Design of a Secure Privacy Preserving Cloud Based Framework for Sharing Electronic Health Data

by

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Chair of Examining Committee	Dr. Jing Ren
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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

Abstract

There exists a need for sharing user health data, especially with institutes for research purposes, in a secure fashion. This is especially true in the case of a system that includes a third party storage service, such as cloud computing, which limits the control of the data owner. The use of encryption for secure data storage continues to evolve to meet the need for flexible and fine-grained access control. This evolution has led to the development of Attribute Based Encryption (ABE). The use of ABE to ensure the security and privacy of health data has been explored. This thesis presents an ABE based framework which allows for the secure outsourcing of the more computationally intensive processes for data decryption to the cloud servers. This reduces the time needed for decryption to occur at the user end and reduces the amount of computational power needed by users to access data.

Keywords: Attribute Based Encryption (ABE); Electronic Health Records (EHR); security; privacy; cryptography; cloud computing

Declaration of Authorship

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Statement of Contributions

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

Dedication

To my mother, my number one fan and biggest supporter in every way for as long as I can remember.

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List of Abbreviations

ABE	**A**ttribute **B**ased **E**ncryption
CP-ABE	**C**iphertext **P**olicy - **A**ttribute **B**ased **E**ncryption
KP-ABE	**K**ey Policy - **A**ttribute **B**ased **E**ncryption
MA-ABE	**M**ultiple **A**uthority - **A**ttribute **B**ased **E**ncryption
EHR	**E**lectrobic **H**ealth **R**ecords
GPP	**G**lobal **P**ublic **P**arameters
GPK	**G**lobal **P**ublic **K**ey
GSK	**G**lobal **S**ecret **K**ey
UID	**U**nique **ID**entifier
AID	**A**uthority **ID**entifier
CA	**C**ertificate **A**uthority
AA	**A**ttribute **A**uthorities
CSP	**C**loud **S**ervice **P**rovider

Chapter 1

Introduction

1.1 Motivation

Secure storage of electronic health data by health institutions, such as hospitals, is made challenging if it is to be made available to other parties while ensuring unauthorized access to user data is prevented and the privacy of their patients is protected. These institutions typically store this data on physical hardware in a secure location on their premises and so are able to prevent unauthorized access through the use of adequate network security infrastructure. They are also able to prevent authorized users from gaining access beyond their levels of control through the use of proper access control mechanisms which ensures accountability. The deployment of more efficient and modern information technology, such as cloud computing, extends the trust boundary of the Information Technology (IT) infrastructure of institutions beyond their facilities while giving them multiple advantages such as a potentially unlimited amount of storage and computational capabilities. However, this new infrastructure exposes data to both internal and external threats as the institutions no longer have physical control of the infrastructure on which their data is stored as that is now in the partial control of the Cloud Service Providers (CSP).

A health institution typically collects data of varying types which varies depending on the medical condition of their patients, with the patient name and id being the link between different data sets. This type of data is called an Electronic Health Record (EHR) [38, 43] and typically contains a variety of information of different levels of sensitivity in relation to patients. Multiple research institutes

may require access to only specific portions of this data across the multiple sets that are related to their area of specialization. This makes access control more complex depending on the number of users involved and their required level of access to data at a granular level. The health institution would want to be able to protect the privacy of their data from the CSP, while being able to grant their partners access to the appropriate portions of the database they have rights to as specified in their research partnership agreement. The access structure of the system becomes increasingly complex as multiple health institutions and research partners are added, with different individuals having similar or slightly varying levels of access across the platform.

One way of ensuring that user data is protected from both the CSPs and from unauthorized users is to encrypt the data before it is stored in the cloud using available encryption schemes. This grants only authorized users access to the required information (usually a key) to gain access to data in its original form. This system becomes a challenge when there is a need to provide fine-grained access to data to third parties in order to ensure that the privacy of users is not violated in relation to privacy laws such as the Personal Health Information Protection Act (PHIPA) [10]. PHIPA governs the collection, use and disclosure of personal information in the health sector in the province of Ontario, Canada. Sharing data with third parties such as universities and research institutes becomes a challenge as the health institutions need to ensure patient privacy is not violated. The maintenance of patient privacy is especially important if data is to be shared for the purposes of necessary research which could lead to advancements in the health industry and improve the service delivery for patients while saving more lives.

The need to meet the privacy and security requirements have led to the creation of systems for the sharing of electronic health data based on a system of encryption called Attribute Based Encryption (ABE) [21, 32, 2, 4, 3, 20, 19, 27]. ABE, developed by Sahai and Waters [35], provides the opportunity for fine-grained access control to data. ABE achieves this be having an attribute based access policy attached to either the secret key of the user or the encrypted ciphertext. This depends on the variant of ABE because if the access policy is contained in the ciphertext then the corresponding attributes will have to be in the secret key and vice

versa. This means that, if there is no match between the attributes of a user's key and the ciphertext, decryption is prevented. This enables the health institutions to be able to grant third parties access to only the specific data that they require to carry out their research while ensuring that Personal Identifiable Information (PII) of patients is not exposed in line with privacy laws and requirements.

1.2 Research Challenge

To allow for the kind of access required as described in the previous section, there is a need to develop a system that enables the secure exchange of Electronic Health Records. These systems would need to take advantage of existing advancements in the field of information technology, such as cloud computing, which gives individuals access to potentially unlimited amounts of storage and processing capabilities. These advancements further extend the trust boundaries of systems that use them as the physical devices that make up the infrastructure are not under the control of users. This makes the storage services that they provide potentially untrustworthy for use with highly sensitive data such as Electronic Health Records (EHRs). We also want to take advantage of the computational capabilities of these services for any operations that are potentially computationally intensive with regards to our data while maintaining the same levels of security and preserving the privacy of the information they contain.

To find a solution to this challenge we need to use effective cryptographic schemes that preserve privacy and provide the levels of security that we require. Security can easily be provided by existing cryptographic schemes but they are limited in their ability to provide fine grained access control and preserve privacy of information at a granular level. Using latest developments in the area of cryptographic research, specifically Attribute Based Encryption (ABE), takes us a step closer to finding a solution to the aforementioned challenge. The use of existing techniques is also needed to modify an effective ABE scheme to be part of a developed framework so that we are able to take advantage of the computational abilities of the third party service with regards to the operations that are computationally intensive. This is with regards to most of the decryption operations of

ABE schemes.

1.3 Thesis Contributions

In this thesis we have developed a framework for the sharing of electronic health data among multiple parties. Our framework ensures security and preserves privacy while allowing for the use of potentially untrusted third party services. The framework is based on a proposed Multi-Authority Ciphertext Policy Attribute Based Encryption with Outsourcing (MACP-ABEwO) scheme with securely outsourced decryption that is based on the ABE scheme in developed by Kan Yang and Xiaohua Jia [44]. Our proposed MACP-ABEwO scheme provides effective decryption outsourcing in a multi-authority setting.

The platform employs symmetric encryption for the security of the actual data sets. The MACP-ABEwO scheme is applied to encrypt the secret keys that users need to gain access to data in its plain form. The use of symmetric encryption for the actual data is as a result of the high amount of computation required for encryption and decryption algorithms of the different available public key encryption schemes, a category that includes the MACP-ABEwO scheme. The security of this protocol had been proven thoroughly in the original work [44] and as a result, we have limited our analysis to the basic security requirements that are to be met by the framework.

The major contribution of this thesis is a framework for the exchange of electronic health data with significant decrease in the computational requirements in terms of time and resources. This decrease is as a result of the outsourcing of the more computationally intensive operation typically involved in the ABE decryption process to the cloud. This enables the secure exchange of sensitive health data among health institutions and other third parties, such as research partners.

This framework architecture could be used to design a system for the exchange of other types of sensitive data of a complex nature that requires a fine grained level of access control.

1.4 Thesis Outline

This thesis is organized as follows: Chapter 2 provides some background technical information on related subjects such as security and privacy, electronic health data, cloud computing, cryptography, and Attribute Based Encryption (ABE). It also provides a review of literature outlining work done in the area of ABE to improve the security and performance original schemes while adding features such as revocation. A review of systems that have been built based on ABE for the handling of health related data is also included. Chapter 3 introduces our secure privacy preserving framework for electronic health records. It provides the description and mathematical construction for the underlying ABE scheme and also a description of the architecture of our framework together with use cases. Chapter 4 provides details of the evaluation of our framework and also the results. It describes our experimental setup, provides a detailed performance evaluation with relation to computation and also provides a security analysis of the framework. Chapter 5 concludes the thesis, highlighting our contribution and also providing information on possible areas for future improvements.

Chapter 2

Background and Literature Review

2.1 Security and Privacy

This section provides a description of the concepts of security and privacy, two key features of the framework described in this thesis. They are both important features of any system that involves the flow of data among multiple parties or entities.

2.1.1 Security

Security according to the National Institute of Standards and Technology (NIST) [23] is defined as any condition that leads to the creation and maintenance of defensive measures to ensure than an information technology infrastructure continues to perform it basic or critical functions irrespective of the risks posed by the threats to its normal operation.

The major considerations when analyzing the security of any system are confidentiality, integrity and availability. These objectives are an essential condition for any system to be considered secure.

Confidentiality [23] assures that only those entities in the system that are authorized have access to data that is either being stored, processed or transferred in the system.

Integrity [23] relates to the verification of the authenticity of data. This means ensuring that data has not been manipulated in any form either while in transit or

while in storage. This ensures that any unauthorized manipulation of data in the form of addition, deletion or substitution is detected.

Availability [23] is a measure of the level of accessibility and usability of a particular system upon request by an authorized user. This means that the system should be able to at all times carry out the various functions in order to meet the demands of its users. This also covers the ability of the infrastructure to remain functional even when some individual makes attempts to compromise its integrity.

Cryptography

Cryptography [23] is the field of study which represents the principles, means and methods used for transforming data in order to hide their original content and prevent unauthorized use or modification. This typically involves the study of several mathematical techniques. Cryptography can be broadly divided into secret key and public key cryptography also known as symmetric and asymmetric schemes.

(1) Secret Key Cryptography (Symmetric) - This type of cryptographic system involve the use of a single secret key which is usually agreed upon by both parties who want to keep their communication secret. This secret key is used to encrypt the original message typically described as the plaintext (i.e encode the plaintext into a ciphertext that cannot be read by a party without the secret key). The receiving party if authorized and in possession of the secret key is able to decrypt the ciphertext and gain access to the original message. Examples of secret key schemes include the Ciphers (Caesar, Monoalphabetic and Polyalphabetic cyphers), Data Encryption Standard (DES), and Advanced Encryption Standard.

(2) Public Key Cryptography (Asymmetric) - This type of cryptographic systems was developed as a result of the challenges in secret key cryptography which include the problem of key management and lack of secure channel for users to exchange keys. Public key cryptography involves the use of two separate keys, a public and private key, which are used to perform complementary operations such as encryption and decryption or signature generation and

verification. Examples of public key schemes include the Diffie–Hellman key exchange protocol, RSA, Elgamal and Elliptic Curve Cryptography.

Cryptographic Adversary Models

Attacks on cryptographic systems aimed at recovering the plaintext from the ciphertext or the secret key can be classified into four broad categories.

(1) Ciphertext Only Attack [31] - A ciphertext only attack is a class of attacks in which the adversary only has access to some ciphertext without any knowledge of the corresponding plaintext. This is the weakest type of attack because the adversary has the least amount of information to work with and any encryption scheme vulnerable to this class of attack is considered to be completely insecure.

(2) Known Plaintext Attack [31] - A known plaintext attack is a class of attacks in which the adversary has access to some plaintext and ciphertext pairs. The adversary is unable to create more pairs and in only able to gain access to these by eavesdropping on the comunication channel between parties. These types of attacks are only marginally more difficult to mount.

(3) Chosen Plaintext Attack (CPA) [31] - A chosen plaintext attack is a class of attacks where the adversary is able to select the plaintext and request for the corresponding ciphertexts. This is typically done through the use of a black box system, typically called an oracle, that is able to produce the corresponding ciphertext when given any plaintext without revealing the key or any information about the plaintext of the original ciphertext that the adversary is trying to decrypt. A variation of this is the adaptive chosen plaintext attack where the adversary chooses the new plaintext based on the ciphertext received for earlier submitted plaintexts.

(4) Chosen Ciphertext Attack (CCA) [31] - A chosen ciphertext attack is a class of attacks where the adversary selects any ciphertext and requests for the corresponding plaintext. This is the direct opposite of the chosen plaintext attack class. This class of attacks are considered to be the strongest model of

attacks when classifying encryption schemes based on their level of resistance. An adaptive chosen ciphertext attack just like the adaptive version of CPA, involves the adversary deciding on what ciphertext to submit based on the plaintext received for earlier requests.

Note that some of the attack types described above are mutually exclusive (for instance, an attack cannot be both chosen plaintext and known plaintext). And also the chosen plaintext/ciphertext attacks are somewhat exclusive to the modern era of cryptography.

2.1.2 Privacy

Privacy is commonly equated with the concept of confidentiality although they are both distinct. While confidentiality is mainly concerned with ensuring that only users who are authorized have access to data which is being stored, processed or transferred within a system. Privacy, on the other hand, is concerned with ensuring that users have more control over the collection, use and storage of information that is related to them. Therefore, while maintaining the confidentiality of a system aids in preserving privacy, confidentiality does not completely ensure privacy as an authorized user may abuse that privilege by violating the privacy of user information [33].

The range of what is considered private information significantly varies in scope depending on the application area. For instance, in the health sector, private information can be regarded as any oral or written information that meets any of the following criteria: relates to the health of the individual, including their family history; relates to health care provision, including the source of care; constitutes as service for individuals who require long term care; relates to payment for health care. More importantly, private information is any information that can be used to identify an individual, either alone or when related to another piece of available information [11].

The Personal Health Information Protection Act (PHIPA) [10] is an act that establishes the guidelines for the collection, use, and disclosure of personal health information in the Ontario province of Canada. The guidelines are to be followed

by individual and organizations that work with health information, both the custodians and those who receive information from the custodians. The guidelines also protects the right to privacy of individuals with respect to their Personal Health Information (PHI) by giving them the authority to have access and request modifications to their PHIs. It also requires that individuals provide consent before their PHI can be collected, user or disclosed.

The privacy of data that is stored in the cloud faces multiple challenges as a result of the different ways in which the data are stored or processed on a machine that is usually owned by a different organization, the CSP. The major issues that exist in this area of privacy relate to trust as users are not completely certain that: their data is not being used for other purposes other than that for which it was collected; that data is destroyed properly in the end; privacy breaches have occurred which may have exposed their information; their information is retained even after they have stopped using a particular service [33].

2.2 Electronic Health Data

There are three broad classes in relation to the electronic collection and storage of health information according to Canada Health Infoway [38]. These classes have been established in order to accelerate the adoption and use of digital health solutions across Canada, and can be defined as:

- Electronic Health Record (EHR) [38] - these records usually contain information about an individual's health and their health care history. Typical information contained in these records include lab results, medication profiles, clinical reports, and diagnostic images. The EHR is made available electronically to authorized health care institutions

- Electronic Medical Record (EMR) [38] - this refers to the digital form of the information acquired during an individual's visit to a health institution. This allows the doctor at the facility to gain access to information about the individual, including potential information stored in the EHR.

- Personal Health Record (PHR) [38] - this is simply a compete or partial record containing information about an individual's health and usually in their custody. The health care institution has no control of this and it is managed by the individual.

The focus of this work is on EHRs which are typically shared among multiple parties and under the control of the medical institution. EHRs as earlier stated provide a comprehensive record of the health information of patients. They are used to share this information with other health care provides and organizations [43, 42]. They also contain the patient administrative and billing data and patient demographics. This is together with other health related information such as vital signs, test results, etc. that they contain. The sensitive nature of the information contained in the EHR makes it important they are stored and shared in a manner that ensures security and privacy.

2.3   Cloud Computing

Cloud computing [30], is "a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." Cloud computing offers considerable advantages to both government and private organizations, which has led to its growth and world wide acceptance in recent years. Some of the advantages offered by the cloud include: easy and fast deployment of IT systems; reduction in the cost of installation and maintenance of infrastructure; easy accessibility; improved flexibility of systems; and a heavy reduction in the responsibilities of the user as most of the traditional tasks will be handled by the provider of the cloud based service, the Cloud Service Provider (CSP).

The different service models for cloud computing are Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS). These delivery models are distinct based on what services the CSP provides and the amount of responsibility that falls on the user in terms of control and management of resources. The IaaS model gives users more responsibilities as they have control

over their operating systems, storage and applications which have been deployed while the SaaS offers the least amount of responsibilities which are limited to some application configuration settings. More detailed information about the different service models can be found in the NIST Definition for Cloud Computing [30].

The deployment models available in cloud computing are the private, community, public and hybrid cloud models. These models are based on the number of parties that share the available deployed infrastructure. The private cloud is typically setup for use for a single organization while the community and public cloud models usually involve multiple parties with the former involving parties that share similar interest and requirements, while the latter is typically provisioned and available for use by the general public. The hybrid cloud model is basically a combination of the any of the other models and is typically a combination of the private and public models with the aim of benefiting from the strengths of the models while eliminating individual model weaknesses. More detailed information about the different deployment models can be found in the NIST Definition for Cloud Computing [30].

The cloud computing deployment model this thesis considers is the public cloud model as this is the model mostly used or a hybrid model potentially involving a private and public cloud model focusing on the vulnerabilities of the public facing infrastructure. Also, users of the private model have more control over their infrastructure and are able, to a certain degree, to ensure that the security and privacy of stored data is assured.

Cloud Computing Security Challenges

The use of cloud computing provides numerous advantages in terms of the ability to provide significant computational and storage resources. These resources are made available in an easy to use manner by providing simplified system setup, operation and maintenance with the added benefit of reduced costs. The unique properties of this environment leads to a different set of security and privacy challenges in addition to the traditional challenges. This is because of the way it is setup. That is, the physical infrastructure is in the control of the CSP and typically shared among their various customers through the use of visualization.

Cloud security challenges include [34]:

- Privacy and User Data Confidentiality - User have limited control as the do not have physical control of the infrastructure on which their data is stored. Also users are not able to prevent critical information from being accessed and used by the providers without the deployment of adequate security mechanisms.

- Multi-Tenancy Issue - This is an issue unique to the cloud computing setup. This is because providers typically have the data and services of multiple users on the same physical infrastructure. This could allow other clients of the CSP to potentially gain illegal access to the data of other users on the same infrastructure.

- Increased Exposure to External Threats - User data is exposed to more external threats through the use of cloud services and results in an increased probability of attacks. This is because adversaries are more likely to attack CSPs in order to gain access to the information of numerous users.

These challenges are even more critical when users who work with highly sensitive data, such as health data, are considering the use of cloud services.

2.4 Technical Preliminaries

This section provides a detailed description of concepts that form the foundation of Attribute Based-Encryption (ABE). ABE is a pairing based form of cryptography that is a fundamental building block of the framework described in this thesis. This includes the different mathematical tools, foundational concepts and a description of the complexity assumptions.

2.4.1 Bilinear Maps

The concept of bilinear maps, or pairings, are the foundation of pairing based cryptography which allowed of the creating of cryptosystems with a great variety

of functionalities. Cyclic groups with efficiently computable bilinear maps form the basis of bilinear maps.

There are two general types of bilinear maps, namely:

1. **Symmetric Pairing [29]** - In this type of pairing we have two cyclic groups G, G_T of prime order p with g as the a generator of G. The efficiently computable bilinear map in this case is represented as

$$e \colon G \times G = G_T$$

2. **Assymmetric Pairing [29]** - In this type of pairing we have three cyclic groups G_1, G_2, G_T with G_1 and G_T of order p and G_2 a group with each element having an order dividing pG. The efficiently computable bilinear map in this case is represented as

$$e \colon G_1 \times G_2 = G_T$$

The type of pairing used in this work is symmetric. Below is a definition of bilinear maps as well as the properties that make it efficient for use in Attribute Based Encryption.

Definition 2.4.1. (Bilinear Maps [29]) Let G, G_T be two cyclic groups (multiplicative or additive) of prime order p. Let g be a generator for G and $e \colon G \times G = G_T$. The bilinear map e has the following properties:

1. Bilinearity: for all $u, v \in Ganda, b \in Z_p$, we have $e(u^a, v^b) = e(u, v)^{ab}$.

2. Non-degeneracy: $e(g, g) \neq 1$

2.4.2   Access Structures

The definitions of access structures and linear secret sharing schemes used in this thesis have been adapted from [5].

Definition 2.4.2. (Access Structures [5]) *Let $\{P_1, \ldots, P_n\}$ be a set of parties. A collection $\mathbb{A} \subseteq 2^{\{P_1, \ldots, P_n\}}$ is monotone if $\forall B, C$: if $B \in \mathbb{A}$ and $B \subseteq C$, then $C \in \mathbb{A}$. An access structure, i.e monotone is a collection $\mathbb{A}$ of non-empty subsets of $\{P_1, \ldots, P_n\}$ i.e., $\mathbb{A} \subseteq 2^{\{P_1, \ldots, P_n\}} \setminus \{\}$. The sets in $\mathbb{A}$ are called the authorized sets, and the sets not in $\mathbb{A}$ are called the unauthorized sets.*

In ABE, attributes play the role of parties in the access structure and the scheme in this thesis only considers access structures that are monotone.

Access policies based on monotone access structures could be represented as either a Linear Secret Sharing Scheme (LSSS) Matrix or with the use of monotonic boolean formulas which could be represented as an access tree in which the core nodes are used to represent the AND and OR gates with the attributes represented by the leaf nodes.

Access policies based on monotone access structures could be represented in two different ways for ABE schemes. The two widely used methods are:

2.4.3 Secret Sharing Schemes

Secret sharing schemes which was first created by Shamir in [36] allows for the division of data among multiple parties in such a way that the original data can only be reconstructed if a party is in possession of at least a fixed number of division, usually the threshold, and possession of a number of pieces less than the threshold reveals no information about the original data. Other earlier works in secret sharing include works by Barkley [8], Benaloh [6] and Ito, Saito and Nishizeki [22]. LSSS are secret sharing schemes in which the reconstruction of the original secret is done using a linear function of the available pieces [5].

Definition 2.4.3. (Linear Secret Sharing Schemes [5, 41]) A secret sharing scheme $\prod$ over a set of parties $\mathcal{P}$ is called linear (over Z_p) if

1. The shared for each party form a vector over Z_p.

2. There exists a matrix M with ℓ rows and n columns called the share-generating matrix for $\prod$. For all $i = 1, \ldots, \ell$, with M_i representing the i'th row of M. The function ρ is defined as the party labelling row i as $\rho(i)$. Consider a

column vector $\vec{v} = (s, r_2, \ldots, r_n)$ where $s \in Z_p$ is the secret to be shared and $r_2, \ldots, r_n \in Z_p$ are chosen randomly, then M_v can be described as the vector ℓ shares of the secret s according to $\prod$. The share $(M_v)_i$ belongs to party $\rho(i)$.

The linear reconstruction property as described in [5] shows that suppose that $\prod$ is an LSSS for an access structure $\mathbb{A}$. Let $S \in \mathbb{A}$ be any authorized set, and let $I \subset 1, \ldots, \ell$ be defined as $I = i : \rho(i) \in S$. Then there exits constants $w_i \in Z_{p_{i \in I}}$ such that, if ρ_i are shares of the secret s according to $\prod$, then $\sum_{i \in I} w_i \lambda_i = s$.

Note that access structures represented as boolean formulas, which are typically represented by binary trees, can be converted into a LSSS form using the techniques described in [39] with the number of rows in the corresponding matrix equal to the number of leaf nodes in the access tree.

2.4.4 Cryptographic Complexity Assumptions

Let G be a cyclic group of prime order p. Let g be a generator for G represented as $G = \langle g \rangle$ and let $x, y, z \in G$. The different complexity assumptions used to show the security of the different pairing based schemes have their foundation in the following core hardness problems [29]:

- **Discrete Log (DLog) Problem** - Given g and g^x, compute x.

- **Computational Diffie-Hellman (CDH) Problem** - Given g, g^x, and g^y, compute g^{xy}.

- **Decisional Diffie-Hellman (DDH) Problem** - Given g, g^x, g^y and g^z, determine if $xy = z$.

2.5 Attribute Based Encryption (ABE)

ABE is a pairing based cryptogaphic scheme that was developed based on Identity Based Encryption (IBE) which was originally proposed by Shamir in 1984 [37]. Shamir proposed a scheme which allowed for the encryption and decryption of information between two different users without the need for any exchange of keys

between both parties. His proposal assumed the existence of a trusted key generation service similar to Certificate Authorities (CA) which were responsible for registration of users as they join a network and also for subsequent verification of their identity. Personal information unique to several users, such as their address, email address or a combination of this information, was used as the public key in the system. This allowed for the encryption of data meant for UserB by UserA using the email address of UserB, e.g "userB@gmail.com". UserB on receiving this encrypted data would then contact the key generation service and, after successful authentication, receives a secret key granting him access to the original data. The scheme proposed by Shamir was further developed and the first practical and secure IBE scheme was presented by Boneh and Franklin in [9], who developed a fully functional IBE scheme which made use of groups for which there existed an efficiently computable bilinear map such as the Weil pairing.

Sahai and Waters in [35] developed a new scheme that improved on the existing IBE schemes by creating a system in which the user identity is viewed as a set of descriptive attributes, allowing a user to encrypt data for all users who have a certain set of attributes. Decryption in this case is only permitted if the identity of a user, and the identity for which the ciphertext was encrypted, were close enough based on their individual attributes. It is in this work that the notion of Attribute Based Encryption is first mentioned.

Goyal et al. in [17] developed an ABE scheme that was more robust than the original ABE scheme proposed by Sahai and Waters [35]. In their scheme, termed Key-Policy Attribute-Based Encryption (KP-ABE), each ciphertext created by the user contains a set of descriptive attributes. Secret keys of individual users are associated with an access structure which specifies the attributes that need to be contained in a ciphertext for successful decryption. The access tree structure could be made up of interior nodes that consist of AND and OR gates with the leaves containing different attributes. For example, if UserA's key in KP-ABE contains "C AND D" as the access policy, the only ciphertexts he should be able to decrypt are those that contains both attributes C and D. A ciphertext with only attribute C or D could not be decrypted by UserA as the requirements for access would not be satisfied. The keys generated for users in this scheme are also collusion resistant

just like the original scheme, meaning that no two users with different attributes could combine their keys to create an overlap of attributes that would give them the ability to decrypt files which they would not normally be able to decrypt.

The authors in [17] mentioned a variant to the KP-ABE scheme known as the Ciphertext-Policy Attribute-Based Encryption (CP-ABE) scheme which they left as an open problem that was solved by [7]. In CP-ABE, the ciphertexts are associated with the access policy while the user keys contain a set of descriptive attributes. This would mean that, for a key to decrypt a particular ciphertext, its attributes need to match the access structure of the access policy of the ciphertext. This scheme, unlike the KP-ABE scheme, gives the user encrypting data more control as the user is able to control who can have access to data being encrypted by making sure the access policy in the ciphertext specifies what attributes need to be possessed for access to be granted.

The four basic algorithms of any ABE based system includes the following:

1. Setup - The setup algorithm is responsible for the selection of the bilinear group and the definition of a bilinear map that has the properties of bilinearity, computability and non-degeneracy. The setup algorithm takes as its input the security parameter which specifies the size of the attribute set and generates a public key (PK) and a master key (MK) as output.

2. Keygen - The keygen algorithm takes as its input two parameters, the MK generated during setup and the set of attributes that the user possesses, and generates a secret key (SK) for the user in CP-ABE. The input for KP-ABE includes the MK, PK and an access structure and outputs SK.

3. Encryption - The encryption algorithm takes as its input PK, a message M, and an access structure for CP-ABE schemes and produces a ciphertext C. It takes as input PK, M and a set of attributes and produces a ciphertext C for KP-ABE schemes.

4. Decryption - The decryption algorithm takes as input PK, C and SK and, if the attributes of either the ciphertext or secret key satisfies the access structure of the other, depending on whether the scheme is a CP-ABE or KP-ABE scheme, decrypts C and outputs M.

Both variants of ABE allows for delegation. This would allow a user with a secret key, for set of attributes (CP-ABE) or containing an access structure (KP-ABE), to derive a new secret key. The derived key would contain a set of attributes that is a subset of the attribute set of the original key or an access structure that is more restrictive than the access structure contained in the original key.

2.6 Revocation

A useful feature with ABE based systems is the ability for user revocation. This is a challenge as multiple users may share a similar attribute which could cause the revocation of one user to affect other users who share a similar attribute. Furthermore it is important that user revocation be flexible and occur at different granular levels which means that revocation could involve removal of a user completely or a partial reduction of a user's access, based on their attributes. The addition of an expiry date to the generated key has been proposed by initial ABE based systems [7] but does not offer an effective means for the revocation of user attributes.

Yu et al. in [46] proposed a scheme that enables secure, scalable and fine grained data access to a cloud based system with a great reduction in the computation overhead by delegating most of the computation intensive tasks to the cloud servers while ensuring the security and privacy of user data through the combination of KP-ABE, proxy re-encryption (PRE) and lazy re-encryption (LRE). In their scheme, the attributes that are assigned to the ciphertexts are all assigned a unique ID which serves as the version number that is stored in a list maintained by the cloud servers, together with the PRE keys used. The cloud servers also maintain a list of all the existing users in the system who are currently authorized to have access to the different stored data. Data files are encrypted using symmetric encryption with the decryption keys encrypted using ABE and appended to the encrypted data file together with a unique file ID. PRE enables the use of a proxy to convert a ciphertext which has been encrypted using the public key of a particular user into another ciphertext that can be decrypted using the private key of a different user, without revealing the contents of the underlying file. In order to revoke a user, the scheme determines the least amount of attributes that need to be updated to

prevent a user from having access and redefines the public and master keys for those attributes while generating the corresponding PRE keys. The revoked user's ID, the attribute set, the PRE keys and the new public key parameters are sent to the cloud servers. The cloud servers then remove the revoked user from the user list, store the new public key parameters and then updates its list of attributes together with the PRE keys used.

Yu et al. in [40] have applied the concept of proxy re-encryption with CP-ABE in order to enable revocation. Liang et al. in [28] have proposed the system Ciphertext Policy Attribute Encryption with Revocation (CP-ABE-R), which makes use of linear secret sharing and binary tree techniques to enable effective revocation of users with the aid of a unique identifier assigned to each user in the system and which is not needed for encryption and decryption. Cheng et al. have proposed a scheme [14] that enables effective revocation in CP-ABE by dividing the original data into multiple parts which they term *slices*, before they are stored in the cloud which allows for revocation by the re-encryption of only one slice. The data is encrypted with a symmetric key and then split into multiple parts using a secret sharing scheme. In the case of the secret sharing scheme applied here, the number of parts that are needed to reconstruct the original file is equal to the number of distinct parts. A particular slice of data is chosen as the dynamic data and it is this slice that is constantly re-encrypted to enable revocation while the static data remains the same. This reduces the computational and storage overhead while ensuring that the security of the system is not compromised.

2.7 Multi-Authority Schemes

The first Multi-Authority Attribute Based Encryption (MA-ABE) scheme was proposed by Chase in [12, 15] and was based on Key Policy Attribute Based Encryption (KP-ABE). In this scheme, there are multiple Attribute Authorities (AA) in addition to a Central Authority (CA) which are responsible for generating secret keys corresponding to the attributes which they handle. Users are assigned a Global Unique Identifier (GUID) which they use to request the shares of the system-wide Master Secret Key (MSK) handled by the different authorities. The GUID is used

by the authorities to tie the shares to a particular user. The system includes a CA which is responsible for aiding users in decryption by ensuring that all the shares generated for a particular user by the different AAs sum up to the same MSK. The CA ensures this by assigning to each user a special value that cancels out all of the shares from the different authorities, providing the user with a function of the system wide MSK. In order to carry out its functions, the CA has knowledge of the MSK and as a result would also be able to decrypt any ciphertext in the system which is in contrast with the idea behind using multiple authorities, which is to distribute trust among several untrusted authorities. Also, in the original system, the users use their GUIDs to identify with the individual AAs, which means that several authorities could combine their information about a particular user and develop a profile based on the attributes that the user has acquired and be able to generate keys with the same level of access as the user.

Chase and Chow in [13] proposed a solution to the original MA-ABE problem which eliminated the use of a CA and also prevented the AAs from having the ability to combine the information about a user by allowing users to use pseudonyms for interacting with the individual AAs in the system instead of the use of their respective GUID. This solution eliminates the CA by applying a set of Pseudo Random Functions (PRF), and having every pair of authorities in the system share a secret PRF seed which allows for a combination of all their individually generated shares. To enable users to communicate with the individual AAs using pseudonyms, the authors have developed a novel Anonymous Key Issuing Protocol. Additional details about the protocol and its functions can be found in [15, 13].

Lewko and Waters proposed a MA-ABE [24, 39] solution in which the different authorities operate independently and do not have to share any common information with each other as in [12] except for an initial set of common reference parameters. Their system has higher tolerance as the failure or corruption of authorities in the system will not have a direct impact on the operation of the fully functioning and uncorrupted authorities. Furthermore, in their solution, any party could become an authority by making available, to the other entities in the system, their verification key and their lift of managed attributes. This solution makes use of Linear Secret Sharing Schemes (LSSS) access structures and the authors show

that boolean formulas could easily be transformed into LSSS structures using techniques found in [39]. Lewko and Waters have used the dual system proof technique to prove the security of their system.

Yang et al. in [45] have developed a solution called DAC-MACS (Data Access Control for Multi-Authority Cloud Storage) in order to make a more efficient CP-ABE based MA-ABE solution that takes advantage of the services available in the area of cloud computing and that is more suited to this domain. Their solution includes an efficient attribute revocation method that enables both forward and backward security. In addition to providing a means for attribute revocation, Yang et al.'s system [45] has better efficiency than other similar solutions. Also, by using a decryption token for the decryption, they have been able to transfer the intensive computations over to the cloud server, thereby reducing the computational overhead on the side of the end user. A flaw in the system is the fact that the different AAs have knowledge of the GUID of the users which would give a revoked user the ability to derive the key update key that they could use to update their own keys by corrupting any AA, together with some non-revoked users.

Yang and Jia [44] have developed a more effective MA-ABE solution based on CP-ABE. In their new system, the secret keys of the different users are not related to the key of the data owner and so users will only need to hold an individual secret key for an authority instead of multiple secret keys associated with multiple owners. This makes it more suitable for a multi-owner setting as storage overhead for user keys is greatly reduced. They have also improved the revocation mechanism by modifying it to require that only ciphertexts associated with a revoked attribute be updated and by using a single update key for the update of both keys and ciphertexts.

The scheme by Yang and Jia [44] will be modified for the development of the proposed scheme as part of the framework in this work and be used in comparison to show the performance of the proposed scheme. This is because their scheme is more efficient in comparison with other existing multi-authority schemes.

2.8 Outsourcing

An important extension to the functionality of available ABE schemes is the ability to outsource the computationally intensive operations such as the decryption of the ciphertext to third party systems such as a Cloud Service Provider (CSP) while maintaining the same levels of security and privacy as the existing ABE schemes. This enables users to have access to the required data using devices with low computational power such as mobile devices with no additional risk.

This was initially proposed by Green et al. in [18]. In their approach, they achieve outsourcing by splitting the traditional decryption algorithm into two components. The first a transformation algorithm to be run externally by the CSP, which given the necessary input transforms the ABE ciphertext into a constant-size El Gamal-style ciphertext. The second component is the decryption algorithm to be executed by the user which with the El Gamal-style ciphertext and the right input produces the original message. The second component to be run by the user is less computationally intensive as it involves a single exponentiation operation compared to the multiple pairing operation involved in the transformation algorithm. They have applied this to single authority KP- and CP-ABE schemes showing improvements with relation to size of the ciphertext at the user end and minimal impact on the bandwidth of the decryption process. Their approach has the added benefit of reducing the amount of code that has to reside on the user device and the main bulk of code which corresponding to the analysis of ABE attributes and the computation of pairings now resides on the third party device allowing for a smaller and more trusted code base on the user end.

Other authors [25, 26] have extended the idea of outsourcing in ABE by outsourcing the key generation algorithm in addition to the decryption algorithm through several other methods with limited improvements on the level of overhead achieved by Green et al. in [18].

Sherman Chow has created a framework in [16] that allows for the construction of an ABE scheme with multiple authorities, revocation capability and outsourcing of the decryption algorithm from a single authority ABE scheme if certain conditions are met. These include the ability to split the ciphertext and secret keys into both attribute-dependent and attribute-independent components. The framework

also requires that the structure of secret keys generated by multiple attribute authorities share a structure that makes them indistinguishable from keys generated by a single authority.

2.9   ABE Based Health Care Systems

Ibraimi et al. proposed a new variant of CP-ABE [21] in order to be able to enforce the required levels of access controls in a multiple domain based system to ensure the security of personal health records (PHR). They have distributed the group of users who normally require access to PHRs into two domains: the professional domain, which consists of the health care providers; and the social domain, made up of family members, friends and possibly fellow patients. Their proposed variant of CP-ABE allows the encryption of health records with an access policy that is made up of attributes issued by two different trusted authorities: the trusted authority in charge of the professional domain and the trusted authority in charge of the social domain.

The authors in [32] have proposed the design of a patient controlled cloud based EHR infrastructure using CP-ABE. They have based their system on the assumptions: a trusted authority (TA) exists that is responsible for the generation of keys for users and is able to store the public parameters and public keys of users in a public directory; each user is associated with a unique identifier and a set of attributes; and the cloud server used for storage is only trusted for the performance of storage operations. They have used a variant of CP-ABE, known as broadcast ciphertext-policy attribute-based encryption (bABE), which extends the traditional CP-ABE to enable revocation of users' keys. They have also provided the functionality of keyword search which allows users to search using a search term by providing a key which allows the cloud provider to perform search operations on the encrypted data without learning anything about the actual data contents.

Akinyele in [2], using ABE, has provided a detailed design and implementation of self-protecting EMR which allows EMR availability even when the providers are offline. Their system makes role- and content-based access control possible. For role-based access control, users are granted explicit access to collections of

data related to their roles that match some specific criteria which the authors have termed content slices. These slices could be as specific as required by the system administrators and the content-based access is used to grant access to users such as contractors, who have no definite roles in the system but require access to records to carry out their functions. They have also implemented a policy engine as part of their design to evaluate new or updated EMRs in order to determine the policies that are to be used for encryption. The policy engine's final decision is based on either the set of policies specified by the administrator, the identity and nature of the EHR, the annotations attached to the EHR, or in some cases the textual content of the record. They have taken advantage of the XML-based EMR standards which include the Continue of Care Record (CCR) and the Continuity of Care Document (CCD) which allows their policy encryption engine to parse each node in order to determine the appropriate access policy and subsequently the access control rule and content related attributes for which the document is to be encrypted. Users will need to be present at the initialization stage to have their mobile devices provisioned with the required decryption keys to be able to use the accompanying mobile application to access their data. CP-ABE is used to grant access to patients and health professionals using keys with fixed attributes related to their roles or responsibilities while users with no definite role are granted access through the use of KP-ABE by generating keys, which contain a specific policy that defines what data they can access and, in some cases, the time periods for which they can have access.

Barua et al. in [4] have proposed a scheme which they called Efficient and Secure Patient-centric Access Control (ESPAC), in which they have used CP-ABE to achieve patient-centric access control allowing different access privileges based on the roles of the data requester and assigning the corresponding attributes based on those privileges. They have constructed their access control policy by assigning attributes, based on the relationship between the patient and the requesting party, which is used to determine the privacy levels of the requesting party before attributes are assigned. Their system is made up of four main entities: the trusted authority (TA), the cloud service provider (CSP), the registered user, and the data-access requester. The scheme makes use of pseudo identity instead of unique

identities to ensure privacy. The scheme enables message integrity checks, non-repudiation and source authentication through the use of signature verification. This scheme is able to ensure forward and backward secrecy.

Suhair et al. in [3] have proposed the design of a cloud based EHR system using CP-ABE to ensure security by using the credentials and attributes of the health care providers as the universal attribute set. Their proposed architecture is made up mainly of three components: the EHR system hosted on the cloud; the participating healthcare providers; and the attribute authority (AA) which is in control of generating the secret keys of users which contain the appropriate attributes. The cloud is used for data storage and computation in their infrastructure. Encryption and decryption of the medical records are performed at the client end through the use of lightweight software. Suhair et al. have proposed the addition of an expiry date to the access policies used for encryption, or complete re-encryption with updated access policies, as a way to achieve revocation in order to avoid the communication overhead involved with the re-distribution of secret keys to authorized users. The use of a single AA presents a focal point of weakness for the security of the system and presents the key escrow problem.

Hupperich et al. in [20] propose an architecture that gives the patient control of the delegation of access to their EHRs, in line with the existing privacy laws. They have proposed a system that would allow patients to authorize the appropriate health care service providers to have access to their EHRs through a flexible channel that would not require the patient to be present. In order to eliminate the use of smart cards for access, and to enable health care providers to have access to EHRs their infrastructure only requires the use of the patient's smart card at the initial stage for the generation of a transaction code (TAC) which the patient can use to grant access by sending to authorized health care professionals. They have used ABE for encryption by using the patient's identity and a TAC that is specific to a particular medical record as the two main attributes for encryption and decryption. They have implemented emergency access by allowing the encryption of certain records using the attribute *"emergency"* without any TAC, with logging implemented to keep track of emergency access. The authors have not mentioned how the system would handle revocation of users and have not implemented a

secure means of transmission for the generated TACs which they have stated could be transferred via traditional means such as a phone or on paper.

The authors in [19] proposed the design for a secure interoperable cloud based service for private health records (PHR) which uses the Continuity of Care Document (CCD) for the storage and exchange of information and employs several security mechanisms using available open standards such as XACML, XML encryption, XML signature and XML key management specification. They have used CP-ABE to achieve patient controlled encryption, and the public key encryption with keyword search (PEKS) scheme to provide privacy-preserving keyword search. They have used the Secure Channel Free PEKS scheme which allows users to perform private searches over encrypted data for specific matching keywords without revealing the keywords or any partial matches to the server.

Li et al. in [27] proposed a framework titled Scalable and Secure Sharing of Personal Health Records in Cloud Computing Using Attribute Based Encryption containing a suite of security mechanisms that aimed to solve the existing issues in cloud-based PHR storage systems which include eliminating the risk of privacy exposure, key management scalability, flexible access and effective revocation of existing users. Their work focuses on the multiple data owner scenario similar to our proposed architecture and thus they have divided the users in the system into two broad security domains similar to [21], which reduces the complexity of key management for data owners and users who require access, with the improvement being that in their scheme the public domain (PUD) is managed by multiple AAs. The personal domain is made up of users who are close to the data owners (i.e. patients) such as family members and friends while the public domain is made up of the various professionals who require access to the patient's records such as doctors and pharmacists. In order to apply ABE to the personal domain, Li et al. have employed the Key Policy ABE with efficient revocation as proposed in [40] with the data owner fully responsible for handling this particular domain. The data owner generates keys for members of this domain with the access structure corresponding to their level of access and sends this keys to the corresponding users in order to grant them access. The authors have employed in the public domain the use of the MA-ABE proposed in [12] and improved in [13]. Since the MA-ABE

scheme they adopted is essentially a KP-ABE scheme with multiple AAs, in which control of access lies with the AAs who generate the keys for the different attributes therefore taking away control from the data owner, Li et al. have made a slight modification to how this scheme is used in their system. In order to grant the data owner more control, the system requires that the key access policies and the general approach for specifying the ciphertext attributes be agreed upon in order to grant the users some level of control in specifying the access policy of the ciphertext from their end by choosing the right attributes. To improve security in the public domain, Li et al. have slightly modified the Multi-authority ABE (MA-ABE) scheme proposed by [13] to enable efficient user revocation by using the revocation technique proposed by [40] which was not a feature of the original scheme. Their system provides dynamic attribute and access policy modification together with on-demand user/attribute revocation, together with break glass access, in order to make records available for use under emergency situations.

Chapter 3

Secure Privacy Preserving Framework for Electronic Health Records (EHRs)

3.1 Overview

This chapter introduces the framework that is the basis of this thesis. We start with a description of the ABE scheme that plays an essential role in providing the features of security and privacy for the framework. The construction of the ABE scheme follows after the definition of the various algorithms. The construction shows the mathematical concepts that confirm the inner workings of the different algorithms.

A description of the entire framework follows with the architecture and its corresponding entities highlighted. We then provide use cases together with a detailed description of the individual use cases and the roles the entities play.

3.2 Proposed Multiple Authority Ciphertext Policy Attribute Based Encryption with Outsourced Decryption

This section contains the formal definition of the underlying proposed ABE scheme for the overall framework. This formal definition provides a description of the algorithms that are part of the ABE scheme. The second part of the section provides more detailed information in the form of the mathematical construction for the ABE scheme.

3.2.1 ABE Scheme Algorithm and Security Definition

Our ABE scheme has been adapted from the scheme developed in [44]. Using similar methods applied in [18], we have modified the scheme with the aim of outsourcing the bulk of the decryption algorithm operation to the CSP. This section contains a definition of the algorithms that make up our ABE scheme.

Algorithm Definitions

The following algorithms make up the ABE scheme. These algorithms include: the setup and system initialization algorithms, the secret key generation algorithm, the encryption, transformation and decryption algorithms as well as the revocation algorithms. They are described a follows:

(1) CASetup - The Certificate Authority Setup algorithm is the algorithm executed by the Certificate Authority (CA) in order to generate the Global Master Key (GMK) and Global Public Parameters (GPP) of the entire scheme. It takes as input the security parameter of the scheme. The CA makes the GPP available to all entities in the system.

   (i) UserReg - The User Registration algorithm is run by the CA whenever new users are being added to the system. The CA assigns a unique id to each new user and also generates two public-private key pairs together with user certificates and their corresponding verification keys for each

new user. The CA sends one each of the generated public and private keys to the user together with the certificate.

(ii) AAReg - The Attribute Authority Registration algorithm is run by the CA whenever new Attribute Authorities (AA) are joining the system. The CA assigns a unique id to each new AA and also send the other public and private keys for each registered user to the AA together with the verification keys for the generated certificates.

(2) AASetup - The Attribute Authority Setup algorithm is run by the individual Attribute Authorities (AAs) and generates the public-secret key pair for the attribute authority. It also generates a public-version key pair for each of the attributes under the control of the AA that is provided as input in the AA universal attribute set.

(3) SKGen - The Secret Key Generation algorithm is run by the corresponding AAs in order to provide the user with the secret key for the attributes that they have been assigned. The AA takes as input the system GPP, the users Global Public Keys (GPKs), one of the user GSKs, the set of attributes and their corresponding public-version key pairs. It provides the user with a secret key that can be used for decryption.

(4) Encrypt - The Encryption algorithm is run by the data owner in order to encrypt the corresponding piece of data. This algorithm takes as input the system GPP, the public keys (PKs) for the AAs involved in the encryption - as they are in control of the attributes that make up the policy under which data is to be encrypted - of the data, and an access policy. It provides as output a ciphertext (CT) which implicitly contains the corresponding access policy.

(5) CTransform - The Ciphertext Transformation algorithm is responsible for the transformation of the CT into an El Gamal style ciphertext that can be easily decrypted by the end user. This algorithm is executed by the Cloud Service Provider (CSP) and takes as input the ciphertext, the secret keys of the attributes in the user's possession and the user's GPK. It produces as

output a partially decrypted ciphertext (CT') if the user's secret keys meet the policy under which the data was encrypted, otherwise it outputs an error.

(6) Decrypt - The Decryption algorithm is run by the end user and takes as input the partially decrypted ciphertext (CT') and the user's global secret key which is not shared with any other entity in the system and produces the original data as output for the user in its plain form.

(7) UKeyGen - The Update Key Generation algorithm is run by the AA under whose control the revoked attribute falls. The algorithm takes as input the SK of the AA, the revoked attribute and the current version key for the revoked attribute. It produces as output an updated version key for the revoked attribute. It also produces an update key to be used to update the corresponding secret keys of users who possess the revoked attributes and whose access is not being revoked. It also produces an update key for the affected ciphertexts whose access policies contain the revoked attribute to allow for users who still maintain access to be able to decrypt while denying revoked users further access.

(8) SKUpdate - The Secret Key Update algorithm is run by each non revoked user in the system and takes as input the corresponding secret key acquired from the AA that control the affected attribute together with the update key for user secret keys generated by the UKeyGen algorithm. It outputs a new secret key for the user.

(9) CTUpdate - The Ciphertext Update algorithm is run the CSP and takes as input the affected ciphertexts and the update key generated by the UKeyGen algorithm for ciphertext update. it outputs a new ciphertext that can only be decrypted by users with a current version of the corresponding revoked attribute.

ABE Scheme Security Definition

The security definition of the ABE scheme is based on the correctness definition of the scheme based on the following conditions:

(1) Encryption and Decryption - Decrypt(CTransform(Encrypt(Message, GPP, PK_{aids}), $SK_{uid,aid}$, GPK_{uid}), GSK'_{uid}) = Message

(2) Revocation - For an attribute $\tilde{x}_{aid'}$, Decrypt(CTransform(CTUpdate(Encrypt(Message, GPP, PK_{aids}), $UK_{c,\tilde{x}_{aid'},uid}$), $SK_{uid,aid}$, GPK_{uid}), GSK'_{uid}) = Message, only if version key for $\tilde{K}_{\tilde{x}_{aid'},uid}$ = version key for $\tilde{x}_{aid'}$

This scheme is secure under the CPA model of security. Further analysis of the security of the underlying ABE scheme together with the security game model and proofs can be found in [44], the original scheme from which this was derived.

We also adopt the security assumptions of the original scheme [44]. The security assumptions are as follows:

(1) We assume the CA is fully trusted in the sense that it will not collude with any users in the system but it should not be able to decrypt any of the ciphertexts in the system alone.

(2) Attribute Authorities are trusted but can be corrupted by an adversary.

(3) The Cloud Service Provider is semi-trusted. By semi-trusted this means that the CSP may want to acquire additional knowledge of the data content, but will always execute tasks/algorithms accurately [44].

(4) We assume that users are dishonest and may potentially collude with other dishonest parties to gain unauthorized access to data.

3.2.2   ABE Scheme Construction

A. CA Setup - This procedure is run by the CA to setup the system

$$CASetup(1^{\lambda}) \longrightarrow GMK, GPP \tag{3.1}$$

where 1^{λ} is the security parameter, GMK is the Global Master Key, and GPP represents the Global Public Parameters.

The CA chooses two multiplicative groups G, G_T with the same prime order p and a bilinear map $e \colon G \times G \to G_T$ and a hash function $H \colon \{0,1\} \to G$. The CA chooses two random numbers $a, b \in Z_p$

The GMK is set as (a, b) and the GPP is set to (g, g^a, g^b, H)

(i) User Registration - This is executed for all users in the system by the CA. Each user is assigned a globally unique uid and for each uid, the CA generates two random numbers $u_{uid}, u'_{uid} \in Z_p$ as its global secret keys

$$
\begin{aligned}
GSK_{uid} &= u_{uid}, \\
GSK'_{uid} &= u'_{uid}
\end{aligned}
\tag{3.2}
$$

The global public keys for each user is generated as

$$
\begin{aligned}
GPK_{uid} &= g^{u_{uid}}, \\
GPK'_{uid} &= g^{\frac{1}{u'_{uid}}}
\end{aligned}
\tag{3.3}
$$

The CA generates a $Certificate uid$ for each user uid and send $(GPK_{uid}, GSK'_{uid}, Cerificate(uid))$ to the user.

(ii) Attribute Authority (AA) Registration - The CA assigns a globally unique authority identity aid to each AA and sends (GPK'_{uid}, GSK_{uid}) for all registered users to AA_{aid}. The CA also sends the verification key vk_{CA} to AA_{aid} for verifying the $Certificate(uid)$ assigned to each user.

B. AA Setup - Let X_{aid} be the set of all attributes managed by AA_{aid}. The AA generates three random numbers $\alpha_{aid}, \beta_{aid}, \gamma_{aid} \in Z_p$ as its secret key.

$$
\begin{aligned}
SK_{aid} &= (\alpha_{aid}, \beta_{aid}, \gamma_{aid}) \\
PK_{aid} &= (e(g,g)^{\alpha_{aid}}, g^{\beta_{aid}}, g^{\frac{1}{\beta_{aid}}})
\end{aligned}
\tag{3.4}
$$

For each attribute $x_{aid} \in X_{aid}$, AA_{aid} generates a public attribute key as $PK_{x_{aid}} = (PK_{1,x_{aid}} = H(x_{aid})^{v_{x_{aid}}}, PK_{2,x_{aid}} = H(x_{aid})^{v_{x_{aid}}\gamma_{aid}})$ where $v_{x_{aid}}$ is the version key of attribute x_{aid} i.e $VK_{x_{aid}} = v_{x_{aid}}$.

C. Secret Key Generation - The Attribute Authority with AA_{aid} assigns a set of attributes $S_{uid,aid}$ to user with uid after authentication and certificate verification. The AA chooses a random number $t_{uid,aid} \in Z_p$ and computes a secret key for the user $SK_{uid,aid}$ as

$$
\begin{aligned}
K_{uid,aid} &= g^{\frac{\alpha_{aid}}{u'_{uid}}} g^{au_{uid}} g^{bt_{uid,aid}}, \\
K'_{uid,aid} &= g^{t_{uid,aid}}, \\
\forall x_{aid} \in S_{uid,aid} \colon K_{x_{aid},uid} &= g^{t_{uid,aid}\beta_{aid}} H(x_{aid})^{v_{x_{aid}}\beta_{aid}(u_{uid}+\gamma_{aid})}
\end{aligned}
\tag{3.5}
$$

If the user uid does not hold any attributes from AA_{aid}, the user secret key $SK_{uid,aid}$ only contains $K_{uid,aid}$.

D. Encryption - Data is divided into components based on the level of granularity required for access control i.e $m = \{m_i, \cdots, m_n\}$. Data components are encrypted using symmetric encryption keys $\kappa = \{\kappa_i, \cdots, \kappa_n\}$. An access structure (M_k, ρ) is defined for each content key $\kappa_i(i = 1, \cdots, n)$ and encrypted using the ABE scheme to produce the corresponding ciphertext. Let M be an ℓ x n matrix, where ℓ denotes the total number of all the attributes and the function ρ associates rows of M to attributes. The function ρ is not required to be injective which allows for an attribute to be associated with more than one row of M.

To encrypt the content key κ_i, the algorithm chooses a random element $s \in Z_p$ which is used as the random encryption exponent. It then selects a random vector $\vec{v} = (s, y_2, \ldots, y_n) \in Z_p$ where $y_2, \ldots, y_n$ are used to share the encryption exponent s. It then computes $\forall 1 \leq i \leq \ell : \lambda_i = \vec{v}.M_i$ where M_i is the vector corresponding to the i-th row of M. It then randomly selects

$r_1, r_2, \ldots, r_\ell$ and computes the ciphertext CT_{K_i} as

$$C = K_i \cdot \Big(\prod_{aid_k \in I_A} PK_{aid_k} \Big)^s,$$

$$C' = g^s,$$

$$C'' = g^{bs},$$

$$\forall 1 \leq i \leq \ell, \rho(i) \in X_{aid_k} : C_i = g^{a\lambda_i} \cdot \big(PK_{i,\rho(i)} \big)^{-r_i}, \qquad (3.6)$$

$$C_i' = g^{r_i},$$

$$D_i = g^{\frac{r_i}{\beta_{aid_k}}},$$

$$D_i' = \big(PK_{2,\rho(i)} \big)^{r_i}$$

Then the encrypted data is uploaded to the cloud server by the owner.

E. Ciphertext Transformation - This involves the transformation of the ciphertext into an El Gamal style ciphertext referred to in this framework as a token through partial decryption while the integrity of the original message is preserved.

The transformation algorithm takes as input the ciphertext CT where $CT = (C, C', C'', C_1, \ldots, C_\ell)$ which contains an access policy (M, ρ), the user's global public key GPK_{uid}, and a set of secret keys from all the involved Attribute Authorities $\{SK_{uid,aid}\}_{aid_k \in I_A}$ i.e $(K, K', K_{x_{aid}} \forall x_{aid} \in S_{aid})$ where S_{aid} is a set of the user attributes. If the attributes provided do not meet the access policy conditions, the algorithm outputs $\perp$. The algorithm proceeds to transform the ciphertext if the set of user attributes S_{aid} meet the conditions of the access policy contained in the ciphertext.

Let I be defined as $\{I_{aid_k} \in I_A\}$, where $I_{aid_k} \subset \{1, 2, \ldots, \ell\}$ can be defined as $I_{aid_k} = \{i : \rho(i) \in S_{aid_k}\}$. Let $n_A = |I_A|$ be the number of AAs involved in the access policy of the ciphertext. The algorithm chooses a set of constants $\{\omega_i \in Z_p\}_{i \in I}$ such that if the shares of a secret represented by $\{\lambda_i\}$ are valid with respect to the matrix component of the access structure, M, then

the secret can be reconstructed as $\sum_{i \in I} \omega_i \lambda_i$. The algorithm computes the partially decrypted ciphertext CT' as

$$
= \prod_{aid_k \in I_A} \frac{e\left(C', K_{uid,aid}\right) e\left(C'', K'_{uid,aid}\right)^{-1}}{\prod_{i \in I_{aid_k}} \left(e\left(C_i, GPK_{uid}\right) e\left(D_i, K_{\rho(i),uid}\right) e\left(C'_i, K^{-1}_{uid,aid_k}\right) e\left(g, D'_i\right)^{-1} \right)^{\omega_i n_A}}
$$

$$
= \prod_{aid_k \in I_A} e\left(g,g\right)^{\frac{s\alpha_{aid}}{u'_{uid}}} \tag{3.7}
$$

F. Decryption - The algorithm for decryption takes as input the partially decrypted ciphertext (CT') and the user's secret key and produces as output the original message. It performs an exponentiation on CT' in order to derive the blinding element (BE) of the original message as

$$
= CT'^{u'_{uid}}
$$

$$
= \prod_{aid_k \in I_A} e\left(g,g\right)^{s\alpha_{aid}} \tag{3.8}
$$

Remember the C element of the main ciphertext $= K_i \cdot \left(\prod_{aid_k \in I_A} PK_{aid_k} \right)^s$ where $PK_{aid_k} = e\left(g,g\right)^{\alpha_{aid}}$. Therefore the original message which in this case is the symmetric key K is computed as

$$
= \frac{C}{BE} \tag{3.9}
$$

G. User Revocation - User revocation which can also be referred to as attribute revocation as used in some of the literature on the subject should achieve two critical criteria. The revoked user should not be able to decrypt new ciphertexts which have been encrypted using the public attribute keys of attributes that the user was previously granted private keys for. This is referred

to as Backward Security. Any new user who has the right attributes should be able to decrypt the original ciphertexts that were encrypted using those public parameters. This is referred to a Forward Security. The revocation algorithm used has been gotten from the scheme by Yang et. al in [44].

(i) Update Key Generation - In order to revoke an attribute $\tilde{x}_{aid'}$ from a particular user, the attribute authority (AA) responsible $AA_{aid'}$ runs the key update algorithm taking as input the secret key $SK_{aid'}$ of the attribute authority, the revoked attribute $\tilde{x}_{aid'}$, and its current version key $VK_{\tilde{x}_{aid'}}$. The algorithm generates a new version key $VK'_{\tilde{x}_{aid'}} = v'_{\tilde{x}_{aid'}} (v'_{\tilde{x}_{aid'}} \neq v_{\tilde{x}_{aid'}})$ for the revoked attribute $\tilde{x}_{ai'd}$.

The $AA_{aid'}$ then generates a unique update key $UK_{s,\tilde{x}_{aid'},uid}$ for secret key update by each non-revoked user uid as

$$UK_{s,\tilde{x}_{aid'},uid} = H(\tilde{x}_{aid'})^{\beta_{aid'}(v'_{\tilde{x}_{aid'}} - v_{\tilde{x}_{aid'}})(u_{uid} + \gamma_{aid'})} \tag{3.10}$$

and generates the update key $UK_{c,\tilde{x}_{aid'},uid}$ for ciphertext update as

$$
\begin{aligned}
UK_{1,\tilde{x}_{aid'}} &= \frac{v'_{\tilde{x}_{aid'}}}{v_{\tilde{x}_{aid'}}}, \\
UK_{2,\tilde{x}_{aid'}} &= \frac{v_{\tilde{x}_{aid'}} - v'_{\tilde{x}_{aid'}}}{v_{\tilde{x}_{aid'}} \gamma_{aid'}}
\end{aligned}
\tag{3.11}
$$

The $AA_{aid'}$ sends the $UK_{s,\tilde{x}_{aid'},uid}$ to the non-revoked user uid and sends $UK_{c,\tilde{x}_{aid'},uid}$ to the cloud server.

The $AA_{aid'}$ then updates the public attribute key, $PK_{\tilde{x}_{aid'}}$ of the revoked attribute $\tilde{x}_{aid'}$ to $\tilde{PK}_{\tilde{x}_{aid'}}$ as

$$\tilde{PK}_{\tilde{x}_{aid'}} = (PK_{\tilde{x}_{aid'}})^{UK_{1,\tilde{x}_{aid'}}} \tag{3.12}$$

(ii) Secret Key Update - This process is run by the non revoked users in the system. The algorithm produces an updated secret key $\tilde{SK}_{uid,aid'}$ using

the update key $UK_{s,\tilde{x}_{aid'},uid}$ for the individual users as

$$
\begin{aligned}
\tilde{K}_{uid,aid'} &= K_{uid,aid'}, \\
\tilde{K}'_{uid,aid'} &= K'_{uid,aid'}, \\
\tilde{K}_{\tilde{x}_{aid'},uid} &= K_{\tilde{x}_{aid'},uid}.UK_{s,\tilde{x}_{aid'},uid}, \\
\forall x_{aid'} \in S_{uid,aid'} \backslash \{\tilde{x}_{aid'}\}: \tilde{K}_{\tilde{x}_{aid'},uid} &= K_{\tilde{x}_{aid'},uid}
\end{aligned}
\tag{3.13}
$$

(iii) Ciphertext Update - The ciphertext CT is updated using $UK_{c,\tilde{x}_{aid'},uid}$ to $\tilde{CT}$ as

$$
\begin{aligned}
\tilde{C} &= C, \\
\tilde{C}' &= C', \\
\tilde{C}'' &= C'', \\
\forall 1 \leq i \leq \ell : \tilde{C}'_i &= C'_i, \\
\tilde{D}_i &= D_i, \\
if \rho(i) = \tilde{x}_{aid'} : \tilde{C}'_i &= C_i.(D'_i)^{UK_{2,\tilde{x}_{aid'}}}, \\
\tilde{D}'_i &= (D'_i)^{UK_{1,\tilde{x}_{aid'}}}, \\
if \rho(i) \neq \tilde{x}_{aid'} : \tilde{C}_i &= C_i, \\
\tilde{D}'_i &= D'_i
\end{aligned}
\tag{3.14}
$$

3.3 Secure Privacy Preserving EHR Framework

This section provides information about the privacy preserving EHR framework that is the main subject of this thesis. We provide a system architectural model that shows the different entities that are part of the framework and how they interact with each other to achieve the functionalities of this framework. We also provide specific use case scenarios together with a detailed description of the individual use cases to provide further information of the different settings in which the framework could be applied.

Our EHR framework is an improvement on the other existing ABE based health care exchange systems in different ways. Our underlying multi-authority scheme is a major improvement on the other single authority schemes in terms of robustness.

Also the introduction of a Certificate Authority for user and authority identification allows for a decentralized system in which attribute authorities cannot collude in order to circumvent the system and gain access to data. Also our framework's use of an ABE scheme with outsourced decryption significantly improves its usability. This allows end users to use devices with low computational power to access the necessary data.

3.3.1   System Architecture/Model

The system architecture is made up of several entities that perform different functions with regards to their roles in the system.

System Entities

(1) Users - Users are the members of the system that add or request data. They could be either data owners or data users with individuals able to play both roles in general with the system.

   (i) Data Owner (DO) - The DO is responsible for the generation of data to be stored on the platform and retains ownership of data for the duration of its life cycle. The Data Owner also specifies what requirements are to be met for any user to have access by indicating what attributes they should possess though the policy used for data encryption.

   (ii) Data User (DU) - The DU represents entities that require access to stored data. They are required to possess the right attributes in order to gain access to stored data on the cloud.

(2) Certificate Authority (CA) - The CA plays the central role of assisting with the verification of the identity of the different entities to enable them to securely communicate with one another. It does this by providing the corresponding certificates and public parameters used in the verification process.

(3) Attribute Authority (AA) - The AA is responsible for providing the appropriate public and private key parameters for the different attributes under their

control to the appropriate owners and users for the encryption and decryption of data.

(4) Cloud Service Provider (CSP) - This entity provides the necessary storage facilities for data on the platform and also the processing capabilities for part of the operation related to the decryption of data.
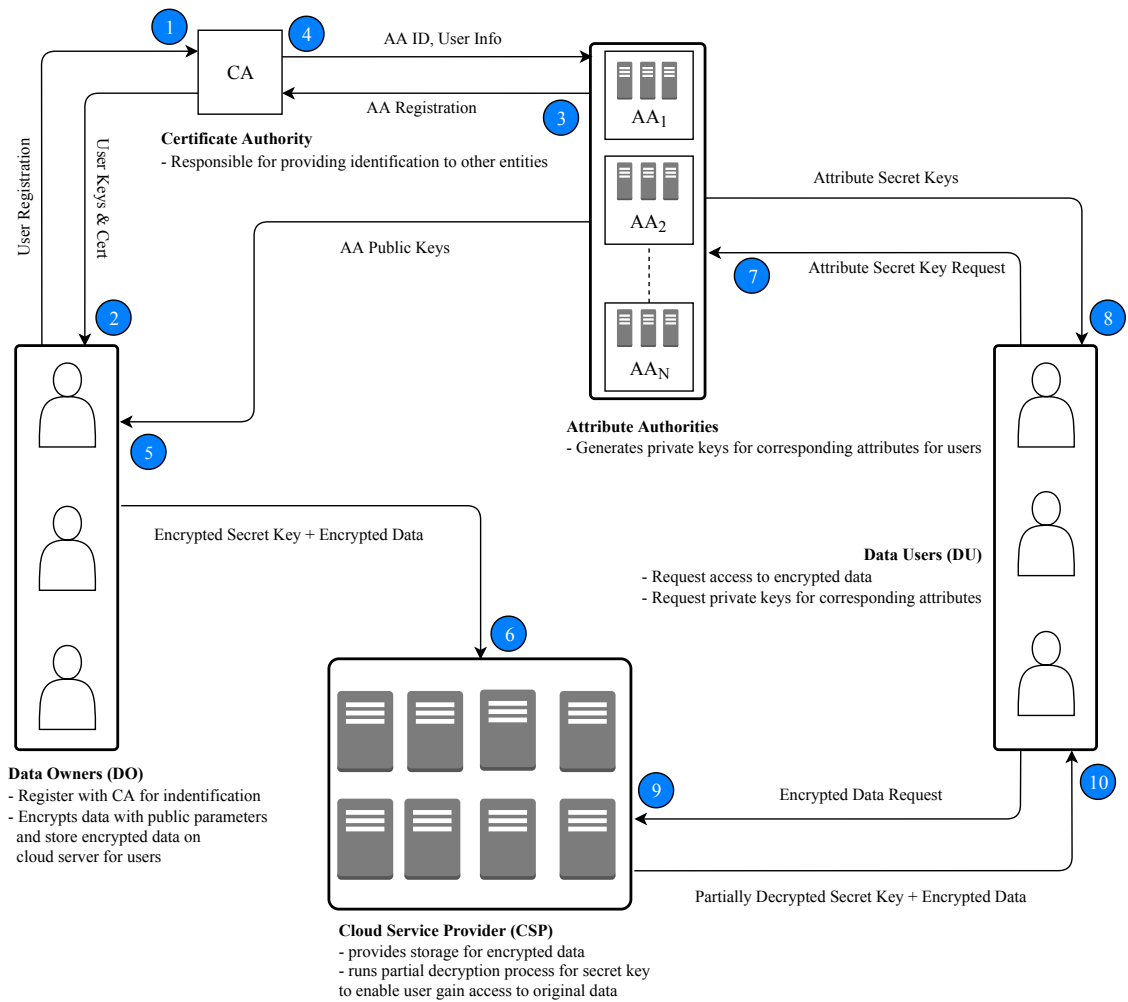

FIGURE 3.1: System architecture diagram showing interaction be-
tween the multiple framework entities with numbers indicating the
typical order of the interactions

System Architecture

Figure 3.1 shows the complete architecture of the entire system framework, indicating the various entities and the different ways in which they interact with each other as part of the overall system. The numbers indicate a typical flow of the different interactions between the entities in the system.

- Step 1 - Data owner owner registers with the CA to get their public-secret key pair, a certificate, and an ID. The public key would be used for the transformation of the ciphertext later through the CSP and the secret key will be used by the user to complete the decryption process on the user end.

- Step 2 - The CA sends the corresponding data to the user in response.

- Step 3 - The Attribute Authorities register with the CA and get an ID and corresponding user information which includes another public-secret key pair and a verification key for the user certificated generated by the CA.

- Step 4 - The CA sends the corresponding data to the AA in response.

- Step 5 - After setting up, the AA makes available to the data owners in the system, its public keys and the public key for the attributes to be used for encryption.

- Step 6 - The Data Owner encrypts the actual data using symmetric encryption and using ABE, encrypts the corresponding symmetric key. Both the encrypted data and encrypted symmetric key are uploaded to the cloud.

- Step 7 - Potential Data users request for the secret key of the attributes that they have been approved for.

- Step 8 - The AA send the corresponding secret keys generated for the users.

- Step 9 - Users request access to data from the CSP and provides the corresponding information which includes, their attribute secret keys and the public key they received from the CA.

- Step 10 - The CSP partially decrypts the symmetric key and send this to the user together with the encrypted data. The user then completes the decryption of the symmetric key using the secret key received from the CA and then using the symmetric key, decrypts the data.

3.3.2 Use Cases

In a real world scenario, hospitals and other medical institutions would play either the role of data owner or data user depending on where the data is collected and where the data is to be used. Hospital A would be an owner for data generated at its location for its patient and Hospital A would be a user when it requires access to data generated at a different hospital which it needs for a range of reasons from treatment to research.

The Attribute Authorities (AAs) in the real world would range from the administrations at different levels in the different hospitals that are part of the framework, the Research Ethic Boards, the administrations at different levels in potential research partners like academic institutions (i.e Universities), etc.

The CSP could be any of the real world cloud service providers such as the AWS cloud, Google cloud to name a few while the CA could be provincial or federal authorities responsible for oversight and regulations related to health care and privacy.

The following figures and tables show different use case scenarios which capture multiple use cases within the framework and the accompanying tables show a more detailed of the use cases captures within the use case scenario diagrams.
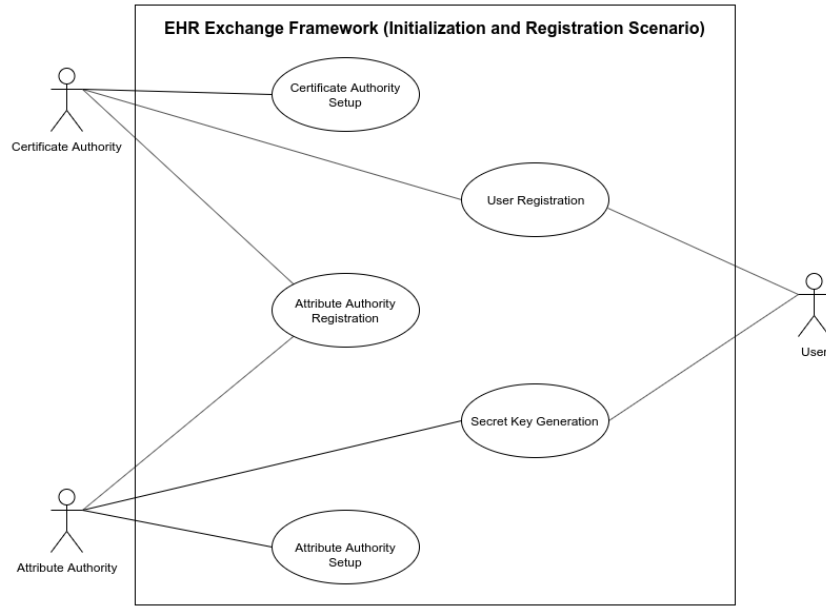
FIGURE 3.2: Use-case diagram for EHR Exchange Framework (Initialization and Registration Scenario)

Use-Case	Certificate Authority Setup
Actors	Certificate Authority (CA)
Description	This use-case occurs when the CA initializes the framework. The CA generates the Global Master Key (GMK) and Global Public Parameters (GPP) for the entire framework which would be used for other processes within the framework.
Stimulus	Certificate Authority runs CASetup algorithm to initialize system
Response	Initialize system and derive GPP and GMK.

TABLE 3.1: Certificate Authority Setup Use-Case Description.

Use-Case	User Registration
Actors	Certificate Authority, User (Data Owner & User)
Description	This use-case occurs when a user requests to be added to the system. The CA verifies their identity and then creates an entry for the new user which includes their unique id and their public parameters.
Stimulus	CA runs UserReg algorithm to register a new user.
Response	New user registered with their public information stored. The user receives a public and secret key, a certificate and the GPP for the framework.

TABLE 3.2: User Registration Use-Case Description.

Use-Case	Attribute Authority Registration
Actors	Certificate Authority (CA), Attribute Authority (AA)
Description	This use-case occurs when an AA requests to be added to the system. The CA verifies their identity and then creates an entry for the new authority which includes their unique id.
Stimulus	CA runs the AAReg algorithm.
Response	New AA registered and the AA receives the public information of all registered users in the system and the verification keys for the generated user certificates. This triggers the Attribute Authority Setup use-case.

TABLE 3.3: Attribute Authority Registration Use-Case Description.

Use-Case	Attribute Authority Setup
Actors	Attribute Authority (AA)
Description	This use-case occurs when a new AA is being initialized. The AA generates its public and secret keys together with the public keys for every attribute under its control.
Stimulus	Attribute Authority runs AASetup algorithm.
Response	AA initialized with its public and private keys together with the public keys for its attributes.

TABLE 3.4: Attribute Authority Setup Use-Case Description.

Use-Case	Secret Key Generation
Actors	User (Data Owner & User), Attribute Authority (AA)
Description	This use case occurs when a user requests a secret key from an AA in the system. The AA verifies the user identity and provides the user with the appropriate secret keys for that authority and the attributes the user has been assigned.
Stimulus	User secret key request.
Response	If the user identity is verified using the available verification key for their certificate, they are provided with unique secret keys from the AA for the corresponding attributes.

TABLE 3.5: Secret Key Generation Use-Case Description.
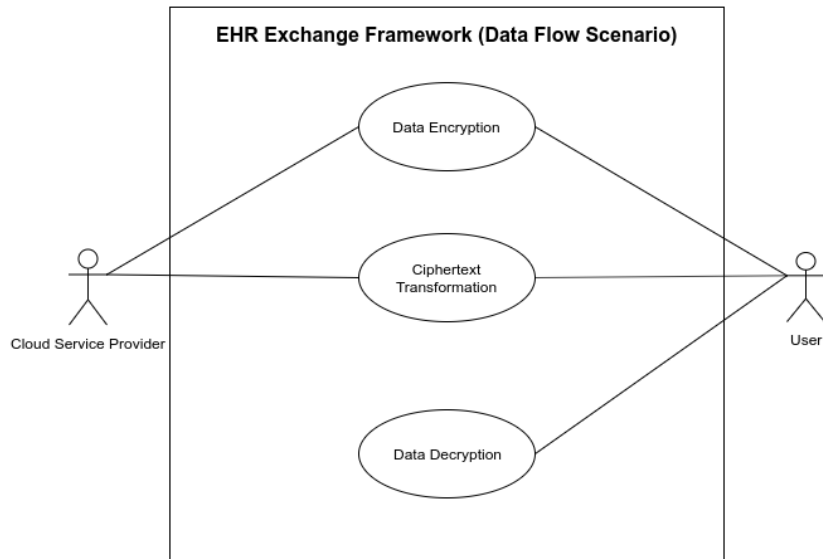
FIGURE 3.3: Use-case diagram for EHR Exchange Framework (Data Flow Scenario)

Use-Case	Data Encryption
Actors	User (Data Owner), Cloud Service Provider (CSP)
Description	This use case occurs when a data owner (also a user) wants to add data to the the framework. The encrypt the data using a symmetric key and then encrypt the symmetric key using the appropriate access policy as part of the underlying ABE scheme. Encrypted data is stored on the cloud.
Stimulus	User data storage.
Response	Encrypted data is stored on the cloud.

TABLE 3.6: Data Encryption Use-Case Description.

Use-Case	Ciphertext Transformation
Actors	User (Data User), Cloud Service Provider (CSP)
Description	This use case occurs when a user is requesting data from the cloud. The user provides the appropriate information and if they are valid, the CSP transforms the stored ciphertext into an El-Gamal style ciphertext
Stimulus	User data request from CSP
Response	CTransform algorithm is run and if the provided information is valid, a partially decrypted ciphertext is returned to the user.

TABLE 3.7: Ciphertext Transformation Use-Case Description.

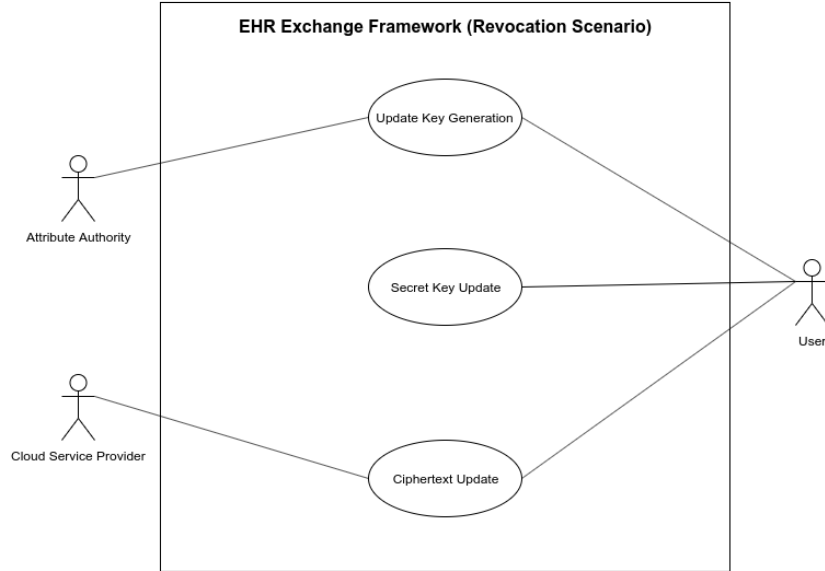| Use-Case	Data Decryption
Actors	User (Data User)
Description	This use case occurs when the user decrypts the partially decrypted ciphertext in order to access the symmetric encryption key which is then used to decrypt the symmetrically encrypted data.
Stimulus	User receives partially decrypted ciphertext.
Response	If successful, user gains access to symmetric key which also grants them access to the original data in plain form.

TABLE 3.8: Data Decryption Use-Case Description.

FIGURE 3.4: Use-case diagram for EHR Exchange Framework (Revocation Scenario)

Use-Case	Update Key Generation
Actors	Attribute Authority (AA), User (Data Owner & User)
Description	This use case occurs when an existing user is being revoked based on attributes they have secret keys for. The AA that has control of the attribute generates an update key pair. One to be used by users who share that attribute and still have valid access. The other to be used by the data owner via the CSP to update the affected ciphertexts.
Stimulus	The user who owns the corresponding data puts in a request with the appropriate AA who runs the UKGen algorithm.
Response	If successful, provided update keys for the secret keys and ciphertexts to the appropriate users.

TABLE 3.9: Update Key Generation Use-Case Description.

Use-Case	Secret Key Update
Actors	User (Data Owner & User)
Description	This use case occurs when still valid users need to update their keys to retain access to ciphertext encrypted with attributes for which an existing user has been revoked. The user uses the update key it has received from the Attribute Authority.
Stimulus	Existing user is revoked and a still valid user updates their secret key for the corresponding attribute.
Response	User's secret keys matching the affected attribute is updated.

TABLE 3.10: Secret Key Update Use-Case Description.

Use-Case	Ciphertext Update
Actors	Cloud Service Provider (CSP), User (Data Owner)
Description	This use case occurs when a data owner requests to update the current ciphertexts that are part of the system after an existing user has had their secret keys revoked. The corresponding ciphertext is updated by the CSP using the provided update key.
Stimulus	User (Data Owner) puts in a ciphertext update request.
Response	Ciphertext is updated to prevent further access by the revoked user.

TABLE 3.11: Ciphertext Update Use-Case Description.

Chapter 4

Evaluation and Results

This chapter highlights the information about the software and hardware specifications involved in the implementation of the underlying framework. It also shows the results of performance tests for the underlying ABE scheme in relation to scalability of computational overhead with regards to the number of attribute authorities and attributes involved in the system for data encryption, data decryption, and user revocation.

4.1 Experimental Setup

We evaluated the performance of our system framework by implementing the underlying ABE scheme in an environment using hardware and software tools as described below. We have focused on the performance of the underlying ABE scheme as there have been well established performance metrics for the multiple available types of symmetric encryption that could be used for the encryption of the actual data, with the ABE scheme used for the encryption of the symmetric key.

4.1.1 Hardware and Software Tools

The following hardware and software tools were used in setting up and running our experiments.

- Linux Server - We used a Linux Server running Ubuntu 18.04.3 LTS with 12GB RAM size and an Intel Core i5-6400 CPU @ 2.70GHz x 4 processor.

- Python - We wrote our underlying code using Python 3.7 as this gave us access to some other effective libraries that played a role in the robustness of our code and evaluation during our experiments.

- Charm Crypto Library[1] - We used the charm-crypto library for the implementation of the ABE components of our framework. Charm is a library implemented in python that has multiple contributors in the cryptographic field and as a result gives access to a robust tool set that provides functionalities related to pairing based public key encryption schemes such as ABE. Our scheme was implemented using 'SS512', a super-singular elliptic curve with a 512-bit base field with groups of prime order.

4.1.2 Framework Development

Using the tools and schemes provided by the charm crypto library, we have developed our framework locally using python and set it up to run on the Linux server. We have developed the different algorithms that are part of the framework into different modules in order to evaluate the performance of those algorithms that would typically reside on the user end in a real world deployment scenario of our framework architecture. We have done this to enable us to measure the performance of our system without incurring the additional cost of purchasing resources using any of the available real world cloud service vendors.

We have setup a different module for our experimental demo in order to scale the number of attribute authorities (AA) and attributes involved in the different algorithms (i.e encryption, decryption, and revocation). We also deployed a policy generation module to ensure that we have an access policy that includes the right number of attributes from the right number of authorities using the appropriate gate for our experiments. These modules allowed us to test the performance of our scheme in an automated form and allowed for easy modification and troubleshooting along the way.

4.2 Performance Evaluation

We evaluated the performance of our system by evaluating the computational times for data encryption and decryption together with the time taken for users to update their attribute based secret keys. We compare the performance of our framework with that of the scheme by Yang and Jia [44] as mentioned in section 2.7. The focus of our evaluation are the processes that are run at the user end as we are working under the assumption that the Cloud Service Provider (CSP) provides in theory unlimited processing power unlike what could be available on the several devices at the user end.

We encrypt and decrypt sample symmetric keys using the underlying ABE scheme. We also use access policies that exclusively have 'AND' gates to push the limits of the maximum number of attributes that can be part of the access policy or user keys with respect to the number of Attribute Authorities (AA) involved. We have setup our experiments for each authority to have ten attributes each as part of the access policy and user attributes for encryption and decryption. This would mean that if ten authorities are involved in particular text, then the result also indicated the performance of the scheme for a hundred attributes. Our experiments have been run for 500 trials with the results being an average of the individual runs. We settled on 500 trials after numerous trial numbers ranging from 10 to 1000 and finding no significant impact on results in the number of trials above five hundred (i.e 750 and 1000).

Our results for encryption as indicated in figure 4.1 show that our encryption system is identical in performance with the encryption algorithm of the adapted scheme for this framework [44]. Encryption requires mostly exponential operations and the amount of time scales linearly with an increase in the number of AAs and attributes that are contained in the access policy under which the file is being encrypted. Our results for encryption show no negative impact on the performance in comparison to the adapted scheme.

Our results for decryption show a constant decryption time irrespective of the number of attribute authorities or attributes in comparison with the increase in decryption time of the adapted scheme [44]. This can be seen in figure 4.2. These results indicate that the amount of time for decryption involving a single attribute
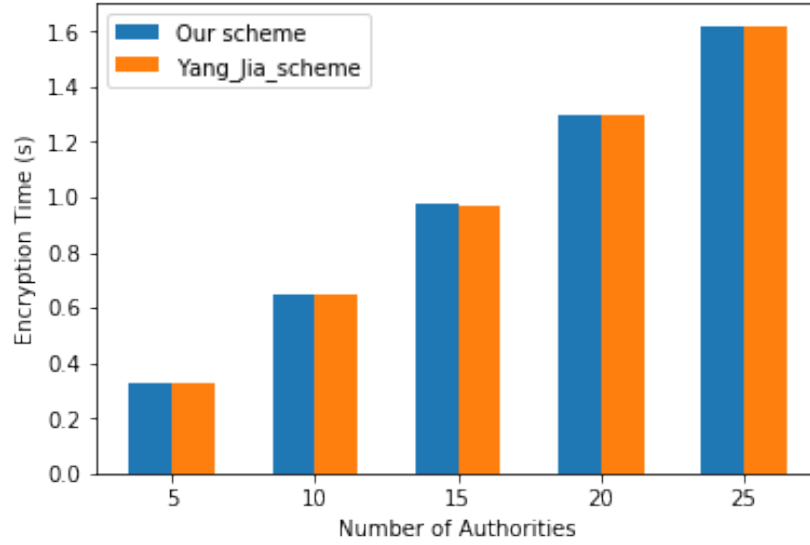
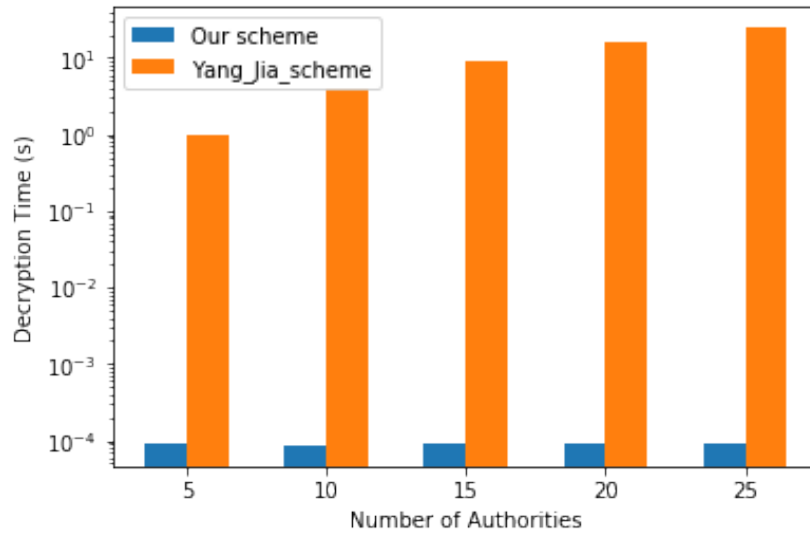FIGURE 4.1: Encryption Computation Time
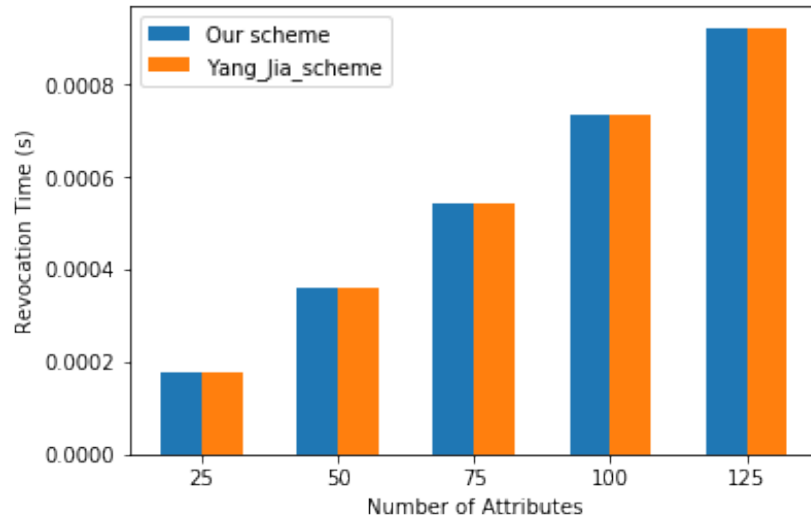

FIGURE 4.2: Decryption Computation Time

FIGURE 4.3: Revocation Computation Time

will be the same as that involving a hundred or more attributes, keeping the computational overhead constant and allowing for the use of low computational devices for the decryption process. This is because decryption in the framework only requires a single exponentiation operation irrespective of the number of AAs or attributes. The pairing operations which would have been part of the decryption process as used in Yang and Jia scheme [44] have been outsourced to the Cloud Service Provider (CSP).

Our setup for revocation was focused on showing how the time for revocation in terms of an existing user updating their attribute based secret keys when an existing user has been revoked scales with an increase in the number of attributes being revoked. Our results show that the time scales linearly with an increase in the number of attributes being revoked. This is as a result of the exponentiation operations that are involved in the update process. The result of our experiment can be seen in figure 4.3. Our results for revocation show no negative impact on the performance in comparison to the adapted scheme. For revocation we show how the time scales with just the attributes as those are the components of the user secret key that are updated when an existing user has their access revoked.

4.3   Security Analysis

In this section we analyze the different security and privacy properties of the framework. We describe how the framework is able to achieve the conditions necessary for confidentiality, integrity, and authentication including how it is able to preserve privacy through its processes. We have shown the security definition of our underlying ABE scheme in section 3.2.1, highlighting the correctness of the scheme when it comes to the encryption, decryption, and revocation processes. We also highlight the security model of the underlying scheme is based on the model of the scheme we adapted and the detailed security proof can be found in [44].

Confidentiality and Integrity

Our framework meets the condition for confidentiality and integrity as described in subsection 2.1.1. The framework is able to ensure confidentiality by ensuring that users are only able to gain access to data that their access levels allow. Users are only able to decrypt data for which they have the required attributes that match the accompanying access structure. Also due to the randomness inserted in the generation of user secret key for attributes, multiple users are unable to combine their secret keys for individual attributes to gain access to data under a policy that they are individually unable to access. The integrity of data is ensured as users are only able to access data that they have been authorized for as there is a record of the different users who have been granted secret keys for attributes that match the policy.

The ability to revoke user access also enables the maintenance of the integrity of the system. Also the certificates generated by the Certificate Authority ensures that only valid users are able to request secret keys from the Attribute Authorities in the system. Also no single AA is able to grant itself access to data within the framework and the CA only plays the role of identity validation and does not have access to a universal key that grants it access to the stored encrypted data. Also the Cloud Service Provider (CSP) never has access to data in its plain form ensuring that confidentiality and integrity are maintained.

Authentication

Our framework has authentication built into its cryptographic processes. The fact that users need access to certain attributes which they need to request from specific authorities is in its own way a form of access control. This ensures that not only do unauthorized users not gain any level of access to the system, the authorized users are only able to gain access to data that they have been authorized for, preventing them from being able to access data for which they do not have any permissions. The access policy acts as the rules while the attributes could be seen as the permissions that grant users access if they fit.

Privacy Preserving

The standard requirements for privacy as described in subsection 2.1.2 are met by our framework. Privacy is preserved by the fact that data owners are able to have some control over the level of access to data by specifying the appropriate access policy when encrypting data before it is stored on the cloud. Also the ability of the system to revoke access also ensures that user access can have a time limit depending on the pre-set rules before they are granted access. Also the strong underlying confidentiality, integrity and authentication mechanisms aid in ensuring data privacy.

Users in the system are unable to combine their secret keys gotten from the appropriate authorities in order to gain increased access to data within the system. This is because of the randomness involved in the secret key generation by the attribute authorities when generating the keys of individual users which makes ABE collusion resistant as describes in section 2.5. Users are also not able to derive the value of this random number due to the discrete log hardness problem in cryptography.

Chapter 5

Conclusion and Future Work

5.1   Overview

This chapter provides a description of the contribution of this thesis and also provides recommendation for future developments that could be implemented in extending the functionalities of the framework.

5.2   Conclusion

The challenge of this thesis was to develop a system that would allow for the secure exchange of EHRs among multiple parties through the use of potentially untrusted third party services, such as cloud computing. The solution to this challenge would need to be able to provide adequate security and privacy as a result of the sensitive nature health data. It would also be important for the solution to be able to provide effective access control at a granular level.

To create this solution, we have developed a framework for the sharing of electronic health data. We have placed the core of this framework an effective ABE schemes, a Multi-Authority Ciphertext Policy Attribute Based Encryption with Outsourcing (MACP-ABEwO) scheme. We have developed our scheme by using existing techniques to modify an effective multi-authority scheme [44]. Our scheme allows for the secure outsourcing of decryption to the Cloud Service Provider (CSP), significantly reducing the computational resources of the end user devices required for accessing data. This is achieved by offloading the more computationally intensive operations of the decryption process to the CSP. This also allows for a

significant reduction in the amount of time for decryption as the framework takes advantage of the resources provided by the CSP in terms of computational power.

Our framework allows for the secure exchange of health data not simply among medical institutions, but also with third party partners, such as researchers, who contribute to developments in the area while preserving privacy. Our framework uses symmetric encryption for the security of data and uses our proposed MACP-ABEwO scheme for the encryption of secret keys users need to access data in its original form.

We have developed our framework using existing tools in order to evaluate the performance of our underlying scheme. We have built the different modules and run them locally on a Linux server in order to save costs and evaluated the performance of the algorithms that would typically run on the end user device. We have evaluated the performance for encryption, decryption and revocation and shown how they scale with an increase in the number of Attribute Authorities and attributes. Our results show no negative impact on the encryption and revocation time of the original scheme in comparison with out but shows a significant decrease in the decryption time. This is because, as a result of outsourcing, the decryption time remains constant irrespective of the number of attribute authorities or attributes involved. We also evaluate the security of our scheme and show how it is able to ensure confidentiality, integrity, and authentication, while also preserving privacy.

5.3 Future Work

There are different areas of improvement in relation to our existing framework as described below:

(1) Accountability - Our current framework is limited in its ability to ensure strong levels of accountability as it can only be limited to the group of users who have been granted secret keys for the corresponding attributes which they share with others with the same level of access. A possible future development would be to extend our underlying ABE scheme potentially using

similar pairing based short signatures that are being developed with minimal overhead on our framework.

(2) Searchable Encryption - Our current setup requires some sort of record in the database to keep track of what type of data are being stored in their encrypted form. Potential future developments would include the extension of our underlying scheme to allow for searching at a more granular level over the encrypted data.

In conclusion, our secure privacy preserving cloud based framework for sharing electronic health data is a platform that allows for the sharing of electronic health records. Taking into accounts the challenges that exist with the use of third party storage services and the sensitive nature of the data being shared, our framework provides potential solutions to the existing limits in the functionality of current systems. Our framework is able to do this through the use of an effective Multi-Authority Ciphertext Policy Attribute Based Encryption with Outsourcing (MACP-ABEwO) scheme to provide adequate levels of security, preserve privacy and allows for effective access control at a granular level.

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