4tm') /\secret({S_ID,O_ID,S_R,O_R},sec1,{Ci,AS})
  /\secret({SNc',CiS3',TSc'},sec2,{Ci,CS}) /\secret({CiS1',CiS2'},sec3,{Ci,CS,AS})
  /\secret({RNspm,UNspm,RNopm,UNopm},sec4,{Ci,CS})

% Ci receives first authorisation response from CS
2.State = 1
  /\RCV(Ci.CSS2tm'.UNspn'.TScstm')=|> State':= 2 /\UNspl':=xor(UNspn',xor(CSS2tm',TScstm'))
  /\TScs':=xor(TScstm',xor(SNc,UNopm)) /\CiS6':={H(SP)} _inv(KCpu)
  /\SSs':=xor(CiS1,xor(CiS3,xor(CSS2tm',xor(CiS4,CiS6'))))
  /\MS':= {SS.SSs'} /\CiS6tm':=xor(CiS6',xor(CiS3,MS'))
  /\secret({OP,CiS4},sec5,{Ci,AS,DS}) /\secret({SP,CiS6,MS',SS},sec6,{Ci,AS})
  /\TSc':=new() /\TSctm':=xor(TSc',xor(SNc,UNspm)) /\UNspn':=xor(UNspl',xor(CiS6tm',TSctm'))
% Ci sends Shamir's response to CS
  /\SND(CS.CiS6tm'.UNspn'.TSctm') /\witness(Ci,CS,auth1,{UNspm,UNopm,TScs})

% Ci receives decision & data from CS
3.State=2
  /\RCV(Ci.CSS2tm'.CSS3tm'.UNspn'.TScstm'.Decision.Data)=|> State':=3
  /\UNspl':=xor(UNspn',xor(CSS2tm',TScstm')) /\TScs':=xor(TScstm',xor(SNc,UNopm))
  /\CSS5':=xor(CiS1',xor(CiS3',xor(CSS2tm',CiS4')) /\CiS5':={H(Data)} _inv(KCSpu)
  /\CiS1':=xor(CSS2tm',xor(CiS3,xor(CiS5',CiS4))) /\CiS2':=xor(CSS3tm',xor(CiS3,xor(CiS5',CiS4)))
  /\CiS3':=xor(CiS2',xor(CSS2tm',xor(CiS5',CiS4)))
  /\CiS4':=xor(CiS1',xor(CiS3',xor(CiS5',CSS2tm')) /\request(Ci,CS,auth2,{SNc,CiS3,CiS4,TSc})
end role

```

Figure 7.30:  $C_i$  role of PAX in HLPSL

```

role centralServer(CS,Ci,AS:agent, KCSpu,KCpu,KASpu:public_key, H:hash_func, SND,RCV:channel(dy))
played_by CS def=
local
    State:nat,TSc,TScs,TSas,TSctm,TScstm,TSastm,Nc,Ncs,SNc,SNcs,SNctm,SNcstm:text, CSS1,CSS2,
    CSS3,CSS4,CSS5,CSS2tm,CSS3tm,CiS1,CiS2,CiS4,CiS1tm,CiS2tm,CiS4tm,CiS6tm:text,
    ASS2,ASS3,ASS7,ASS2tm,ASS3tm:text, Decision,Data:text,
    UNspl,UNspm,UNopl,UNopm,RNspl,RNspm,RNopl,RNopm, RNspn,RNopn,UNspn,UNopn:text
const
    sec2,sec3,sec4,sec7,auth1,auth2,auth3,auth4:protocol_id
init
    State := 0
transition
% CS receives XACML's request from Ci
1.State=0
    /\RCV(CS.CiS1tm'.RNspn'.UNspn'.Nc'.TSctm'.SNctm'.CiS2tm'.RNopn'.UNopn'.Nc'.CiS4tm')=|>
    State':=1/\RNspl':=xor(RNspn',xor(CiS1tm',SNctm'))
    /\RNopl':=xor(RNopl',xor(CiS2tm',SNctm')) /\UNspl':=xor(UNspn',xor(CiS1tm',SNctm'))
    /\UNopl':=xor(UNopl',xor(CiS2tm',SNctm')) /\CiS4':=xor(CiS4tm',xor(UNspm,xor(UNopm,CiS2tm')))
    /\SNc':=xor(UNspm,xor(UNopm,xor(SNctm',xor(CiS4',CiS1tm'))))
    /\Tsc':=xor(TSc',xor(SNc',xor(RNspm,UNspm))) /\CSS1':={H(SNc')}_inv(KCpu)
    /\CiS1':=xor(CiS1tm',CSS1') /\CiS2':=xor(CiS2tm',CSS1')
    /\CSS2':={H(RNspm.UNspm.Nc'.Tsc')}_inv(KCpu)
    /\CSS3':={H(RNopm.UNopm.Nc'.Tsc')}_inv(KCpu)
    /\secret({SNc',CSS1',Tsc'},sec2,{CS,Ci}) /\secret({CSS2',CSS3'},sec3,{CS,Ci,AS})
% CS creates authorisation request to AS
    /\SNcs':=new() /\TScs':=new() /\CSS4':={H(SNcs')}_inv(KCSpu)
    /\CSS2tm':=xor(CSS2',CSS4') /\CSS3tm':=xor(CSS3',CSS4')
    /\Ncs':=xor(Nc',xor(TSc',xor(TScs',SNcs')) /\TSctm':=xor(TSc',xor(SNcs',xor(RNspm,UNspm)))
    /\TScstm':=xor(TScs',xor(SNcs',xor(RNopm,UNopm)))
    /\SNcstm':=xor(UNspm,xor(UNopm,xor(SNcs',xor(CiS4',CSS2tm'))))
    /\CiS4tm':=xor(CiS4',xor(UNspm,xor(UNopm,CSS3tm')))
    /\RNspn':=xor(RNspl,xor(CSS2tm',SNcstm')) /\RNopn':=xor(RNopl,xor(CSS3tm',SNcstm'))
    /\UNspn':=xor(UNspl,xor(CSS2tm',SNcstm')) /\UNopn':=xor(UNopl,xor(CSS3tm',SNcstm'))
% CS sends request to AS
    /\SND(AS.CSS2tm'.RNspn'.UNspn'.Ncs'.TSctm'.Tscstm'.SNcstm'.CSS3tm'.RNopn'.UNopn'.CiS4tm')
    /\secret({RNspm,UNspm,RNopm,UNopm},sec4,{CS,AS}) /\secret({SNcs',CSS4',TScs',Nc'},sec7,{CS,AS})

% CS receives authorisation response from AS
2.State=1
    /\RCV(CS.ASS2tm'.UNspn'.TSastm')=|>State':=2 /\CSS2tm':=xor(ASS2tm',xor(CSS4',CSS1))
    /\TScs':=new() /\TScstm':=xor(TScs',xor(SNc,UNopm)) /\UNspn':=xor(UNspl,xor(CSS2tm',TScstm'))
    /\witness(CS,AS,auth3,{UNspm,UNopm,Nc,TSc,TSas})
% CS sends authorisation response to Ci
    /\SND(Ci.CSS2tm'.UNspn'.Tscstm')

% CS receives Shamir's response from Ci
3.State=2
    /\RCV(CS.CiS6tm'.UNspn'.TSctm')=|>State':=3
    /\UNspl':=xor(UNspn',xor(CiS6tm',TSctm')) /\Tsc':=xor(TSc',xor(SNc,UNspm))
    /\CiS6tm':=xor(CiS6tm',xor(CSS1,CSS4)) /\request(CS,Ci,auth1,{UNspm,UNopm,TScs})
    /\TScs':=new() /\TScstm':=xor(TScs',xor(SNcs,UNopm)) /\UNspn':=xor(UNspl,xor(CiS6tm',Tscstm'))
% CS sends Shamir's response to AS
    /\SND(AS.CiS6tm'.UNspn'.Tscstm')

% CS receives decision & data response from AS
4.State=3
    /\RCV(CS.ASS2tm'.ASS3tm'.UNspn'.TSastm'.Decision.Data)=|>State':=4
    /\UNspl':=xor(UNspn',xor(ASS2tm',TSastm')) /\TSas':=xor(TSastm',xor(SNcs,UNopm))
    /\ASS7':=xor(CSS2,xor(CSS4,xor(CiS4,ASS2tm))) /\CSS5':={H(Data)}_inv(KASpu)
    /\ASS2':=xor(ASS2tm',xor(CSS4,xor(ASS7,CiS4))) /\ASS3':=xor(ASS3tm',xor(CSS4,xor(ASS7,CiS4)))
    /\CiS4':=xor(ASS2tm',xor(CSS4,xor(ASS7,ASS2')) /\request(CS,AS,auth4,{SNcs,CSS1,CiS4,TScs})
    /\TScs':=new() /\CSS2tm':=xor(CSS2,xor(CSS1,xor(CSS5,CiS4)))
    /\CSS3tm':=xor(CSS3,xor(CSS1,xor(CSS5,CiS4)))
    /\TScstm':=xor(TScs',xor(SNc,UNopm)) /\UNspn':=xor(UNspl,xor(CSS2tm',Tscstm'))
% CS sends decision & data response to Ci
    /\SND(Ci.CSS2tm'.CSS3tm'.UNspn'.Tscstm'.Decision.Data)
    /\witness(CS,Ci,auth2,{SNc,CSS1,CiS4,TSc})
end role

```

Figure 7.31: CS role of PAX in HLPSP

```

role attributesServer(AS,CS,DS:agent, KASpu,KCSpu,KDSpu:public_key, Ssp,Sop:text,H:hash_func, SND
RCV:channel(dy))
played_by AS def=
local
  State:nat, TSc,TScs,TSas,TSds,TSctm,TScstm,TSastm,TSdstm,Nc,Ncs,SNcs,SNas,SNcstm,SNastm:text,
  ASS1,ASS2,ASS3,ASS4,ASS5,ASS6,ASS7,ASS2tm,ASS3tm,ASS6tm:text, CiS4,CiS4tm,CiS6tm,CSS2,
  CSS3,CSS2tm,CSS3tm,DSS2tm,DSS4tm,DSS4:text, SP,OP,URsp,UNsp,URop,UNop,RNsp,RNop:text,
  UNSpl,UNspm,UNsph,UNopl,UNopm,UNoph:text, RNspl,RNspm,RNsph,RNopl,RNopm,RNoph:text,
  RNspn,RNopn,UNspn,UNopn:text, S_ID,O_ID,S_R,O_R:message,Ci:agent,SSs,MS,Data,Decision:text
const
  sec1,sec3,sec4,sec5,sec6,sec7,sec8,sec9,sec10,auth3,auth4,auth5,auth6:protocol_id
init State := 0
transition
% AS receives from CS
1.State = 0
  /\RCV(AS.CSS2tm'.RNspn'.UNspn'.Ncs'.TSctm'.TScstm'.SNcstm'.CSS3tm'.RNopn'.UNopn'.CiS4tm')=|>
  State' := 1/\RNspl' := xor(RNspn',xor(CSS2tm',SNcstm')) /\RNopl' := xor(RNopn',xor(CSS3tm',SNcstm'))
  /\UNspl' := xor(UNspn',xor(CSS2tm',SNcstm')) /\UNopl' := xor(UNopn',xor(CSS3tm',SNcstm'))
  /\CiS4' := xor(CiS4tm',xor(UNspm',xor(UNopm',CSS3tm'))))
  /\SNcs' := xor(UNspm',xor(UNopm',xor(SNcstm',xor(CiS4',CSS2tm'))))
  /\TSc' := xor(TScstm',xor(SNcs',xor(RNspm',UNspm))) /\TScs' := xor(TScstm',xor(SNcs',xor(RNopm',UNopm)))
  /\Nc' := xor(Ncs',xor(TSc',xor(TScs',SNcs')))) /\ASS1' := {H(SNcs')}_inv(KCSpu)
  /\CSS2' := xor(CSS2tm',ASS1') /\CSS3' := xor(CSS3tm',ASS1')
  /\ASS2' := {H(RNspm'.UNspm'.Nc'.TSc')}_inv(KCSpu) /\ASS3' := {H(RNopm'.UNopm'.Nc'.TSc')}_inv(KCSpu)
  /\ASS4' := {H(RNoph'.UNoph'.TSc')}_inv(KCSpu) /\SP' := URsp.UNsp/\OP' := URop.UNop
  /\secret({S_ID,O_ID,S_R,O_R},sec1,{AS,Ci}) /\secret({ASS2',ASS3'},sec3,{AS,CS,Ci})
  /\secret({RNspm',UNspm',RNopm',UNopm'},sec4,{AS,CS}) /\secret({OP',CiS4'},sec5,{AS,DS,Ci})
  /\secret({SP',Ssp,MS,SSs},sec6,{AS,Ci}) /\secret({SNcs',ASS1',Nc},sec7,{AS,CS})
  /\secret(Sop,sec8,AS)
% AS creates Shamir's request
  /\TSas' := new() /\ASS2tm' := xor(ASS2',xor(ASS1',xor(SSs',xor(CiS4',Ssp))))
  /\TSastm' := xor(TSas',xor(SNcs',UNopm)) /\UNspn' := xor(UNspl',xor(ASS2tm',TSastm'))
% AS sends Shamir's request to CS
  /\SND(CS.ASS2tm'.UNspn'.TSastm')

% AS receives Shamir's response from CS
2.State=1
  /\ RCV(AS.CiS6tm'.UNspn'.TScstm')=|> State' := 2/\UNspl' := xor(UNspn',xor(CiS6tm',TScstm'))
  /\TScs' := xor(TScstm',xor(SNcs',UNopm)) /\MS' := xor(CiS6tm',xor(Ssp,ASS1))
  /\request(AS,CS,auth3,{UNspm',UNopm',Nc,TSc,TSas})
% AS creates data retrieval request
  /\SNas' := new() /\TSas' := new() /\ASS5' := {H(SNas')}_inv(KASpu)
  /\ASS6' := {H(RNopm'.UNopm'.SNas'.TSas'.CiS4')}_inv(KASpu)
  /\RNopn' := xor(RNopl',xor(TSas',SNas')) /\ASS6tm' := xor(ASS6',xor(TSas',ASS5'))
  /\TSctm' := xor(TSc',xor(SNas',UNoph)) /\TSastm' := xor(TSas',xor(SNas',UNopm))
  /\SNastm' := xor(UNopm',xor(SNas',xor(CiS4',ASS6tm'))))
  /\CiS4tm' := xor(CiS4',xor(UNoph',xor(SNastm',UNopm))) /\UNopn' := xor(UNopl',xor(ASS6tm',TSastm'))
  /\secret({SNas',ASS5',TSas'},sec9,{AS,DS}) /\secret({RNoph',UNoph',ASS6'},sec10,{AS,DS})
% AS sends data retrieval request to DS
  /\SND(DS.ASS6tm'.RNopn'.UNopn'.SNastm'.TSctm'.TSastm'.CiS4tm')
  /\ witness(AS,DS,auth5,{CiS4',ASS6'})

% AS receives data retrieval response from DS
3.State=2
  /\ RCV(AS.DS.DSS2tm'.DSS4tm'.UNopn'.TSdstm'.CiS4tm'.Data) =|> State' := 3
  /\UNopl' := xor(UNopn',xor(DSS2tm',TSdstm')) /\TSds' := xor(TSdstm',xor(SNas',UNoph))
  /\CiS4' := xor(CiS4tm',xor(ASS5',TSds')) /\DSS4' := xor(DSS4tm',xor(ASS5',CiS4'))
  /\ASS6' := xor(DSS2tm',xor(DSS4',xor(TSds',ASS5))) /\ASS7' := {H(Data)}_inv(KDSpu)
  /\request(AS,DS,auth6,{SNas',ASS5',RNoph',UNoph})
% AS creates decision & data response
  /\TSas' := new() /\ASS2tm' := xor(ASS2',xor(ASS1',xor(ASS7',CiS4)))
  /\ASS3tm' := xor(ASS3',xor(ASS1',xor(ASS7',CiS4))) /\TSastm' := xor(TSas',xor(SNcs',UNopm))
  /\UNspn' := xor(UNspl',xor(ASS2tm',TSastm'))
% AS sends data retrieval response (Data and Decision) to CS
  /\SND(CS.ASS2tm'.ASS3tm'.UNspn'.TSastm'.Decision.Data)
  /\witness(AS,CS,auth4,{SNcs',ASS1',CiS4',TScs})
end role

```

Figure 7.32: AS role of PAX in HLPSL

```

role dataServer(DS,AS:agent, KDSpu,KASpu:public_key, H:hash_func,SND,RCV:channel(dy))
played_by DS def=
local
  State:nat,
  TSc,TSctm,TSas,TSastm,TSds,TSdstm,SNas,SNastm:text,
  OP,UNop1,UNopm,UNoph:text, RNop1,RNopm,RNoph,RNopn,UNopn:text,
  DSS1,DSS2,DSS3,DSS4:text, DSS2tm,DSS4tm,CiS4,CiS4tm,ASS6tm:text,
  Ci:agent,Data:text
const sec5,sec9,sec10,auth5,auth6:protocol_id
init State := 0
transition
1.State = 0
  /\ RCV(DS.ASS6tm'.RNopn'.UNopn'.SNastm'.TSctm'.TSastm'.CiS4tm')=>State:=1
  /\UNop1':=xor(UNopn',xor(ASS6tm',TSastm')) /\CiS4':=xor(CiS4tm',xor(UNoph,xor(SNastm',UNopm)))
  /\SNas':= xor(UNopm,xor(SNastm',xor(CiS4',ASS6tm')) /\TSc':=xor(TSctm',xor(SNas',UNoph))
  /\TSas':=xor(TSastm',xor(SNas',UNopm)) /\RNop1':=xor(RNopn',xor(TSas',SNas'))
  /\DSS1':={H(SNas')}_inv(KASpu) /\DSS2':={H(RNopm.UNopm.SNas'.TSas'.CiS4')}_inv(KASpu)
  /\DSS3':={H(RNoph.UNoph.TSc')}_inv(KASpu)
  /\secret({OP,CiS4'},sec5,{DS,AS,Ci}) /\secret({SNas',DSS1',TSas'},sec9,{DS,AS})
  /\secret({RNoph,UNoph,DSS2'},sec10,{DS,AS}) /\request(DS,AS,auth5,{CiS4,DSS2})
% DS Creates data retrieval response
  /\TSds':=new() /\DSS4':={H(Data)}_inv(KDSpu) /\DSS4tm':=xor(DSS4',xor(DSS1',CiS4'))
  /\DSS2tm':=xor(DSS2',xor(DSS4',xor(TSds',DSS1'))) /\CiS4tm':=xor(CiS4',xor(DSS1',TSds'))
  /\TSdstm':=xor(TSds',xor(SNas',UNoph)) /\UNopn':=xor(UNop1',xor(DSS2tm',TSdstm'))
% DS sends data retrieval response to AS
  /\SND(AS.DSS2tm'.DSS4tm'.UNopn'.TSdstm'.CiS4tm'.Data)
  /\ witness(DS,AS,auth6,{SNas,DSS1,RNoph,UNoph})
end role

```

Figure 7.33: *DS* role of PAX in HLPSP

- **Simulation Result**

Figure 7.35 displays the simulation result with the CL-AtSe backend, PAX clearly and accurately achieves the SAFE result in the SUMMARY section, bounded number of sessions in the DETAILS section, the goals of the scheme achieved (as\_specified) in the GOAL section as well as statistical numbers such as time, number of nodes, and analysed states in the STATISTICS section. It has proven that the PAX is capable of preventing passive and active attacks such as replay, MITM, and impersonating, and that the goals of the scheme in Figure 7.34 prevents the violation of legitimate users' information in the network authorisation.

## 2. Security Comparison

Tracking back to Chapter 2, where we reviewed the PERMIS HC system. Here we will show that the PAX has not suffered from PERMIS's problems (Chadwick et al. 2006) because each request to the healthcare provider has been signed randomly with the ECDSA algorithm, which includes both the roles ( $RN_s$ ) and the pseudonyms ( $UN_s$ ). In PAX, the policies are stored on the attributes server as Sigs and pseudonym rather than as explicit attributes in XACML (each user in PAX has attributes separate from other users that prevent the inheritance of attributes). Compared with Quantin et al. (2011), PAX has solved all requests' standardization and structure problems by including XACML v3.0 and ECDSA. XACML v3.0 offers standardization,



and generic and rich policy language and is unified with the context of subject requests. It does not have problems converting requests from different sources. We also use ECDSA to generate very small keys relative to RSA to improve server performance.

Furthermore, PAX does not need the keys complexity of PIPE (Riedl et al. 2008) because XACML has the flexibility to handle practitioners' and patients' requests, and we use only one high-performance signature algorithm. In PAX, all the attributes in the requests and policies are not clearly written as in Gajanayake et al. (2014). Moreover, data is anonymous to the patient when the data is transferred from the source to the target due to its link with a random pseudonym.

```

role session(Ci,CS,AS,DS:agent, KCpu,KCSpu,KASpu,KDSpu:public_key, H:hash_func, S_ID,O_ID,S_R,
             O_R:message,Ssp,Sop:text)
def=
local SND1,RCV1,SND2,RCV2,SND3,RCV3,SND4,RCV4:channel(dy)
composition
  clienti(Ci,CS,KCpu,KCSpu,H,S_ID,O_ID,S_R,O_R,SND1,RCV1)
  /\centralServer(CS,Ci,AS,KCSpu,KCpu,KASpu,H,SND2,RCV2)
  /\attributesServer(AS,CS,DS,KASpu,KCSpu,KDSpu,Ssp,Sop,H,SND3,RCV3)
  /\dataServer(DS,AS,KDSpu,KASpu,H,SND4,RCV4)
end role

role environment()
def=
const
  ci,cs,as,ds,i:agent, kCpu,kCSpu,kASpu,kDSpu,ki:public_key,s_id,o_id,s_r,o_r:message, ssp,sop:text,
  h:hash_func, sec1,sec2,sec3,sec4,sec5,sec6,sec7,sec8,sec9,sec10,
  auth1,auth2,auth3,auth4,auth5,auth6,auth7,auth8:protocol_id

  intruder_knowledge={i,ci,cs,as,kCpu,kCSpu,kASpu,kDSpu,ki,inv(ki)}
composition
  session(ci,cs,as,ds,kCpu,kCSpu,kASpu,kDSpu,h,s_id,o_id,s_r,o_r,ssp,sop)
% Check replay attack
  /\session(ci,cs,as,ds,kCpu,kCSpu,kASpu,kDSpu,h,s_id,o_id,s_r,o_r,ssp,sop)
% Check MITM attack
  %/\session(cs,ci,as,ds,kCSpu,kCpu,kASpu,kDSpu,h,s_id,o_id,s_r,o_r,ssp,sop)
% Check impersonate Ci
  %/\session(i,cs,as,ds,ki,kCSpu,kASpu,kDSpu,h,s_id,o_id,s_r,o_r,ssp,sop)
% Check impersonate CS
  %/\session(ci,i,as,ds,kCpu,ki,kASpu,kDSpu,h,s_id,o_id,s_r,o_r,ssp,sop)
% Check impersonate AS
  %/\session(ci,cs,i,ds,kCpu,kCSpu,ki,kDSpu,h,s_id,o_id,s_r,o_r,ssp,sop)
% Check impersonate DS
  %/\session(ci,cs,as,i,kCpu,kCSpu,kASpu,ki,h,s_id,o_id,s_r,o_r,ssp,sop)
end role

goal
  secrecy_of sec1,sec2,sec3,sec4,sec5,sec6,sec7,sec8,sec9,sec10
  authentication_on auth1,auth2,auth3,auth4,auth5,auth6,auth7,auth8
end goal
environment()

```

Figure 7.34: Session, environment, and goal roles of PAX in HLPSL

Instead of one situation (emergency) as in HCPP, our project used several realistic situations such as doctor advisors, physician researchers, emergency

```

SUMMARY
SAFE

DETAILS
BOUNDED_NUMBER_OF_SESSIONS
TYPED_MODEL

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

GOAL
As Specified

BACKEND
CL-AtSe

STATISTICS

Analysed   : 6912 states
Reachable  : 6912 states
Translation: 2.12 seconds
Computation: 139.21 seconds

```

Figure 7.35: Simulation result of PAX using CL-AtSe backend

doctors, and patients' relatives for healthcare users and used the XACML v3.0 policy language, which is effective for authorising users. The PAX does not require continuous mining (Sun et al. 2011) of patient data, but relies on the internal pseudonym to access medical records. XACS in Jo & Chung (2015) offers protection only against external attacks, whereas PAX offers protection against internal and external attacks by preventing attackers from identifying the personal information of legitimate users or patient data. In addition, the access control model in Seol et al. (2018) deals with real attributes, whereas PAX integrates signatures and pseudonyms within XACML policies and requests to prevent the clear exchange of user attributes during the authorisation process in healthcare applications.

The scheme in Wang et al. (2019) suffers from impersonation and timing threats. As well, the intruder can exploit cases of indirect users to trigger a DoS attack. PAX uses mutual authentication to prevent impersonation attacks and it uses random signatures to prevent timing and DoS attacks. There are a few of other scheme designed for HC systems. For instance, the scheme in Shafeeq et al. (2019) focuses on protecting the authorisation policy without paying attention to secure trusted authority and the single key in symmetric encryption. Also, their scheme relies solely on the ABAC model to determine access to the repository. PAX integrates security advantages into both RBAC and ABAC and does not have datasets/keys protection problems. Table 7.7 compares the security features provided in PAX and related works.

Table 7.7: Comparison of security features between PAX and other authorisation schemes

Security feature	Chadwick et al. (2006)	Quantin et al. (2011)	Riedl et al. (2008)	Gajanayake et al. (2014)	Sun et al. (2011)	Jo & Chung (2015)	Seol et al. (2018)	Wang et al. (2019)	Shafeeq et al. (2019)	<b>PAX scheme</b>
Mutual authentication										✓
Preserving anonymity		✓	✓		✓			✓	✓	✓
Pseudonym		✓	✓		✓				✓	✓
Anti DoS	✓		✓		✓					✓
Anti dataset attack							✓	✓		✓
Anti MITM	✓	✓	✓		✓		✓	✓	✓	✓
Anti replay	✓		✓	✓	✓	✓	✓		✓	✓
Anti privileged insider					✓				✓	✓
Anti traceability			✓		✓					✓
Anti impersonation									✓	✓
Anti timing					✓					✓
Anti leakage			✓		✓			✓		✓
Authorisation policies	✓			✓		✓	✓	✓	✓	✓

### 7.4.3 Performance Analysis

A performance analysis is conducted to examine the computation processes of PAX in improving the performance of authorisation processes.

- **Theoretical Performance Analysis**

When the users become authenticated within the network it needs to send authorisation requests to the servers to access patient data in the EHR repository. Authorisation requests should perform lightweight processes to maintain network performance, especially if the user performs many authorisation requests at frequent and convergent times. PAX relies mainly on a range of techniques, such as ECDSA, XACML, Shamir scheme and random pseudonyms that perform lightweight procedures compared to other technologies.

First, PAX uses the ECDSA algorithm to sign subjects' and objects' information in both requests and policies. This algorithm is ideal for authorisation schemes compared to public key signature algorithms as described in Chapter 2, Table 2.2. To maintain performance, we were careful to reduce the number of signatures to reduce the burden on users' devices and servers. For instance, full processing associated with sending an authorisation request to access patient data requires  $C_i = 6$  signatures,  $CS = 5$  signatures,  $AS = 7$  signatures and  $DS = 4$  signatures (indirect user's case). In short, reducing the number of signatures will improve the performance of the PAX scheme. In addition, PAX uses XACML technology to build robust policies in determining access to patient data. XACML provides the best caching storage procedures (Ilhan et al. 2015), flexibility in defining multiple rules,

simplicity in configuring policy combination (Duan et al. 2016), response times, the grouping of requests and making decisions (WSO2 Team 2017) of existing technologies.

Furthermore, PAX relies on the Shamir scheme to prevent tracking of user information in special cases such as advisor, relative, researcher and emergency rather than encryption mechanisms. The Shamir scheme provides PAX with robust security while performing light operations compared to encryption procedures. PAX uses the Shamir scheme only in cases of indirect users which are lower relative to direct users such as nurses and doctors. As a result, authorisation requests with the Shamir scheme will be fewer, and the burden on the servers *CS* and *AS* will be lower. Moreover, the PAX scheme uses the Shamir scheme with  $TH = 3 - 10$ . The dependency of  $TH$  with efficient range allows the Shamir scheme to support both security and performance in PAX meritoriously (Al-Adhami et al. 2017). Finally, PAX uses random pseudonyms to prevent the sending of real information through the network instead of  $k$ -anonymity and encryption mechanisms that perform complex processes and increase overheads. Therefore, PAX is considered a performance efficient scheme because it supports lightweight and high-performance mechanisms.

- **Experimental Performance Analysis**

Communication costs (storage overheads) and computation (execution time) are calculated to extract PAX's performance. Applications codes ( $C_i$ , *CS*, *AS* and *DS*) are written in Java Programming Language. The authorisation decision engine is supported on Balana XACML 3.0 open source available at <https://github.com/wso2/balana>, and is explained and managed by the WSO2 server. We used Maven to deal with Balana XACML as a library in Java. Also, PAX's results have been implemented on Ubuntu 16.04 LTS, processor Intel Core i5 2.6GHz, OS type 32-bit, Memory 4 GiB and disk 32.0 GB.

To compute the cost of communication, we compute the bits of all security parameters. Signature length (ECDSA) is 256-bit. The number of messages transmitted through the direct user authorisation is six and the indirect user authorisation is 10. In addition, response size is 196 bytes to 205 bytes, request size is 2091 bytes to 2098 bytes, policy size is 1483 bytes to 1492 bytes, policy with Shamir size is 1489 bytes to 1495 bytes, user information (attributes) is 586 bytes to 621 bytes, non-real patient data is 337 bytes to 500 bytes and non-real all patient data size for researchers is 1159 bytes to

2688 bytes (25 patients).

On the  $C_i$  side, it produces a request of subject attributes ( $C_iSig_1=128$ ,  $RN_{sptm}=128$ ,  $UN_{sptm}=128$ ,  $N_C=8$ ,  $TS_{Ctm}=16$  and  $SN_{Ctm}=128$ ) and object attributes ( $C_iSig_2=128$ ,  $RN_{optm}=128$ ,  $UN_{optm}=128$ ,  $N_C=8$  and  $C_iSig_4=128$ ). The total size of the parameters is 1056 bytes and the number of bits (attributes) inside the XACML request is 4224 bits. When  $C_i$  sends response to  $CS$ , this response includes security parameters ( $C_iSig_{6tm}=128$ ,  $UN_{sptm}=128$ , and  $TS_{Ctm}=16$ ). The total size of the parameters is 272 bytes and the number of bits inside the XACML response is 1088 bits. On the  $CS$  side, it produces a request subject attributes ( $CSSig_2=128$ ,  $RN_{sptm}=128$ ,  $UN_{sptm}=128$ ,  $N_{CS}=8$ ,  $TS_{Ctm}=16$ ,  $TS_{CStm}=16$  and  $SN_{CStm}=128$ ) and object attributes ( $CSSig_3=128$ ,  $RN_{optm}=128$ ,  $UN_{optm}=128$  and  $C_iSig_4=128$ ). The total size of the parameters is 1064 bytes and the number of bits inside the XACML request is 4256 bits. When  $CS$  sends the response to  $C_i$ , this response includes security parameters ( $CSSig_{2tm}=128$ ,  $CSSig_{3tm}=128$ ,  $UN_{sptm}=128$ , and  $TS_{CStm}=16$ ). The total size of the parameters is 400 bytes and the number of bits inside the XACML response is 1600 bits. On the  $AS$  side, it produces a XACML request that includes security parameters ( $ASSig_{6tm}=128$ ,  $RN_{optm}=16$ ,  $UN_{optm}=128$ ,  $SN_{AStm}=128$ ,  $TS_{Ctm}=16$ ,  $TS_{AStm}=16$  and  $C_iS_{4tm}=128$ ). The total size of the parameters is 560 bytes and the number of bits inside the XACML request is 2240 bits. Also, it produces response attributes ( $ASSig_2=128$ ,  $ASSig_3=128$ ,  $UN_{sptm}=128$  and  $TS_{AStm}=16$ ). The total size of the parameters is 400 bytes and the number of bits inside the XACML request is 1600 bits. On the  $DS$  side, it produces response attributes ( $DSSig_2=128$ ,  $DSSig_4=128$ ,  $UN_{optm}=128$ ,  $TS_{DStm}=16$  and  $C_iSig_{4tm}=128$ ). The total size of the parameters is 528 bytes and the number of bits inside the XACML request is 2112 bits.

To compute the cost of computation, we had obtained preliminary results about running time for ECDSA-256 key generation, signature and verification (100 times, information size of 2091 bytes) as shown in Figure 7.36. We noted execution time of ECDSA's procedures is faster than signature algorithms dependant results in Suárez-Albela et al. (2019). The minimum execution time for ECDSA 256-bit key generation is 0.002009 ms, signature is 0.002994 ms, verification is 0.003496 ms and full time for ECDSA 256-bit is 0.00921 ms.

- **Performance Comparison**

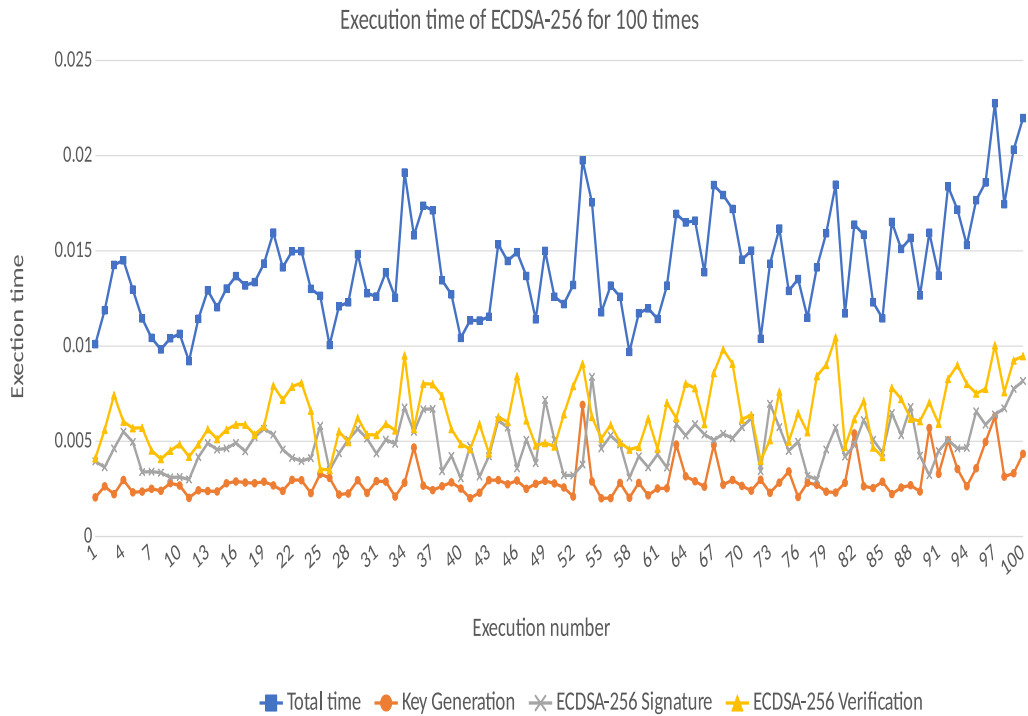


Figure 7.36: Implementations of ECDSA 256-bit

In this section, we will compare the superiority of PAX over the authorisation schemes in the performance side. Although the implementation environment for authorisation schemes varies, we have made some comparisons that demonstrate the superiority of PAX’s performance over existing schemes.

The scheme in Chadwick et al. (2006) is based on X.509 to manage certificates/security policies and Shibboleth authentication to provide a single sign-on. Their scheme requires additional storage for certificates (PKCS#12) as well as policies. Also, the implementation of Shibboleth on servers performs complex operations affecting the performance of servers and it does not correspond with the speed of the Internet. In addition, Shibboleth has a security vulnerability that may allow unauthorised users to access an EHR repository frequently and affects network performance. PAX relies on XACML for efficient policy management and ECDSA-256 bit and produces small keys for signing authorisation requests more efficiently and securely than Shibboleth. PAX also does not require additional storage to store certificates. The scheme in Riedl et al. (2008) suffers from problems with multiple key complexity expenses, the complexity of encryption and the consumption of storage sources that adversely affect server performance. While PAX uses the ECDSA public key algorithm that does not require large storage (small

keys) and the use of random public/private keys without complexity (Riedl et al. 2008). The scheme in Quantin et al. (2011) has major problems with low performance: the diversity of authorisation requests contexts and the cost of encrypting data by RSA. Compared to PAX, it uses XACML which is efficient in standardising contexts of authorisation requests as well as ECDSA which provides better performance efficiency than RSA.

Moreover, instead of using four access control models (DAC, MAC, RBAC and PBAC) in the scheme (Gajanayake et al. 2014), these models further complicate authorisation processes and the difficulty of managing security policies and authorisation requests. PAX relies on RBAC and ABAC to determine user access to data with support for flexibility, ease of implementation and efficient management. The XACS scheme in Sun et al. (2011) uses XML to design an authorisation system. XML is used to structure data/information and not to specify access to the repository. Using XML authorisation policies reduces performance in responding to authorisation requests. PAX uses XACML which is essentially designed to manage efficiently authorisation policies and user requests. The HCPP scheme in Jo & Chung (2015) relies on encryption to protect the database and prospecting/searching to access legitimate user information. Both mechanisms consume storage and server time. PAX relies on signatures to protect user information without the need for full encryption of the database. It also relies on multiple pseudonyms to efficiently access user information. The scheme in Seol et al. (2018) is based on XACML 2.0, which has problems with decision precedence between 'Not Applicable' and 'Indeterminate'. Also, their scheme performs the process of signing the encrypted information in the authorisation request partly or fully. PAX relies on XACML 3.0 which is more functional, faster and better logical results in decision precedence. Also, PAX performs the signing process directly on user attributes only without overheads of encryption.

The scheme in Wang et al. (2019) suffers from many shortcomings affecting performance such as data/policy decryption costs, use of RSA for encryption and signing, costing and management of secret key, management of users' attributes by a single authority, updating of keywords list when adding new keyword and operations search by keywords consumes server time. Compared to PAX, it does not require costly decryption operations and uses XACML and pseudonyms techniques to access patient data safely and with high performance. The scheme in Shafeeq et al. (2019) has significant storage and

Table 7.8: Comparison of performance between PAX and existing authorisation schemes

Scheme	Storage	Management	Communication	Computation
Chadwick et al. (2006)	$M_E$	$M_E$ (X.509)	$S$	$H_E$ ( $Sig$ )
Riedl et al. (2008)	$L_E$	$L_E$	$S$	$L_E$ ( $Enc + Sig$ )
Quantin et al. (2011)	$M_E$	$L_E$ (MRSE)	$S$	$L_E$ ( $Enc + Sig$ )
Gajanayake et al. (2014)	-	$M_E$ (Models)	-	-
Sun et al. (2011)	$M_E$	$L_E$ (SSE)	$S$	$M_E$ ( $Enc + Sig$ )
Jo & Chung (2015)	$L_E$	$M_E$ (XML)	$F + G$	$M_E$ ( $Enc$ )
Seol et al. (2018)	$H_E$	$H_E$ (XACML)	$F + S + G$	$L_E$ ( $Enc + Sig$ )
Wang et al. (2019)	$L_E$	$L_E$ (ABE)	$S + G$	$L_E$ ( $Enc + Sig$ )
Shafeeq et al. (2019)	$L_E$	$H_E$ (XACML)	$F + S + G$	$M_E$ ( $Enc + Sig$ )
<b>PAX</b>	$H_E$	$H_E$ (XACML)	$F + S + G$	$H_E$ ( $Sig$ )

computation costs. Their scheme requires a large size for key storage. In addition, using multi-signature is extremely expensive on network performance as the size of the signature increases with the number of signatures. Moreover, their scheme requires the size of 2500 characters to store policy and five seconds to fetch the policy. While PAX requires 256 bits for key storage, size 1465 characters for policy storage without Shamir, size 1477 characters for policy storage with Shamir and less than a second to fetch policy. Ultimately, PAX does not require encryption costs used in schemes (Riedl et al. 2008, Quantin et al. 2011, Jo & Chung 2015, Seol et al. 2018, Wang et al. 2019) but relies on signatures performed efficiently by ECDSA.

Table 7.8 shows performance comparison between PAX and existing authorisation schemes ( $H_E$  is high efficiency,  $M_E$  is medium efficiency,  $L_E$  is low efficiency,  $F$  is flexibility,  $S$  is scalability,  $G$  is granularity,  $Enc$  is encryption and  $Sig$  is signature).

## 7.5 Summary of the Chapter

In this chapter, we introduced a security testing tool (simulation and mathematical logic) to analyse protocols security. Thereafter, we discussed and analysed the security results in terms of data collection, authentication and authorisation in preventing a wide spectrum of attacks. For each scheme, REISCH, PAX and RAMHU, we have made a theoretical and experimental analysis for both security and performance analysis. All these analyses are shown by presenting their experimental data/figures, in comparison with the existing schemes.



# Chapter 8: Conclusions and Future Directions

In this chapter, we summarise our research journey and experiences, and list intended future directions. Our objective was to explore an innovative strategy to develop an efficient and secure healthcare application using the latest information technology, in particular electronic health/medical records (EHR) and a wireless sensor network (WSN).

## 8.1 Conclusions of the Thesis

After three or so years of arduous efforts, we have developed the general structure of a HC application that consists of four components: data-collection using WSNs, an EHR/EMRs repository, user privacy protection and the user differentiated access control.

In terms of the data collection scheme, wireless sensor networks provide unique and important care services when combined with EMR. Unfortunately, these networks suffer from performance and security problems as mentioned in the previous chapters. Therefore, we have proposed a REISCH scheme to address performance and security problems and cover gaps in existing research. As a result, the REISCH uses ECDSA-BLAKE2bp which provides better performance than the original ECDSA-SHA1 algorithm. REISCH with the modified algorithm saves more than 24% alive *SNs*. In addition, the results of the security analysis prove that REISCH is safe against attacks in the threat model.

In terms of an authentication scheme, healthcare systems require robust authentication to ensure that only legitimate users exchange patient data. During the investigation of previous authentication protocols, we found that they were vulnerable to some known attacks. Therefore, we proposed a new robust authentication protocol (RAMHU) to prevent internal, external, passive, and active attacks. We have used a variety of mechanisms that ensure the protection

and concealment of personal information to legitimate users. Our scheme uses multi pseudonyms for both users and medical centres to prevent the transmission of real information in the authentication request and MAC address to prevent counterfeit devices from connecting to the network. We used lightweight encryption and signature algorithms (as described in Chapter 3 Sections 3.4.2 and 3.4.3) to ensure that RAMHU's efficient interaction with user requests is ensured. In addition, we provided a formal and informal security analysis to demonstrate the effectiveness of RAMHU in repelling known attacks. We conclude that the RAMHU scheme provides high-level security and performance that maintains authentication information for users against various attacks.

In terms of the authorisation scheme, the security and privacy of medical records have, in recent years, become essential requirements for the establishment of any healthcare system. To ensure the provision of security and privacy, this thesis proposes a PAX authorisation system that supports pseudonym, anonymity and XACML. Specifically, the proposed system uses pseudonyms to separate personal information about patient data, anonymity to hide subjects' information, and XACML to create distributed access control policies to authorise subjects' requests to objects' records in the EHR. Different from the large amount of theoretical investigation in the existing literature, this scheme achieves the security and privacy preservation by utilizing the pseudonym and anonymity techniques, which can reduce the unnecessary consumption of time and burden on the server. We conclude that the PAX system provides a security level that maintains patient privacy, and the system particularly protects patient information from indirect users (advisors, patients' relatives, researchers, and emergency doctors), who are considered a serious security threat to any healthcare system because they can carry out internal attacks using the privileges granted to them.

## 8.2 Future Directions

To further develop the proposed HC project, we intend to add some features to support security and privacy in EMR and EHR.

1. After storing collected data in the EMR, our project needs supporting security procedures between *CS* and *DS* to store partial records in the remote repository. This process requires accurate and robust security procedures to prevent intruders from modifying historical patient data
2. The NTRUSign algorithm is more efficient in term of performance than ECDSA, but is less secure (Driessen et al. 2008). We intend to investigate

the integration of NTRUSign performance features with ECDSA to improve computation operations and energy savings in the HWSN. In addition, we will try to compare NTRUSign-BLAKE2bp and ECDSA-BLAKE2bp in terms of security and performance

3. Support our scheme using ECDSA-BLAKE2bp with efficient curves such as the Edward curve, efficient PM methods such as Frobenius, and system coordinates such as  $\lambda$ -Projective in Oliveira et al. (2014) to improve the efficiency of patient data signing in the HWSN
4. We intend to integrate our scheme into a real HWSN environment to evaluate the efficiency and feasibility of REISCH algorithms to improve the lifetime of *SNs* in patient data collection as much as possible
5. To support the authentication scheme (RAMHU), we intend to add users' biometric properties such as fingerprint, iris, or sound recognition to the authentication procedures. This procedure strengthens security precautions that prevent external attackers from accessing network services. However, adding these features requires performance evaluation in the login and authentication protocols
6. RAMHU uses lightweight and efficient performance algorithms that, according to many researchers, have shown that ECIES and PHOTON are efficient encryption and signature algorithms, respectively. We intend to evaluate RAMHU in terms of efficiency and discovery of performance standards such as end-to-end request delay, throughput, and error rate
7. From other future works, we intend to use a robust security mechanism with  $\oplus$  operation to support the exchange and management of public keys. Broadcasting public keys in general needs more attention to prevent various attacks. Public key storage on users' devices can also be a source of compromised authentication
8. For more testing to prevent the analysis of authorisation requests and responses, we intend to test the authorisation scheme with side-channel attacks (SCA) such as simple power analysis (SPA), differential power analysis (DPA), template and ransomware attacks. In addition to performance testing, we intend to test XACML (PDP engine) with complex combining policies and algorithms while maintaining the confidentiality of user information and preventing leakage to intruders
9. We will focus on patient data without the use of cryptographic mechanisms in examining patients' daily conditions, use real patient data to test PAX

with large data, and allow PAX to distinguish between patient history, daily status, and the purpose of data access. We will also encrypt the patients' old medical records (within a certain period) that are not frequently retrieved by healthcare providers in a manner that does not affect the efficiency of the server in providing service to users

10. We will investigate the application of a light hash algorithm to generate key ephemeral  $k$  in ECDSA and patient pseudonyms, to support increased randomization while maintaining system performance as an additional security measure to protect the privacy of medical records in the EHR.

### 8.3 Summary of the Chapter

We summarise our study by giving the conclusions of our project schemes (the data collection, authentication and authorisation schemes) in the construction of a robust HC application in support of security and privacy issues. Then, we described the future work to develop our project in terms of data collection, authentication and authorisation. We should conclude this thesis by saying that "writing this up is just to summarise this period of experience, it will never be at an end; it just opens a door for us to go further!".

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# Appendices



# Appendix A: REISCH

## A.1 SHA Hash Function

Secure hash algorithm (SHA) is one of the traditional hash algorithms that provide integrity and authentication when used with digital signatures (Guesmi et al. 2016). For example, SHA1 was used in the ECDSA algorithm to perform the signature process in public key cryptography. SHA consists of several varieties SHA0, SHA1, SHA2 and SHA3. The National Security Agency (NSA) replaced SHA0 with SHA1 to improve security by adding rotation to the compression function. Both SHA2 and SHA3 consist of SHA-224, SHA-256, SHA-384 and SHA-512, but SHA3 uses a different structure than the rest of the SHA family. SHA0, SHA1 and SHA2 are built on the basis of the Merkle-Damgard structure as shown in Figure A.1 (Shi et al. 2012) and were designed by the NSA. SHA3 is also known as KECCAK and is built on sponge construction as shown in Figure B.2. It uses two-stage absorbing and squeezing. Since 2007, NIST has adopted KECCAK because of the practical attacks on SHA1 and SHA2. KECCAK became the rival standard in 2015 (Shi et al. 2012). However, some research (Amy et al. 2016, Luo et al. 2016, 2017) have indicated that SHA3 can suffer from fault injection threats.

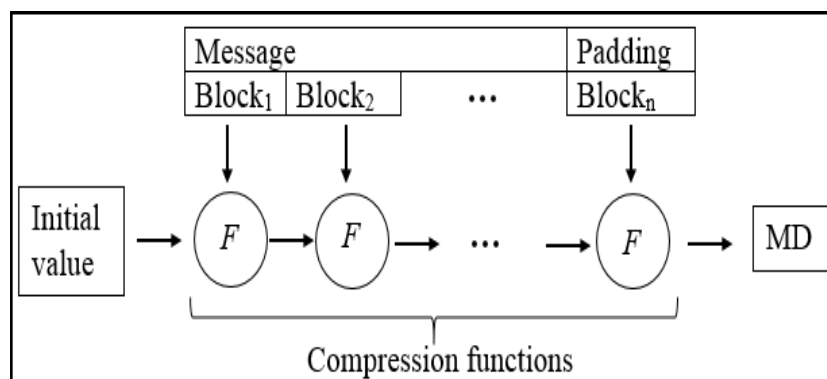


Figure A.1: The Merkle-Damgard construction of SHA (0, 1 and 2) hash functions

SHA is a one-way function consisting of two phases that divide the message into blocks of the same size (such as 512 or 1024). A set of zeros is added and followed

Table A.1: Comparison of SHA family

Algorithm	SHA1	SHA2				SHA3			
MD	160	224	256	384	512	224	256	384	512
Word size	32	32	32	64	64	64	64	64	64
Block size	512	512	512	1024	1024	1152	1088	832	576
Message size	$<2^{64}$	$<2^{64}$	$<2^{64}$	$<2^{128}$	$<2^{128}$	-	-	-	-
Iterations	80	64	64	80	80	24	24	24	24
Security	80	112	128	192	256	112	128	192	256
Weak security	Yes, practical such as Collision and preimage	Yes, practical such as preimage and length extension				Yes, theoretical such as fault injection			
Performance	Fast	Less				Lowest			
Year	1995	2004				2015			
Designer	NSA					Guido Bertoni and et al.			
Construction	Merkle-Damgård					Sponge			

by one at the end of the last block of the message (Kodali 2013). This phase is called preprocessing or padding. The second stage is the MD computation. At this stage, all message blocks are entered into the iterations (SHA1 (80), SHA2 (64) and SHA3 (256)) one by one, containing constants and logic operations (OR, AND, XOR) in compression function ( $F$ ) to produce MD. Each hash algorithm produces a fixed length of MD, such as 160 for SHA1, 224, 256, 384 and 512 For SHA2 and SHA3 (Boubiche et al. 2016, Chaves et al. 2016). Table A.1 shows comparison of SHA1, SHA2 and SHA3 (Guesmi et al. 2016, Dobraunig et al. 2015). Many existing schemes to employed to collect data in WSN (Kodali 2013, Boubiche et al. 2016, Al Maashri et al. 2016, Lu et al. 2016, Saha et al. 2016, Elhoseny, Yuan, El-Minir & Riad 2016*a*) have used a SHA algorithm to support integrity and authentication. However, these schemes do not address the collision and preimage problems in the SHA algorithm (Xia et al. 2016, Rasjid et al. 2017, Chiriaco et al. 2017, Merrill 2017, Yang et al. 2017, Giechaskiel et al. 2018, Brockmann 2018, Park & Kim 2018).

## A.2 BLAKE Hash Function

Aumasson et al. (2008) proposed a BLAKE hash algorithm to overcome efficiency problems in previous hash algorithms. This algorithm offers several features, such as simplicity, speed and parallel operations in hardware and software implementations. It is immune to second preimage, side-channel and length-extension attacks. BLAKE implements HAIFA construction which is an enhanced version of Merkle-Damgård. This development of construction is accomplished by adding a salt and a counter to the algorithm stages to prevent security vulnerability for second preimage attacks in Merkle-Damgård. Also, BLAKE's local wide-pipe structure makes collision attacks impossible (Shi et al. 2012). BLAKE uses the LAKE hash algorithm and compresses the message blocks in hash-tree constructions with Bernstein's stream cipher ChaCha which is a variation of Salsa20-256 (Mozaffari-Kermani & Azarderakhsh 2015). NIST was considered a BLAKE of competing algorithms in

Table A.2: Versions of BLAKE hash function

BLAKE version	Word	Message	Block	MD	Salt	Round
BLAKE-28	32 bits	$<2^{64}$	512	224	128	14
BLAKE-32	32 bits	$<2^{64}$	512	256	128	14
BLAKE-48	64 bits	$<2^{128}$	1024	384	256	16
BLAKE-64	64 bits	$<2^{128}$	1024	512	256	16
BLAKE2s	32 bits	-	256	128-256	64	10
BLAKE2b	64 bits	-	512	160-512	128	12

the final round of hash algorithms, such as KECCAK, Skein and Grøstl (Cho 2018). BLAKE supports several versions: 244, 256, 384 and 512. Then, Aumasson, Neves, Wilcox-O’Hearn & Winnerlein (2013) developed BLAKE2 to improve the speed in software implementation and reduce memory. BLAKE2 has 32% less memory than BLAKE. In addition, BLAKE2 contains two versions, BLAKE2s and BLAKE2b, to be used with 32 bits and 64 bits platform respectively. Table A.2 shows the BLAKE family (Chaves et al. 2016).

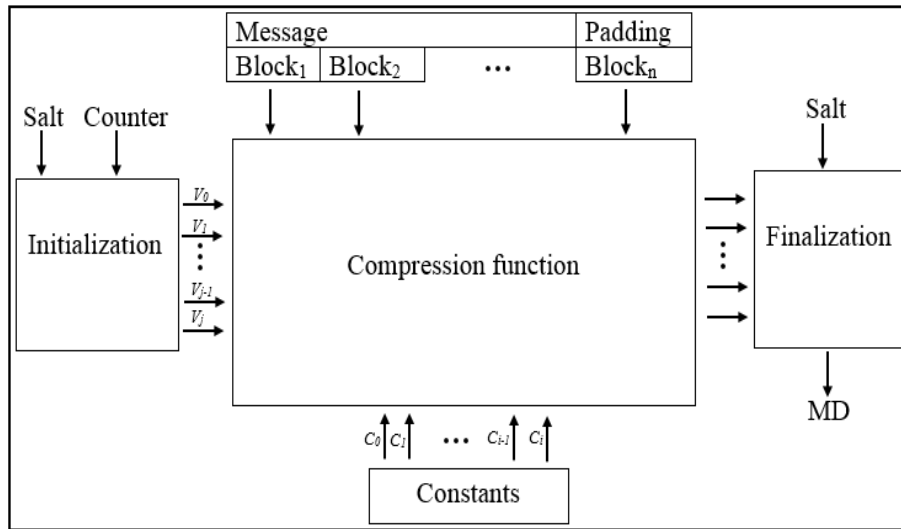


Figure A.2: Architecture of BLAKE hash function

Figure A.2 shows the architecture of the BLAKE hash function. In BLAKE, the message is divided into blocks, and the last block is padded with 1 followed by zeros to complete the last block size to 512 or 1024 bits. BLAKE consists of two parts: the compression function and iteration mode. Compression function consists of chain value, message blocks, salt value and counter value. The BLAKE compression function uses three phases: initialization, round functions and finalization. The initialization phase uses the chain value, salt and counter to create a matrix  $4 * 4$  and produces a 16-word value for different initializing states ( $V$ ). These states are entered into the round function ( $r$ ) with parallel rounds in the round functions phase. The output of this phase is a new  $V$  that is used to generate the chain value for the finalization phase. In the finalization phase of the chain, salt and new state

values are applied with  $\oplus$  operations to produce a new chain value. BLAKE is one of the fastest hash algorithms and has strong security (Chaves et al. 2016, Körber et al. 2018). Much research has pointed out that BLAKE is a conspicuously suitable algorithm for source restricted devices (Mozaffari-Kermani & Azarderakhsh 2015, Homsirikamol et al. 2011, Sugier 2017, Mozaffari-Kermani et al. 2017, Yang et al. 2018, Prakasha et al. 2018).

### A.3 ECDSA with BLAKE Hash

The hash algorithm is one of the important processes used by the ECDSA algorithm to complete the signing. The ECDSA algorithm uses a secure hash algorithm (SHA1) provided by NIST in 1995 to preserve the message integrity. This algorithm produces a digest 160-bit size with 6122 gate-equivalent (GE). It needs the complex operations to accomplish message digestion. In digital signatures, the hash algorithm should be collision (Wang et al. 2005), preimage and second preimage resistance (Knellwolf & Khovratovich 2012). Rijmen & Oswald (2005), Wang et al. (2005), Knellwolf & Khovratovich (2012), Stevens (2013) pointed out that this algorithm can suffer from practical attacks such as collision and preimage. But SHA1 is still used in many signature algorithms, such as ECDSA.

We propose using the BLAKE2 hash algorithm for signature in the ECDSA rather than the SHA1. The BLAKE2 algorithm produces digest 256-bit size with 1058 GE. This algorithm was developed in 2013 in order to reduce the memory, energy, speed requirements and resistance to attacks. BLAKE2 is faster and lighter than the SHA family of algorithms and even message digest (MD5), as shown in Figure A.3 (Aumasson, Neves, Wilcox-O’Hearn & Winnerlein 2013). Also, this algorithm is resistant to attacks, such as collisions, multicollisions, distinguishers, preimage and second preimage.

The ECDSA algorithm is used to ensure the integrity of messages. This algorithm prevents the attacker from changing the message data, since any change in the message will be discovered by the receiver. ECDSA produces the signing of the message  $(r, s)$ . The  $r$  parameter is the value used to calculate the signature in the process of signature verification, and  $s$  is the signature. The sender signs the message  $(m)$  by ECDSA and gets  $(r, s)$ . The sender sends the message  $m$ ,  $r$  and  $s$  to the receiver, who checks the message. During this transfer,  $r$  and  $s$  can be attacked to extract the private key  $(K_{pr})$ . If the attacker is able to get  $K_{pr}$ , this attacker can produce the same original signatures. A side channel attack (SCA) can penetrate ECDSA signatures and thus get  $K_{pr}$ . Where  $K_{pr}$  is the security in this algorithm,

if the attacker discovers the private key, data is easily penetrated. These attacks rely on information leaked to the ephemeral key ( $k$ ) and the value of  $r$  is publicly available.

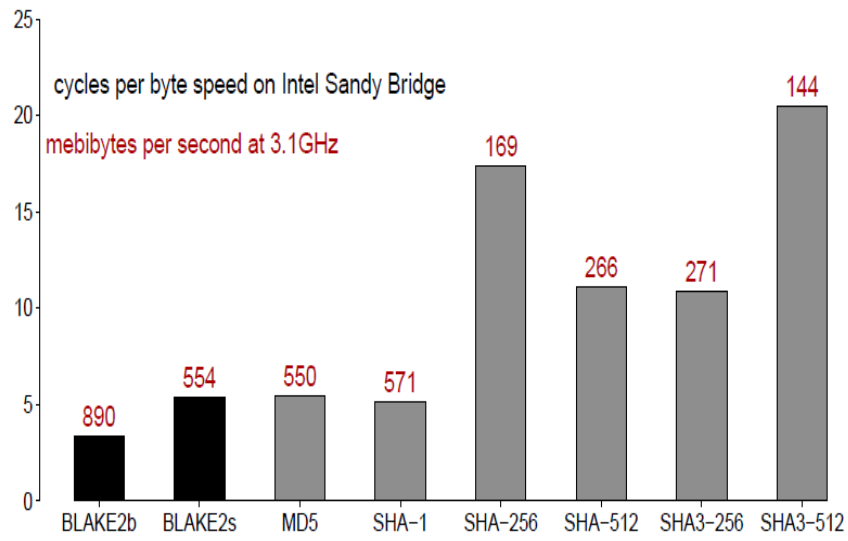


Figure A.3: Comparison of hash functions speed





# Appendix B: RAMHU

## B.1 Elliptic Curve Integrated Encryption Scheme (ECIES)

This algorithm was independently proposed by Neal Koblitz and Victor Miller in 1985 (Imran et al. 2018). It depends on elliptic curve discrete logarithm problem (ECDLP), ECDLP means difficulty obtaining  $k$  from  $P$  and  $Q$  (where  $k$  is the integer, and  $P$  and  $Q$  are two points on the curve). The small parameters used in ECC help to perform computations quickly. These computations are important in constrained-source and large environments (such as HC systems) that require processing power, memory, bandwidth, or power consumption (Diro et al. 2017). ECC provides encryption (elliptic curve integrated encryption scheme (ECIES)), signature (elliptic curve digital signature algorithm (ECDSA)), and exchange keys (elliptic curve Diffie-Hellman (ECDH)) approaches (Teguig et al. 2017). Many operations are performed in ECC algorithms (described in four layers), as shown in Figure B.1 (Nabil et al. 2012). ECIES has provided confidentiality and integrity, and has proven to be extremely efficient in its performance, as it uses small keys. Thus, the cost of computation is small compared with other public key cryptography algorithms, such as RSA. Table 2.2 in Chapter 2 shows a comparison of key sizes for public key encryption algorithms in addition to some information about these algorithms.

ECC uses two finite fields (prime field and binary field). The binary field uses two types to represent basis (normal and polynomial basis) (Imran et al. 2017), and is well suited to implementation in hardware (Nabil et al. 2012). The prime field is well suited to implementation in software more than hardware, and the prime field is more suited to security operations than the binary field. Let  $F_q$  indicate field type, if  $q=p$  (where  $p > 3$ ) then ECC uses prime field ( $F_p$ ). In the second case, if  $q=2$  then ECC uses binary field ( $F_{2^m}$ ) where  $m$  is the prime integer (Oliveira et al. 2018). ECC consists of a set of points  $(x_i, y_i)$ , where  $x_i, y_i$  are integers and the point at infinity ( $O$ ). It uses  $O$  to provide an identity for the Abelian group rule that

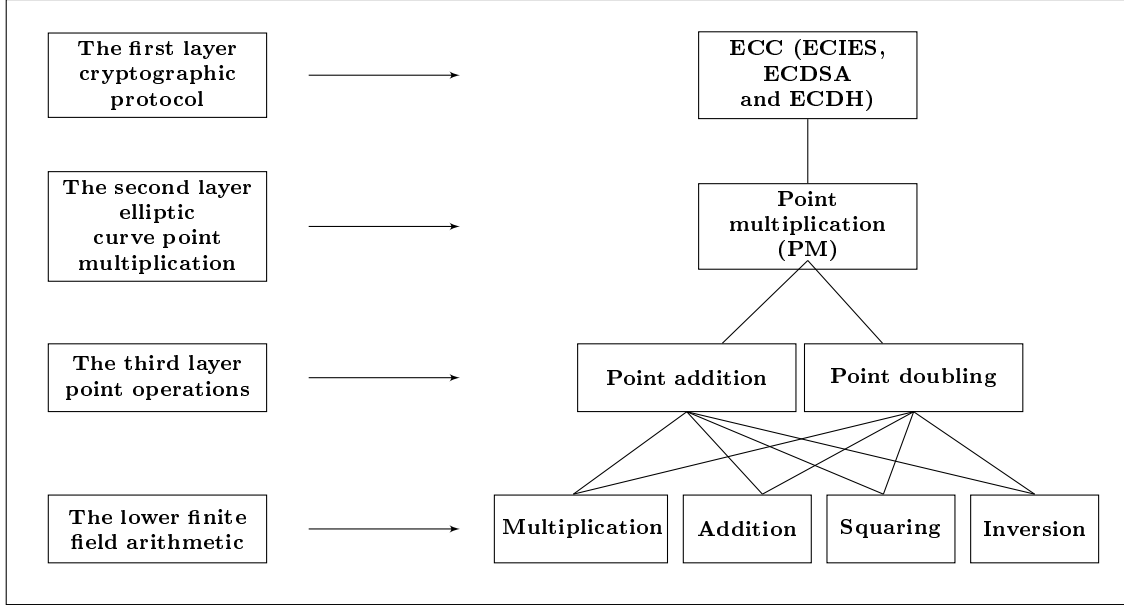


Figure B.1: Arithmetic operations in ECC hierarchy

satisfies long-form for the Weierstrass equation (with Affine coordinate):

$$y^2 + a_1xy + a_3y = x^3 + a_2x^2 + a_4x + a_6 \quad (\text{B.1})$$

When the prime field is used over ECC, the simplified equation is as follows:

$$y^2 = x^3 + ax + b \quad (\text{B.2})$$

Where  $a, b \in F_p, 4a^3 + 27b^2 \neq 0(\text{mod } p)$ . The law of chord-and-tangent is used in ECC to add two points on the curve (Pan et al. 2017). Let us suppose that  $P$  and  $Q$  are two points on the curve; these two points have coordinates  $(x_1, y_1), (x_2, y_2)$  respectively and the sum of these two points is equal to a new point  $R(x_3, y_3)$  (i.e.  $P(x_1, y_1) + Q(x_2, y_2) = R(x_3, y_3)$ ) (Wang et al. 2006, Islam et al. 2017).

ECC uses two operations for addition that are point addition ( $P+Q$ ) and point doubling ( $P+P$ ) (Figure B.1), as in the following equations:

In the case of the point addition ( $P + Q$ ) where  $P$  and  $Q \in E(F_p)$ :

with using the slope  $\lambda = \frac{y_2 - y_1}{x_2 - x_1}$

$$x_3 = \lambda^2 - x_1 - x_2, \quad y_3 = \lambda^2(x_1 - x_3) - y_1 \quad (\text{B.3})$$

In the case of the point doubling ( $P + P$ ) where  $P \in E(F_p)$ :

with using slope  $\lambda = \frac{3x_1^2 + a}{2y_1}$

$$x_3 = \lambda^2 - 2x_1, \quad y_3 = \lambda^2(x_1 - x_3) - y_1 \quad (\text{B.4})$$

---

**Algorithm 1** ECC encryption and decryption algorithm:

---

- 1: Alice and Bob use same parameters domain  $D = \{a, b, q, G, n, h\}$ , where  $a, b$  are coefficient,  $q$  is field type,  $G$  is base point,  $n$  is order point and  $h$  is cofactor.
  - 2: Alice selects random integer  $AK_{pr}$  as private key.
  - 3: Alice generates public key  $K_{pu} = AK_{pr}G$  and sends  $K_{pu}$  and  $G$  to Bob.
  - 4: Bob receives message  $m$  from Alice, selects random integer as private key  $BK_{pr}$  where  $BK_{pr} \leq n$ .
  - 5: Bob encrypts  $m$  with point  $P$  in elliptic curve  $E(F_q)$ .
  - 6: Bob computes  $C_1 = P + BK_{pr}K_{pu}$ ,  $C_2 = BK_{pr}G$  and sends  $C_1$  and  $C_2$  to Alice.
  - 7: Alice receives Bob's  $m$  and decrypts the  $m$  by computing  $C_1 - AK_{pr}C_2$  to obtain plaintext.
- 

When the binary field is used over ECC, the simplified equation is as follows:

$$y^2 + xy = x^3 + ax^2 + b \quad (\text{B.5})$$

Where  $a, b \in F_{2^m}, b \neq 0$  (Johnson et al. 2001), as addition operations are in the following form:

In the case point addition ( $P + Q$ ) where  $P$  and  $Q \in E(F_{2^m})$ :

with using the slope  $\lambda = \frac{y_1 + y_2}{x_1 + x_2}$

$$x_3 = \lambda^2 + \lambda + x_1 + x_2 + a, \quad y_3 = \lambda(x_1 + x_3) + x_3 + y_1 \quad (\text{B.6})$$

In the case point doubling ( $P + P$ ) where  $P \in E(F_{2^m})$ :

$$x_3 = x_1^2 + \frac{b}{x_1^2}, \quad y_3 = x_1^2 + (x_1 + \frac{y_1}{x_1})x_3 + x_3 \quad (\text{B.7})$$

ECC operations for encryption and decryption are explained through the following algorithm 1 (Zhong et al. 2016):

## B.2 Lightweight Hash-Function Algorithm

The hash function is a method that takes the variable length of data as an input and produces a constant length of the size called message digest (MD). This algorithm is called the one-way algorithm. Namely, when the data is encoded into the MD, the process cannot be reversed to access the original data (Wazid et al. 2016). It is eminently useful in data signature processes, offering high efficiency compared to traditional cryptography algorithms. Recently, lightweight hash algorithms (such as PHOTON, QUARK, and SPONGENT) have emerged to improve efficiency and security rather than traditional hash algorithms (such as MD5, SHA1, and SHA2). Many advantages can be provided in the hash algorithm to satisfy the signature

principle, such as first preimage resistant (FPR), second preimage resistant (SPR) and collision resistant (CR) (Giri et al. 2015). Suppose that  $h$  is a hash function, MD is a hash result and  $m$  is a message, the definition of the signature principles is as follows:

- **FPR:** This principle is also known as one-wayness. When the attacker gets a MD, it is arithmetically difficult to find  $m$  and produces the same MD ( $h(m) = \text{MD}$ ) (Harran et al. 2018)
- **SPR:** This principle is also known as weak collision resistant. When the attacker gets MD and  $m$ , it is difficult to calculate a different message ( $m'$ ) where  $m \neq m'$  to produce the same MD ( $h(m) = h(m')$ ) (Aitzhan & Svetinovic 2018)
- **CR:** This principle is also known as strong collision resistant. It is computationally difficult for the attacker to calculate two different messages ( $m$  and  $m'$ )  $m \neq m'$  and to produce the same MD ( $h(m) = h(m')$ ). CR is not the FPR guarantee (Esiner & Datta 2019, Cantu et al. 2017).

The PHOTON is one of the lightweight hash function algorithms. This algorithm is tremendously suitable for projects that require a robust and reliable signature. This algorithm is based on a sponge-like construction and AES-like primitive for domain extension and permutation efficiently (Anandakumar et al. 2014, Porambage et al. 2015, Ijaz & Pasha 2017). PHOTON is available in several versions (80, 128, 160, 224, and 256). It is a balance between the efficiency in the execution of computations on the one hand and security in the implementation of the features of the signature principles (FPR, SPR and CR) on the other hand.

PHOTON algorithm uses sponge construction and applies two phases of absorbing and squeezing as shown in the Figure B.2. The message ( $m$ ) in the PHOTON is divided into  $n$  blocks ( $m_0, \dots, m_{n-1}$ ) after adding padding by appending a "1" bit followed many zeros. In the absorbing phase, the internal state ( $t$ -bit) is composed of the capacity ( $c$ -bit) and the bitrate ( $r$ -bit). The  $t$  is first initialized with some fixed value. In each iteration, this algorithm achieves the process of changing for  $t$  by computing  $r + c$  and uses the exclusive-or ( $\oplus$ ) operation between message blocks. After each  $\oplus$  operation, the permutation ( $P$ ) operation of the internal state has been performed. After the end of the absorbing phase, when all the blocks of messages are treated, the squeezing phase begins. At this stage, the input of the squeezing phase is the output of the absorbing phase (internal state and permutation). This phase continues to squeeze the input until the desired MD obtains, the hash output size is  $64 \leq \text{MD} \leq 256$ . More details are available in (Guo

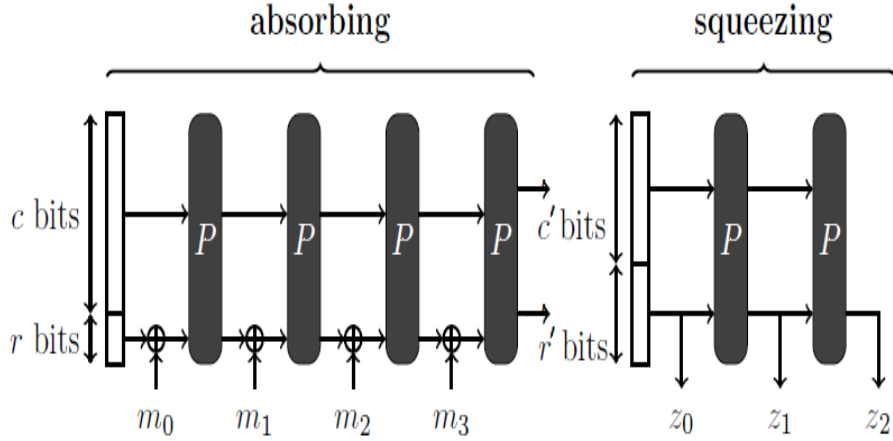


Figure B.2: The PHOTON hash function

et al. 2011).

Table B.1 provides a comparison of the lightweight hash algorithms (the latest version of these algorithms) in terms of security and efficiency (Yoshida et al. 2007, Aumasson, Henzen, Meier & Naya-Plasencia 2013, Kavun & Yalcin 2010, Guo et al. 2011, Bogdanov et al. 2011, Berger et al. 2012, Anandakumar et al. 2014). Standard hash algorithms, however, are still used in applications such as SHA1 (5527 GE, MD 160-bit) and SHA2 (10868 GE, MD 256-bit). Lightweight hash algorithms, such as PHOTON (2177 GE, MD 256-bit), provide the perfect solution for handling complex signatures in large HC systems.

As Table B.1 shows that the PHOTON-256 (2177 GE) offers the best performance compared to all the lightweight hash functions. It also shows that the PHOTON-256 offers a high level of security through the application of signature features FPR (224), SPR (128) and CR (128). Linear and differential attacks are the most powerful attacks in the MD analysis of hash functions. Compared to PHOTON, ARMIDILLO and SPONGENT-256 also offer signature features, but both are vulnerable to attacks. ARMIDILLO2 has been attacked by local linearization (practical semi-free-start collision attack) (Naya-Plasencia & Peyrin 2012). All versions of SPONGENT have been attacked by linear distinguishers (23 rounds) (Abdelraheem 2012) and (13 rounds) (Zhang & Liu 2017). Both need the most computations (3281 GE and 8653 GE) compared with PHOTON-256 (2177 GE). PHOTON is a reliable algorithm against linear and differential attacks (Guo et al. 2011). It has a high level of security and efficiency; therefore, it is suitable for our scheme as a signing mechanism in our authentication protocol between parties of the HC applications (clients and servers).

Table B.1: Comparison of lightweight hash function algorithms

Algorithm	Performance		MD	Security			Author (s)	Year
	Gate equivalent area	Throughput (kbps)		FPR	SPR	CR		
SQUASH	2646 GE	0.15	64	64	64	0	Shamir	2005
MAME	8100 GE	146.7	256	-	-	-	Yoshida et al.	2007
C-PRESENT-192	8048 GE	59.26	192	192	192	96	Bogdanov et al.	2008
ARMADILLO2	8653 GE	9.38	256	256	256	128	Bald et al.	2010
S-QUARK	2296 GE	3.13	256	224	112	112	Aumasson et al.	2010
KECCAK-f[400]	5090 GE	14.4	128	128	128	64	Kavun and Yalcin	2010
GLUON	4724 GE	32	224	224	112	112	Berger et al.	2011
SPONGENT-256	3281 GE	11.43	256	240	128	128	Bogdanov et al.	2011
PHOTON-256	2177 GE	0.88	256	224	128	128	Guo et al.	2011

# Appendix C: PAX

## C.1 Elliptic Curve Digital Signature Algorithm (ECDSA)

Proposed by Scott Vanstone in 1992 (Johnson et al. 2001, Fan et al. 2016), the elliptic curve digital signature algorithm (ECDSA) is an asymmetric signature algorithm. It depends on the use of the points of the curve to integrate and sign data. It has been used to provide integrity, authentication, and non-repudiation properties in the communications network with limited capacity in terms of power and processing. The algorithm depends on the elliptic curve discrete logarithm problem (ECDLP) (Sghaier et al. 2016, Dikshit & Singh 2017). ECDSA uses small parameters which expedite performance of computations, thus reducing time and storage (Sojka-Piotrowska & Langendoerfer 2017). These features are extremely important for large organisations and constrained-source devices, such as WSN, because these networks require processing power, memory, bandwidth and power consumption (Dou et al. 2017).

The data integrity of messages is exceedingly important in networks because attackers can modify messages when they are transferred from source to destination (Bachiller et al. 2018). Many organisations, such as ISO (1998), ANSI (1999) and, IEEE and NIST (2000), use it as a standard (Hoceni et al. 2017). This algorithm is similar to the digital signature algorithm (DSA). Both algorithms depend on the discrete logarithm problem (DPL), but the ECDSA algorithm uses a set of points on the curve and the generating keys are notably small. The ECDSA algorithm with key length 160-bit provides the equivalent of symmetric cryptography with a key length of 80-bit (Driessen et al. 2008, Abueh & Liu 2016). It is significantly convenient for devices with constrained-source because it uses tremendously small keys and provides computation speed in the signature (Cheneau et al. 2010). Moreover, four-point multiplication operations are used in the ECDSA algorithm: one is in public key generation, one for signature generation and two for signature verification (Xu et al. 2012). In addition, this algorithm consists of three procedures: key

generation, signature generation, and signature verification. These operations are explained as follows:

- **Key generation:**

- 1 Select a random or pseudorandom integer  $d$  in the interval  $[1, n - 1]$ .
- 2 Compute  $K_{pu} = K_{pr}G$
- 3 Public key is  $K_{pu}$ , private key is  $K_{pr}$ .

- **Signature generation:**

- 1 Select a random or pseudorandom integer  $k$ ,  $1 \leq k \leq n-1$ .
- 2 Compute  $\text{SHA1}(m)$  and convert this bit string to an integer  $e$ .
- 3 Compute  $kG = (x_1, y_1)$  and convert  $x_1$  to an integer  $\bar{x}_1$ .
- 4 Compute  $r = x_1 \bmod n$ . If  $r = 0$  then go to step 1.
- 5 Compute  $k^{-1} \bmod n$ .
- 6 Compute  $s = k^{-1}(e + K_{pr}r) \bmod n$ . If  $s = 0$  then go to step 1.
- 7 Signature for the message  $m$  is  $(r, s)$ .

- **Signature verification:**

- 1 Verify that  $r$  and  $s$  are integers in the interval  $[1, n-1]$ .
- 2 Compute  $\text{SHA1}(m)$  and convert this bit string to an integer  $e$ .
- 3 Compute  $w = s^{-1} \bmod n$ .
- 4 Compute  $u_1 = ew \bmod n$  and  $u_2 = rw \bmod n$ .
- 5 Compute  $X = u_1G + u_2K_{pu}$ .
- 6 If  $X = \theta$  then reject the signature. Otherwise, convert the  $x$ -coordinate  $x_1$  of  $X$  to an integer  $\bar{x}_1$ , and compute  $v = \bar{x}_1 \bmod n$ .
- 7 Accept the signature if and only if  $v = r$ .

The ECDSA algorithm is unsuitable for signing messages (integration) if used poorly and incorrectly. Validation of domain parameters is significantly important for ensuring strong security against a variety of attacks. This algorithm becomes strong if the parameters are well validated (Save & Chhatani 2015, Franeková et al. 2017). The authors' recommendations are to update the validation scheme. In our authorisation scheme, we used ECDSA 256-bit to add a high-security level and we took care to consume system resources. Furthermore, it supports the provision of anonymity of users' policies and requests. More details about ECDSA's signature and verification are available in Rafik & Mohammed (2013).



# Appendix D: Security Test Tool

## D.1 AVISPA

After designing any authentication, authorisation or data collection scheme, this scheme includes a set of protocols and each protocol should be checked and its accuracy verified under a test model, such as the Dolev-Yao to analyse, trace and detect the possibility of attack theoretically. However, this analysis needs to be simulated in a practical manner to detect errors and hidden traces of the protocol's designer, threats tracking, statistics analysing and accurate results, checking several techniques on the same protocol (Al-Zubaidie et al. 2019 $b,c$ , Bojjagani & Sastry 2019, Iqbal & Shafi 2019, Ostad-Sharif et al. 2019). The AVISPA tool provides the features listed above, and offers ease, simplicity, robustness, and applicability for implementing security protocols such as authentication, authorisation and data collection (Bojjagani & Sastry 2017). AVISPA is a formal tool for analysing security schemes and is applied by researchers to evaluate recent security protocols (Gupta et al. 2018, Babu & Padmanabhan 2018, Xu et al. 2018, Dong et al. 2018).

The AVISPA tool is a push-button (as shown in Figure D.1), testing/proofing model and is based on high-level protocol specification language (HLPSL). This language uses directives and expressive terms to represent security procedures. It is integrated with four backends that are the On-the-Fly Model-Checker (OFMC), the Constraint-Logic-based Attack Searcher (CL-AtSe), the SAT-based Model-Checker (SATMC), and Tree Automata based on Automatic Approximations for the Analysis of Security Protocols (TA4SP) to perform the simulation in AVISPA. Each backend gives the result of simulation analysis statistics that is different from the other. More details are available in The AVISPA Team (2006). SATMC and TA4SP backends do not work with security protocols that implement the XoR gateway; therefore, we relied on OFMC and CL-AtSe backends to simulate the proposed project's schemes (authentication (RAMHU), authorisation (PAX) and data collection (REISCH)).

- OFMC: It analyses protocols problems and builds infinite tree in demand-driven manner. Also, state-space in this backend has formatted by



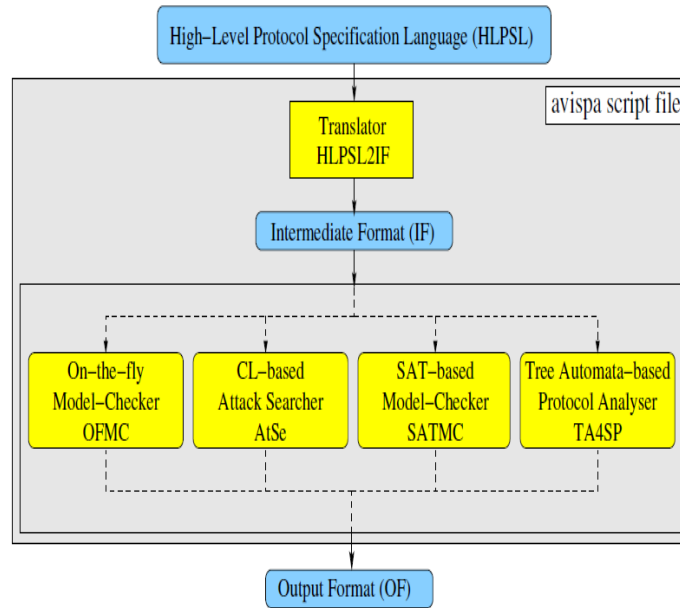


Figure D.2: AVISPA's architecture (The AVISPA Team 2006)

Table D.1: Some HLPSL's symbols and statements

Symbol	Description
<i>init</i>	Initial value for the state
<i>def</i>	Role definition
<i>state</i>	Sequential value for transition
<i>new</i>	Fresh value
<i>start</i>	Beginning signal for role
<i>:=</i>	Assign Mark
<i>xor</i>	Exclusive or operation
<i>.</i>	Concatenation
$\{\}_Kp$	Asymmetric encryption with public key
$\{\}_invKp$	Asymmetric signature with public key
<i>played_by</i>	Used to link the role with the intended entity
<i>=   &gt;</i>	Reaction transitions to relate event with act
$\wedge$	Conjunction
<i>protocol_id</i>	Goal identifier
<i>secrecy_of</i>	The goal of protecting the secret between entities permanently
<i>authentication_on</i>	The goal of strong authentication between entities
<i>intruder_knowledge</i>	What intruder knows about network

schemes (authentication, authorisation and data collection) in AVISPA depend on security features in the goal specification. Each protocol contains a set of goals (authentication and secret) in authenticating each party with the other. The goals in *secrecy\_of* demonstrate that secrets are not exposed or hacked to non-intended entities, while the goals in *authentication\_on* demonstrate that strong authentication has been applied between entities based on witness and request. Our simulations are based on the AVISPA tool with the current version v.1.1 (13/02/2006) available on the website in The AVISPA Team (2006).



# Appendix E: List of Publications

These publications based on thesis.

1. Al-Zubaidie, M., Zhang, Z. & Zhang, J. 2019, 'RAMHU: A new robust lightweight scheme for mutual users authentication in healthcare applications', *Security and Communication Networks*, doi:10.1155/2019/3263902, vol. 2019, pp. 1-26, 2019.
2. Al-Zubaidie, M., Zhang, Z. & Zhang, J. 2019, 'PAX: Using pseudonymization and anonymization to protect patients' identities and data in the healthcare system', *International Journal of Environmental Research and Public Health*, doi:10.3390/ijerph16091490, vol. 16, no. 9, pp. 1-36, 2019.
3. Al-Zubaidie, M., Zhang, Z. & Zhang, J. 2019, 'Efficient and secure ECDSA algorithm and its applications: A survey', *International Journal of Communication Networks and Information Security*, vol. 11, no. 1, pp. 7-35, 2019.
4. Al-Zubaidie, M., Zhang, Z. & Zhang, J. 2020, 'REISCH: Incorporating Lightweight and Reliable Algorithms into Healthcare Applications of WSNs', *Applied Sciences*, doi.org/10.3390/app100620072020, vol. 10, no. 6, pp. 1-36 2020.
5. Al-Zubaidie, M., Zhang, Z., & Zhang, J. 2021 'User Authentication Into Electronic Health Record Based on Reliable Lightweight Algorithms', *In Handbook of Research on Cyber Crime and Information Privacy-IGI Global*, doi: 10.4018/978-1-7998-5728-0.ch032, pp. 700-738, 2021.