A ROLE AND ATTRIBUTE BASED ENCRYPTION APPROACH TO PRIVACY AND SECURITY IN CLOUD BASED HEALTH SERVICES

by
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This thesis has been prepared
under my supervision
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with the Master's regulations.

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Signature of Supervisor

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Date

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Publications Arising From this Thesis

The research presented in this thesis has been published in part in the following papers to date:

Sabah Mohammed, Daniel Servos, and Jinan Fiaidhi (2010). HCX: A Distributed OSGi Based Web Interaction System for Sharing Health Records in the Cloud. In Proceedings of the 2010 IEEE/WIC/ACM International Conference on Web Intelligence and Intelligent Agent Technology - Volume 03, 102-107. (Chapter 2)

Sabah Mohammed, Daniel Servos, and Jinan Fiaidhi (2011). Developing a Secure Distributed OSGi Cloud Computing Infrastructure for Sharing Health Records. Autonomous and Intelligent Systems, Lecture Notes in Computer Science Volume: 6752, 241-252. (Chapter 2 and 3.2)

Future publications are planned for the contents of chapter 4 and possibly 3.1.

Abstract

Cloud computing is a rapidly emerging computing paradigm which replaces static and expensive data centers, network and software infrastructure with dynamically scalable “cloud based” services offered by third party providers on an on-demand basis. However, with the potential for seemingly limitless scalability and reduced infrastructure costs comes new issues regarding security and privacy as processing and storage tasks are delegated to potentially untrustworthy cloud providers. For the eHealth industry this loss of control makes adopting the cloud problematic when compliance with privacy laws (such HIPAA, PIPEDA and PHIPA) is required and limits third party access to patient records.

This thesis presents a RBAC enabled solution to cloud privacy and security issues resulting from this loss of control to a potentially untrustworthy third party cloud provider, which remains both scalable and distributed. This is accomplished through four major components presented, implemented and evaluated within this thesis; the DOSGi based Health Cloud eXchange (HCX) architecture for managing and exchanging EHRs between authorized users, the Role Based Access Control as a Service (RBACaaS) model and web service providing RBAC policy enforcement and services to cloud applications, the Role Based Single Sign On (RBSSO) protocol, and the Distributed Multi-Authority Ciphertext-Policy Shared Attribute-Based Encryption (DMACPSABE) scheme for limiting access to sensitive records dependent on attributes (or roles) assigned to users. We show that when these components are combined the resulting system is both scalable (scaling at least linearly with users, request, records and attributes), secure and provides a level of protection from the cloud provider which preserves the privacy of user’s records from any third party. Additionally, potential use cases are presented for each component as well as the overall system.

Chapter 1

1 Introduction

The increasingly popular cloud computing paradigm brings new opportunities to reduce hardware, maintenance and network costs associated with the traditional infrastructure required to offer large scale internet based services or even smaller localized application and storage solutions. However, with the dynamic scalability, reduced risk and potential cost savings comes a loss of control that creates new challenges for adopting cloud based infrastructure. For the health care industry, the need for cost efficient and low maintenance Electronic Health Record (EHR) systems is clear (Urowitz, et al., 2008). However, data privacy, security and compliance with local and global privacy laws are significant barriers blocking adoption of public cloud offerings.

This thesis presents work towards a potential solution to the problem of cloud privacy and security in public, private, and hybrid cloud environments including protection for transmission and storage of documents in situations where access to online services may be limited or impossible. Additionally, methods for adapting Distributed OSGi (DOSGi) for cloud based environments are detailed and a DOSGi framework for sharing health records is presented.

1.1 Background Information

Subject areas including cloud computing, role based access control, and identity and attribute based cryptology are covered in this thesis. The following sub-sections give

a brief overview and background in each area as well as a description of the DOSGi platform used in chapter 2.

1.1.1 Cloud Computing

Due to the increased popularity in using "cloud computing" as a buzzword for any web based application or service, a single unified definition of "cloud computing" has become increasingly hard to arrive at. Multiple differing definitions have been used in both scientific and business literature (Geelan, 2008) to describe both the applications delivered through the cloud as well as the hardware and systems that comprise it. However, some work has been done to come to a standardized definition, such as the editorial note by LM. Vaquero, et al (2008). which presented the following proposed definition:

> *"Clouds are a large pool of easily usable and accessible virtualized resources (such as hardware, development platforms and/or services). These resources can be dynamically reconfigured to adjust to a variable load (scale), allowing also for an optimum resource utilization. This pool of resources is typically exploited by a pay-per-use model in which guarantees are offered by the Infrastructure Provider by means of customized SLAs."* (Vaquero & al., 2008)

For the purposes of this thesis the definition of Cloud Computing offered by R. Buyya, et al. (2008) will be used where Cloud Computing is concerned:

> *"...a type of parallel and distributed system consisting of a collection of interconnected and virtualised computers that are dynamically provisioned and presented as one or more unified computing resources based on service-level agreements established through negotiation between the service provider and consumers"* (Buyya, Yeo, & Venugopal, 2008)

A large driving force in the adoption of Cloud Computing is the increased interest

by businesses in utility computing over owning and operating their own data centres and computer resources. In the utility computing model, Software, Platform and Infrastructure are sold in a similar way as traditional utilities such as power, water, and gas. Businesses are charged based on the amount of resources used and the length of time they are utilized. An example would be Amazon's EC2 service (http://aws.amazon.com/), where businesses are charged based on the amount of time an instance (a virtual machine) is active as well as the amount of resources used (e.g. the amount of RAM, number of CPUs, etc. being used by an active instance). When such services are sold to the public, the cloud is deemed to be a "public cloud". Offering public cloud services allows companies such as Amazon and Google who have vast computing and network resources for their core business functions, to leverage their existing infrastructure (which may be largely underutilized at off peak times) to businesses and organizations that have a limited or nonexistent infrastructure. Alternatively, organizations may operate their own "private cloud" for internal use or a hybrid system involving both public and private components.

For the healthcare industry, cloud computing offers the potential to enable patients, physicians, healthcare workers and administrators immediate access to a wide range of healthcare resources, applications and tools. For hospitals, physician practices and emergency medical service providers, the lowered initial investment and the elimination of data center, hardware, and related IT costs offered by cloud computing can help overcome the financial barriers blocking the wide adoption of EHR systems (Urowitz, et al., 2008) and provide the infrastructure needed to make patient accessible records possible in a secure manner.

In general, cloud computing can be subdivided into three main layers; Application, Platform, and Infrastructure. The Application layer consists of cloud based applications that provide direct services to end users, commonly over a web browser interface (e.g. Google Health (http://www.google.com/health/)). The Platform layer provides frameworks and/or services that enable developers to easily create cloud applications (e.g. Google's app Engine (http://code.google.com/appengine/), OSGi (http://www.osgi.org), Windows Azure (http://www.windowsazure.com)) and finally the Infrastructure layer provides the hardware and software resources that power the actual virtualization and serving of cloud resources (e.g. Eucalyptus (http://www.eucalyptus.com/), and NIMBUS (http://www.nimbusproject.org/)). When provided as a service, these layers are often referred to as SaaS (Software as a Service), PaaS (Platform as a Service) and IaaS (Infrastructure as a Service) respectively. Figure 1.1 illustrates the main layers of any cloud computing system.

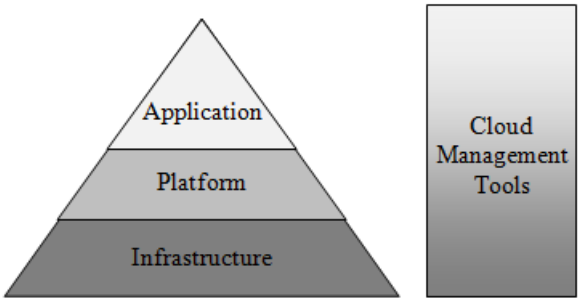


Figure 1.1: Cloud computing layers.

1.1.2 Distributed OSGi

OSGi is a dynamic service-oriented module platform for Java, maintained and created by the OSGi Alliance which allows service modules to be created and registered

with a central service registry, enabling consumer modules to find and use registered services. This allows for the development of very modular and reusable systems where service modules provide and register an interface that consumer modules may plug into to use the resources and functionality associated with the service. Having parts of a system encapsulated in their own modules provides the means for increased reusability as new systems may simply plug into the existing services to use and extend their functionality. OSGi also allows for these services to be remotely installed, uninstalled, started, stopped and updated without the need to restart or make manual changes to a given system. Consumer modules are able to detect changes in services (additions, removals, etc.) and respond accordingly.

On its own, OSGi only provides the services and registry to consumer modules running on the same machine, which is inadequate for use in the cloud or distributed systems. To resolve this, a specification for OSGi remote services and discovery was added to the OSGi 4.2 Compendium Specification (Chapter 13)(http://www.osgi.org/Release4/Download/) and implemented by the Apache CXF Distributed OSGi (DOSGi) subproject (http://cxf.apache.org/distributed-osgi.html). Apache's DOSGi enables remote OGSi services through the use of web services (SOAP over HTTP) and discovery using Apache Hadoop's Zookeeper (https://zookeeper.apache.org/). This allows for OSGi services to be shared in the distributed environments and for consumers to dynamically discover and use services as they become available (or stop using them as they are lost).

For cloud computing, DOSGi provides a platform on which to build cloud

services and consumers which dynamically adapt to changes in the cloud (e.g. new instances coming or going offline) and allows for simple deployment of OSGi bundles to newly executed instances that lack persistent storage (as is common for most cloud based virtual machines). For these reasons the HCX system described in Chapter 2 makes heavy use of the DOSGi platform for connecting HCX services with HCX consumers and providing a scalable architecture by balancing requests between DOSGi based HCX services.

1.1.3 Role Based Access Control

Role based access control (RBAC) offers a more flexible and policy neutral alternative to discretionary access control (DAC) and mandatory access control (MAC) that focuses on assigning users to roles rather than directly to permissions on operations or data objects. That is, rather than granting a user the right to read, write, execute, etc. a data object, RBAC grants a role the right to perform an operation such as add the results of an operation to a patient's health record, update their contact information or view their insurance information (see Figure 1.2). In the RBAC model, permissions are associated with high level roles found in an organization and users are assigned to one or more roles relating to their responsibilities within the organization. Roles remove the need to directly map users to low level objects and allow for easy permission management through the creation of roles granting only the necessary access to organization operations that a user may be required to perform. For example an EHR information system may have a role for patients which grants them permissions to view their own health records, as well as a role

for doctors and health care professionals that grant them the ability to view and update records for the patients under their care. This would be in direct contrast to the access control list (ACL) model of access control which would have a user or group assigned access rights to each individual data object (in this example a health record) rather than enforcing a more abstract access control policy such as “patients can access an operation to view their own health record” or “doctors can access an operation to view their patients’ health records and an operation to update their patients’ health records”.

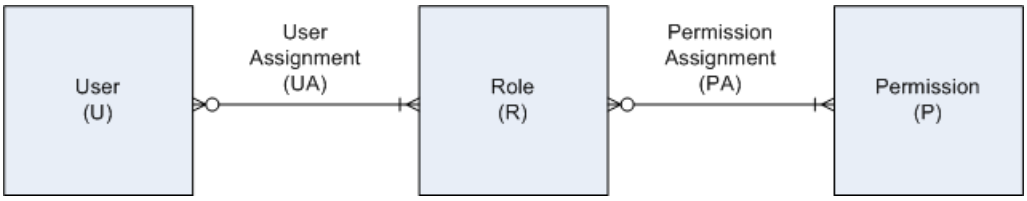


Figure 1.2: Basic RBAC model.

The RBAC model greatly simplifies the management of user permissions on large systems and ensures that administrators can enforce the security principles of least privilege and separation of duty/privilege (Saltzer & Schroeder, 1975) as they have a very clear idea of the level of access a given user has by the roles they have been assigned. RBAC also simplifies the problem of ensuring that users are given correct access rights to a system. As users are assigned roles which map to permissions that in turn map to abstract operations on an information system, an administrator would only need to check that a user has been assigned the correct roles to ensure they have the correct access rights (assuming the roles and permissions were created correctly). Similarly, changing the level of access a role is given to match changes in organizational

policy or structure is trivial in RBAC as only the role-permission assignment would need to be altered to affect the access rights of every user assigned to the role.

1.1.4 Identity and Attribute Based Cryptography

Identity based cryptography is a category of public key crypto systems where the public key for a corresponding private key may be any publicly known string. This allows for greatly simplified public key distribution as a user's public key may be an existing string associated with the user such as an e-mail address, physical address, or host name. Most ID-based encryption schemes, such as that of Boneth and Fraklin (2001), require a centralized trusted authority to act as a private key generator which distributes private keys to users of the system. A more detailed and technical explanation of identity based encryption is given in subsection 4.1.3 of Chapter 4.

Attribute Based Encryption (ABE) (first introduced by Sahai and Waters (2005)) builds on the concepts of ID-based encryption and allows a cipher text to be encrypted such that only a user with a secret key containing the correct subset of attributes may decrypt the document. More recent ABE schemes such as the Key Policy ABE (Goyal, Pandey, Sahai, & Waters, 2006) and Cipher Text Policy ABE (Bethencourt, Sahai, & Waters, 2007), allow for more complex attribute based access policies to be embedded in the ciphertext or secret key. A more detailed and technical explanation of attribute based encryption is given in Chapter 4 (particularly in subsection 4.1.3, 4.2.1, 4.2.2, and 4.2.3).

For the cloud, ABE offers the potential to have documents protected with an access policy independent of the system holding them. Records encrypted with ABE are protected both on and off the cloud with the same policy as well as both on and off line.

For the health care environment, such consistent protection that extends to records both on and off line is critical when health services must be provided when access to EHR systems may be unavailable (e.g. during a disaster which compromises online EHR services) or in environments were a stable connection is not possible (e.g. remote areas).

1.2 The Cloud Problem

While cloud computing may offer potential cost savings and dynamically scalable infrastructure, it also brings with it new security and privacy issues that need to be addressed:

- **Confidentiality:** Protecting cloud based storage and network transmissions from possible unwanted access by cloud providers or data leakage to other cloud users.
- **Auditability:** Maintaining logs of users' actions with the system and ensuring that no part of the system has been tampered with or compromised.
- **Security:** Preventing user credentials, which may be used for multiple services on and off the cloud, from being obtained by untrusted parties including the cloud provider or other cloud users.
- **Legal:** Complying with data privacy laws that may be in effect in given geographical regions (eg. PIPEDA, HIPA, HIPAA, etc.).

Zhang, et al. list data security among one of the top open research problems in cloud computing (Zhang, Cheng, & Boutaba, 2010) while Armbrust, et al. list data

confidentially and auditability among the top 10 obstacles for cloud computing (Armbrust, et al., 2009) and for good reason; when utilizing a cloud based platform, potentially sensitive information must be transmitted to, and stored on, a cloud provider's infrastructure. It is left to the cloud provider to properly secure their hardware infrastructure and isolate customer's processing and storage tasks. This transfer of trust may be acceptable in most cloud use cases. However, in industries like healthcare that must comply with data privacy laws such as PIPEDA, HIPA and HIPAA, allowing sensitive information to be processed or stored on a public cloud directly may not be feasible.

While many solutions for these issues exist for traditional systems, public cloud infrastructure removes control of the physical infrastructure that makes it possible to ensure a cloud provider properly secures their services and is not performing any potentially malicious activities. It may seem unlikely that large public cloud operators would intentionally violate their user's privacy, but external factors in some regions (such as legal pressure from local governments, e.g. USA PATRIOT Act) may force disclosure of sensitive information. Hardware based solutions, such as Trusted Platform Module (TPM), that would normally provide protection for a remote system, are difficult to implement in cloud environments due to instances being created on a number of physical servers that share the same hardware and lack of support from major cloud providers. Additionally, cloud computing has several challenges related to taking full advantage of the scalability gained from cloud infrastructure that limit potential solutions including:

- **Bottlenecks**: The cloud may provide seemingly limitless scalability for virtual server resources and storage, but any connections to systems outside of the cloud or lacking the same scalability quickly become a new bottleneck for the system. For example, if multiple machine instances are spawned to meet an increase in demand but all connect to the same database or authentication backend provided by the same server, a bottleneck will be formed that will limit the scalability of the whole system.
- **Distributed Design**: While cloud computing is distinct from traditional distributed computing, many of the same concepts apply and must be considered in the design of a cloud application or platform. Cloud applications must be built to offer their services from multiple machine instances distributed in the same cloud rather than a traditional single server to client architecture.
- **Volatile Storage**: Most cloud infrastructure solutions (such as Amazon's EC2) do not provide persistent storage by default to their machine instances. Applications built upon such infrastructures need to take into account this static nature in their design and use additional services or solutions (such as Amazon's S3 or EBS) for permanent storage.
- **Dynamic IPs**: In most cases when cloud instances are launched, a public IP address is dynamically assigned. While this may be selected from a list of static IP addresses, autonomous cloud systems are often used which automatically create and destroy instances, each obtaining an unused address when initialized. This can create issues for traditional systems that expect static or unchanging addresses for servers.

There are still many legal questions regarding how cloud computing fits into, and may comply with, the privacy laws present in most developed countries. Complicating matters is the global nature of the cloud, a cloud provider may offer data centers in multiple jurisdictions, while customers may be from another. In the European Union, processing and security of personal data is mainly regulated by Directive 95/46/EC, which outlines responsibilities of member states, data controllers (the one who determines the means and processes of processing personal data) and data processors (the one who processes personal data on behalf of the controller). In a cloud computing environment it is not always straightforward which actor falls under which role (Balboni, 2010); cloud providers may have some level of control over the method in which data is processed which would put them in more of a controller role than a pure processor role. However, "regardless of whether the CSP [(cloud provider)] is to be considered a Controller or a Processor, the customer will have to ensure that the CSP has appropriate security measures in place" (Balboni, 2010). Under Directive 95/46/EC Article 17, this requires implementing appropriate technical and organizational security measures to protect personal data against accidental loss, alteration, unauthorised disclosure or access, as well as any other form of unlawful processing. Article 17 also requires the controller to choose a processor that provides sufficient guarantees with respect to the technical, security, and organisational measures governing the processing to be carried out while ensuring compliance with those measures.

In the United States of America data privacy falls under several acts, most notably the Health Insurance Portability and Accountability Act (HIPAA) which regulates the use and disclosure of identifiable health information by principal health care providers and

health plans. HIPAA requires that a covered entity must have a business associate agreement (§§ 164.502(e), 164.504(e)) with the cloud provider and comply with the same standards that apply to the entity. "A service provider cannot use or disclose health records in a way that conflicts with the HIPAA standards. Thus, a HIPAA-covered entity could violate HIPAA by storing patient records at a cloud provider with a terms of service that allows the provider to publish any information stored on its facilities" (Gellman, 2009). Additionally, many similar acts restrict the use of personal data in other industries, including; the Gramm-Leach-Bliley Act (15 U.S.C. § 6802) which limits financial institutions from disclosing financial information to third parties, the Video Privacy Protection Act (18 U.S.C. § 2710) and Cable Communications Policy Act (47 U.S.C. § 551) that limit video rental records and cable television subscription records from disclosure to third parties, tax preparation laws (e.g. 26 U.S.C. §§ 6713, 7216; 26 C.F.R. § 301.7216) which limit online tax preparers from sharing or storing personal information (such as a social security number) with/on a foreign cloud without the taxpayer's consent, and federal agencies are prevented from disclosing personal information to third parties such as cloud providers as it would likely violate the Privacy Act of 1973 (U.S.C. § 552a) (Gellman, 2009). Furthermore, it is likely that the Electronic Communications Privacy Act of 1986 (ECPA) provides some privacy protection regulations for service providers (despite being originally drafted to give protections against wiretapping telephone communications) and is further complicated by the requirements set forth by the USA PATRIOT Act, requiring the FBI to have access to any business record (including any record maintained by a cloud provider).

In Canada, standards for the private sector's collection, use and disclosure of personal information are established by the federal Personal Information Protection and Electronic Documents Act (PIPEDA). Beyond giving individuals the right to request details on what personal information relating to them an organization may have and how it is used, the PIPEDA requires organizations to obtain consent when personal data is collected, used or disclosed to a third party. This required consent would likely cause issues when moving to the cloud unless prior consent was obtained from all parties or steps were taken to ensure the data could not be accessed or disclosed to the cloud provider. In addition to PIPEDA, four provincial privacy laws add provincial provisions to protect personal information: An Act Respecting the Protection of Personal Information in the Private Sector (Quebec), The Personal Information Protection Act (Alberta), The Personal Information Protection Act (British Columbia) and The Personal Health Information Protection Act (Ontario).

In Ontario the Personal Health Information Protection Act (PHIPA), requires that a health information custodian (hospitals, doctors offices, etc.) and their agents (including companies contracted for data storage and other IT tasks) comply with the custodian's information practices outlined in section 10(2) and "ensure that the records of personal health information that it has in its custody or under its control are retained, transferred and disposed of in a secure manner" (section 13 (1)). Additionally, information custodians are made responsible for "tak[ing] steps that are reasonable in the circumstance to ensure that personal health information in the custodian's custody or control is protected against theft, loss and unauthorized use of modification or disposal" (section 12 (1)). This would seem to imply that in a cloud environment used for health

care, the consumer (acting as the health information custodian) and not the cloud provider (acting as the custodian's agent) would be made responsible for ensuring personal health information on the cloud is properly secured and disposed of. If extra steps outside of the services offered by the cloud provider are not taken, it is likely that meeting these requirements would not be possible as the consumer has no way of ensuring true disposal of electronic records or the security of the cloud provider's data center or virtual instances.

We categorize security on cloud based infrastructure into 6 levels, ranging from totally unsecure but easy to implement and process data (level 0), to highly secure but with a more complex implementation required (level 5):

- **Level 0:** No encryption, authentication or security is used when communicating with, processing data on, or storing data on cloud based infrastructure.
- **Level 1:** User authentication of some kind is required, however, no security or encryption is required when communicating with the cloud application, storing data on cloud based storage or processing data on cloud infrastructure.
- **Level 2:** Same requirements as level 1 but a secure channel is required for communications between the cloud based application and the user (e.g. SSL).
- **Level 3:** Same requirements as level 2 but all data stored on the cloud must be securely encrypted (e.g. encrypting data on S3 with AES encryption).
- **Level 4:** Same requirements as level 3 but no unencrypted sensitive data should be handled by any part of the system exposed to the cloud provider (i.e. the cloud application/instances should not have access to the encryption keys

used to decrypt data stored on cloud based storage and no raw sensitive data should be processed by the application or cloud providers network).

- **Level 5:** Same requirements as level 4 but it should be impossible for the cloud provider to identify the user of the system beyond an IP address and anonymized user ID. (i.e. the cloud provider should be unable to determine any potentially sensitive or identity revealing information about the user of the system).

In most cases level 2 or 3 is enough to satisfy the requirements set forth by data privacy laws and protect against an eavesdropper not associated with the cloud provider. However, in cases where the cloud may not be trustworthy or could potentially become compromised, a level of 4 or higher would be required to fully protect sensitive information from an attacker with access to the cloud provider's hardware and datacenter resources. Level 5 is required to ensure both the privacy and confidentiality of the data as well as some level of anonymity for the users of the system. This may be critical for applications such as patient portals which enable patients to view and possibly modify their health records and related medical information online.

1.3 Cloud Security Approaches and Techniques

While the problem of cloud security and confidentiality in a public cloud is still largely open (Zhang, Cheng, & Boutaba, 2010), several efforts have put forth approaches and techniques to either minimize the issue (Pearson, Shen, & Mowbray, 2009) or used hardware based solutions (Itani, Kayssi, & Chehab, 2009), (Chow, et al., 2009) to regain

some level of control from cloud providers. To our knowledge, there is still no purely software based solution for providing complete confidentiality of data stored on a public cloud from a potentially untrustworthy cloud provider that remains scalable, distributed and practical in a cloud based environment. The traditional and somewhat trivial solution amounting to "throwing encryption at the problem" (commonly suggested as a potential solution (Armbrust, et al., 2009)) falls short for standard symmetric encryption methods. While sensitive data on cloud based storage may be encrypted, it may not be processed by the same provider (e.g. to serve to clients via a web based interface) without relinquishing the keys required to decrypt or access the data. Similarly, access policies enforced by cloud based systems are vulnerable to compromised or untrustworthy cloud providers as they ultimately control the hardware, network and virtualization resources.

1.3.1 Privacy as a Service: Privacy-Aware Data Storage and Processing in Cloud Computing Architectures (Itani, Kayssi, & Chehab, 2009)

1.3.1.1 Summary

Itanit, et al. (2009) presents a set of security protocols, named PaaS (Privacy as a Service), for providing privacy and security of user's data in the cloud through the use of cryptographic coprocessors. Their solution allows users to configure software and data privacy mechanisms which dictate how their data will be protected in the cloud as well as provide feedback on any potential risk that may affect the confidentiality and security of their sensitive information.

Cryptographic coprocessors (Best, 1980) (Tygar & Yee, 1994) are isolated "computer on a chip" systems dedicated to performing cryptographic operations separate

from the computer hardware/system they are installed in. Most coprocessors take the form of small PCI-based hardware cards which contain an independent and complete computing system including separate RAM, processor, networking adaptor and non-volatile storage. The key feature that makes such coprocessors different from common computing systems is a specialized tamper-resistant encasing that provides several physical security measures against physical attacks (e.g. manually extracting data from the non-volatile storage). These security measures commonly include automated "zeroization" (overwriting memory with zeros such that it cannot be recovered) of volatile and non-volatile storage, tamper-detection/reporting, and authentication of both the software and operating system before loading/booting.

Itanit, et al. (2009) suggests that a trusted (to both cloud users and providers) third party organization could configure, install, inspect, and distribute secure cryptographic coprocessors to cloud providers. This trusted third party (TTP) would configure each coprocessor such that it could be shared among multiple virtualized systems (as a single coprocessor for each virtualized machine instance would quickly become unmaintainable) and load the private/public key pairs (PU_{CID}/PR_{CID}) into the non-volatile storage of each coprocessor as well as its own private key (K_{TTP}). The TTP would then become primarily responsible for allocating each key pair to a single customer as requested and updating/replacing key pairs as necessary (this is possible through the use of the private key KTTP to authenticate as the TTP with each coprocessor).

Cloud users are made responsible for configuring their software application to support the coprocessor model by dividing their application into the logical components of protected and unprotected. Protected components are executed within the coprocessor

while unprotected components are executed in the standard virtualized environment. Protected components are encrypted with the customers credentials (based on PU_{CID}/PR_{CID}) and stored on the cloud provider's storage until executed on a coprocessor. Data is secured based on one of three classifications; No Privacy: data is not encrypted and no effort is made to protect it beyond possible transmission via SSL, Privacy with Trusted Provider: data is encrypted with a key potentially known to the cloud provider and is transmitted and stored in an encrypted state, and Privacy with Non-Trusted Provider: data is encrypted using a secret key (K_{CID}) shared only with the coprocessor (shared by authenticating with coprocessor and starting a secure session with PU_{CID}/PR_{CID}) and uploaded to standard cloud storage in the encrypted state (which may be accessed only by protected parts of the application on the coprocessor using K_{CID}).

Privacy feedback is provided through the use of a daemon executed on the same coprocessor as protected application components which keeps a detailed encrypted (with K_{CID}) audit log of all privacy-related operations (e.g. execution of application components, decryption of "Privacy with Non-Trusted Provider" data, etc.). A hash chain of the encrypted audit log (Schneier & Kelsey, 1999) (Itani, Kayssi, & Chehab, 2005) is then created by hashing the i^{th} record (HC_i) and the chain entry of the last record (HC_{i-1}), making it possible to authenticate the integrity of all previous records simply by authenticating HC_i. The audit log and chain are made available to the cloud user via a special application which polls and verifies the contents of the log periodically at set intervals.

1.3.1.2 Criticisms

While Itanit, et al. (2009) present an effective means of securing cloud applications and data using cryptographic coprocessors, they ignore the realities of current cloud offerings and assume a rather optimistic view of the financial and technical feasibility of incorporating large numbers of coprocessors in cloud infrastructure and services. The largest issue is the lack of support for any kind of tamper- proof coprocessor in the current cloud offerings. To date there are currently no cloud providers which offer cryptographic coprocessors hardware or services that the PaaS protocol requires. Additionally, there is little if any financial incentive for cloud providers to add coprocessors hardware to their existing data center infrastructure and even less incentive to give full access to their data centers to a third party for the required periodic inspection, installation and maintenance of coprocessors.

Another issue with Itanit, et al. (2009)'s PaaS is moving a large part of a cloud application's execution from scalable cloud infrastructure to limited coprocessors execution. Most modern coprocessors provide only limited processing, RAM and persistent storage resources. However, large cloud application serving sensitive information to clients (such as banking or EHR systems) will require heavy use of the coprocessor to encrypt/decrypt data and transmit/receive it to/from clients. While the PaaS system allows for a single coprocessor to be shared by multiple virtual systems, sharing may not be technically feasible if applications make anything but occasional use of protected components.

The sharing of coprocessors presents a potential point of attack against a cloud application when a malicious user is sharing the same resources. Unlike cloud processing

and storage resources which are strictly isolated, resources on a shared coprocessor would be accessible to all users on the system. While most sensitive data would be protected with each user's individual secret key (K_{CID}) and applications isolated using the ABYSS processor model (White & Comerford, 1990) a malicious user could still stage a denial-of-service type attack by having their protected applications use as much processing, network, storage and memory resources as possible to slow or even stop the execution of other protected applications sharing the same coprocessor.

Finally, the heavy use of a trusted third party by PaaS simply shifts the control from a cloud provider to the party managing and maintain the coprocessors. Since a third party would have full control over each coprocessor they would easily be able to extract the value of K_{CID} from memory and decrypt sensitive data or simply extract the data as it is being processed. It may be hard to find a party that could be realistically trusted more than a cloud provider to perform this role.

1.3.2 A Privacy Manager for Cloud Computing (Pearson, Shen, & Mowbray, 2009)

1.3.2.1 Summary

S. Pearson, et al. (2009) introduces a privacy manager for cloud computing aimed at reducing the potential risk of sensitive data being stolen or misused on the cloud. The privacy manager obfuscates sensitive data for storage on the cloud and performs de-obfuscation as needed when data is requested. This obfuscation is performed by encrypting the data with a key chosen by the cloud user which is shared with the privacy manger but not the cloud provider. The obfuscation is based on a process where for some

plain text x a cloud application may only compute $f(x)$ for some function f when given the cipher text but not the value of x itself.

This obfuscation is accomplished as follows: A key k and encryption functions o_1, .., o_m are picked (for some positive value of m) such that it is hard to determine x from the tuple $o_1(k,x)$, .. $o_m(k,x)$ without k and that there is a decryption function d such that $d(k, f_1(o_1(k,x)),\ldots, f_m(o_m(k,x))) = f(x)$ were f is the function for the desired calculation on x and f_1 to f_m are calculations done by the application. Obfuscation is accomplished by first encrypting x with each encryption function and a secret key k to produce $o_1(k,x)$, .. $o_m(k,x)$. This tuple is then sent to the cloud application which computes the values $f_1(o_1(k,x)),\ldots, f_m(o_m(k,x))$ and sends them back to the client. The client may then use the decryption function d and key k to obtain the result of the function f, $f(x)$.

Examples are given of how to apply this method to obfuscating patient names in health records (by having m=1, k being the map of patient IDs to pseudonyms o_1 being the application of k and d the inverse map), obfuscating SQL queries and several other use cases.

1.3.2.2 Criticisms

The main issue with the obfuscation method proposed by S. Pearson, et al. (2009) is that it only works for trust-worthy cloud providers who are unlikely to put the effort in to de-anonymizing or de-obfuscating records. For example, in the use case of health records presented where patient names are replaced with pseudonyms, it would be somewhat trivial for a malicious or compromised cloud provider to de-anonymize records by comparing the contents of the EHR to publicly available information. This could be

done by cross referencing emergency contact phone numbers with a phone book or narrowing down owners of a given record by age, past conditions/ailments, and location (from an address, or postal code). At a minimum, a k-Anonymity (Sweeney, 2002) type approach would be required to properly anonymize sensitive information.

Secondly, this approach only deals with the case where a client of a cloud application needs to send sensitive data to the application and receive the result of some computation. As the data is encrypted with a key known only to the client, the encrypted data is isolated to only that client and may not be shared or stored in a meaningful or unanonymized form. Similarly, this approach may not be used to share secured sensitive information stored on cloud storage as clients of the application would lack access to the key used to obfuscate the data.

1.3.3 Towards Trusted Cloud Computing (Santos, Gummadi, & Rodrigues, 2009)

1.3.3.1 Summary

Santos, et al. (2009) proposes a design for a Trusted Cloud Computing Platform (TCCP) which enables cloud providers to guarantee confidential execution of cloud user provided virtual machines. Santos, et al. (2009) extends the idea of the trusted platform module (TPM) to the cloud to prevent tampering with a virtualized machine instances memory. TPMs are a type of cryptographic coprocessor proposed by the Trusted Computing Group (http://www.trustedcomputinggroup.org/) with the ability to provide "remote attestation" that a system is running a specified software package as its operating system, BIOS, bootloader, etc. at boot time. This is accomplished as follows: initially every TPM is assigned a public/private key pair by the manufacture for which the public

key is publicly known and verifiable. At boot time the TPM creates a measurement list containing hashes of all software involved in the boot sequence of the system, which is stored in the protected storage of the TPM. Once booted, a remote entity may request attestation of the boot software by challenging the system with a random nonce, for which the system must reply with the measurement list and nonce encrypted with the TPM's private key. The remote system may then verify that the measurement list was sent by the TPM by decrypting the message with the TPM's public key.

While this method serves to verify the boot sequence of server, it is not enough on its own to secure the virtual machines executed upon it as a system administrator may make changes to the system after the boot sequence, migrate the virtual machine, or simply not run the virtual machine on a system protected by a TPM. To solve these issues, Santos, et al. (2009) have created the TCCP which consists of a trusted virtual machine monitor (TVMM) and trusted coordinator (TC). The TVMM consists of a host operating system for executing guest virtual machines which prevents privileged users from alerting or inspecting the state of running machine instances. The TVMM is installed on the cloud providers nodes equipped with a TPM module capable of proving attestation to the boot sequence. A trusted third party is required to run and maintain the TC which manages the nodes running the TVMM, recoding their TPM's public key ($EK^{pub}{}_{n}$) and expected measurement list (ML_n) while publicly publishing its own TPM's public key ($EK^{pub}{}_{tc}$), expected measurement list (ML_{tc}), and trust key ($TK^{pub}{}_{tc}$).

Node registration occurs when a node is booted and proceeds with both the node and TC requesting attestation of the others boot sequence and the node generating a new public/private key pair ($TK^{pub}{}_{n}$ / $TK^{prv}{}_{n}$) of which the public key is sent to the TC and

registered, certifying that the node is trusted. To ensure the security of the system, $TK^{prv}{}_{n}$ is to only be stored in memory on the node so that it may not be extracted from the node's hard drive when offline. Upon each reboot, the registration sequence is repeated and a new $TK^{pub}{}_{n}$ / $TK^{prv}{}_{n}$ pair is generated.

To guarantee that a virtual machine is launched on a trusted node and that a system administrator is unable to alter its contents, TCCP requires the following protocol for registering and running a virtual machine. When a cloud user wishes to register a virtual machine image (a), they first compute a hash of the image ($a\#$) and generate a session key (K_{vm}). They then proceed by encrypting a and $a\#$ with K_{vm} ($\{a, a\#\}\ K_{vm}$) and encrypting a random nonce (n) and K_{vm} with $\mathrm{TK}^{\mathrm{Pub}}{}_{\mathrm{TC}}$ ($\{n, K_{vm}\}\mathrm{TK}^{\mathrm{Pub}}{}_{\mathrm{TC}}$)and sending both to the cloud provider. The cloud provider may then store both ciphertexts for use when the user wishes to execute the image on the cloud. When the user gives such an order, the ciphertexts are sent to the trusted node on which the image is to be executed and the node requests K_{vm} from the TC by sending it the ciphertext $\{n, K_{vm}\}\mathrm{TK}^{\mathrm{Pub}}{}_{\mathrm{TC}}$, and a random nonce ($n_n$) encrypted with $TK^{prv}{}_{n}$ and appended with the nodes ID and further encrypted with $\mathrm{TK}^{\mathrm{Pub}}{}_{\mathrm{TC}}$. If the request is valid (i.e. the TC is able to decrypt the cipertext containing n_n and $\{n, K_{vm}\}\mathrm{TK}^{\mathrm{Pub}}{}_{\mathrm{TC}}$ using $TK^{pub}{}_{n}$) it responds to the node with the values of n_n, n, and K_{vm} (which it decrypted using $\mathrm{TK}^{\mathrm{prv}}{}_{\mathrm{TC}}$) encrypted with $TK^{pub}{}_{n}$. Finally the node is able to decrypt the value of K_{vm} using $TK^{prv}{}_{n}$ and use K_{vm} to decrypt the machine image and hash, a and $a\#$, and run the instance. Santos, et al. (2009)'s TCCP also provides similar methods for securing live virtual machine migration and protecting both the machine's state and image from inspection or alteration by a system administrator during migration.

1.3.3.2 Criticisms

Like Itanit, et al. (2009)'s PaaS approach (see section 1.3.1), Santos, et al. (2009)'s TCCP is dependent on the presence and support of an additional hardware component (in this case a TPM) that is not currently offered by any cloud provider. This brings with it similar issues resulting from lack of support making it impossible to use at the current time. However, unlike PaaS, TCCP does not have the same scalability and sharing risks as only a single TPM is needed and is only used by each node directly (rather than by the cloud user directly). Also, like Itanit, et al. (2009)'s approach, Santos, et al. (2009)'s method is dependent on a trusted third party taking control of some part of the cloud provider's process/system. However, rather than simply shifting control to the third party, TCCP properly divides trust between the cloud provider and third party such that in theory, they would both need to be colluding to compromise the system.

One large issue with TCCP is that it is built on the assumption that a malicious system administrator would not have access to the hardware components in a trusted node. If the administrator had such access, or the whole cloud provider was untrustworthy, there are several avenues of attack they could attempt. With the proper tools, sophisticated attacks are possible to read the contents of RAM in an active system with only access to the hardware (Samyde, Skorobogatov, Anderson, & Quisquater, 2003) and possibly more concerning "cold boot" attacks are possible against most types of RAM for a few seconds after power is lost where data may be extracted even at room temperature and without special tools (Halderman, et al., 2009). If a malicious administrator or cloud provider were able to extract TK^{prv}_{n} from the RAM of a node they would be able to fake a trusted node and compromise the security of the whole system.

Furthermore, if a decrypted copy of the virtual machine image is being stored on a node's hard drive even temporarily it may be possible for an attacker to extract sensitive information either by powering off the node while the virtual machine is active and extracting the information from the hard drive or setting up a hot swappable disk in a RAID 1 setup such that the main disk is mirrored to a second disk and may be removed while the machine instance is active and read without disrupting service.

1.5 Towards Cloud Security and Privacy for Sharing EHRs

While the current hardware approaches for cloud security and confidentiality (Itani, Kayssi, & Chehab, 2009) (Santos, Gummadi, & Rodrigues, 2009) are promising, they rely on hardware components and support by cloud providers that is currently not offered nor necessarily desired (there is little incentive for cloud providers to install potentially expressive cryptologic coprocessors and hand over control to a third party). Current software and encryption based solutions (Pearson, Shen, & Mowbray, 2009) only offer partial security (e.g. data obfuscation or anonymization) and rely on a partially trusted cloud provider (at least one that will not extract encryption keys from a running virtualized machine instance). The approach presented in this thesis aims to overcome the limitations of a hardware based approach (i.e. requiring support from the cloud provider and investment in new cloud hardware infrastructure) and provide full protection of data both on and off the cloud (including cases were no internet or network access is possible).

The research put forth is a step forward towards creating a system for ensuring cloud security with the ultimate goal of securing an untrusted public cloud to the point

where it may be used for health care applications such as storing and processing EHRs. Such protections in a cloud environment require that several design objectives be met in a secure and reasonably efficient way:

- **Regulatory Compliance**: A system that wishes to deal with EHRs of real penitent's personal and potentially sensitive information must often meet with strict local laws governing the use, transmission and storage of personal health information. In most cases this requires that at a minimum unanonymized records be encrypted and protected from view by any unauthorized third party including the cloud provider (for a more detailed description of laws applying to EHRs see section 1.2).
- **Comprehensive Security**: Sensitive data stored in the cloud needs to be protected at all points in its use. This includes enforcing access policies during storage on the cloud, processing in the cloud, transmission to, from and within the cloud and off the cloud where users may store or transmit copies locally. The access policy under which records are secured needs to be independent of the system on which they are stored and processed and consistent on all systems to which it may be transmitted.
- **Confidentiality**: Both records and information on the system's users should be isolated from outside entities (e.g. the cloud provider) as much as possible to avoid both the leakage of private information and the potential of an attacker compromising user accounts. User credentials and authentication must be isolated from the public cloud to avoid possible exploitation by a malicious cloud provider or cloud system administrator (e.g. a malicious entity with control of an

authentication system on a public cloud may be able obtain user credentials from the memory or storage of the virtual machine instance).

- **Role Based Access Policies:** To provide simple administration of users and protection of resources that models the real life policies of organizations, a role based access control system is required. At a minimum, such a system should allow for the creation of roles that may be mapped to a set of permissions that dictate access to system resources. Similarly, users should be mapped to roles related to their real life roles in an organization to enable system access.
- **Distributed:** The nature of the cloud (i.e. multiple virtualized machine instances which may be spawned and destroyed dynamically) requires a distributed model to ensure scalability and reliability. However, more importantly, administration and control of the system must be distributed in many scenarios. For example in the case of sharing EHRs on the cloud, multiple organisations (e.g. hospitals, doctor's offices, labs, etc.) will have their own sets of users, administrators and access policies which need to be supported and independent of other parties while still enabling sharing when appropriate.
- **Scalable:** One of the main advantages of cloud computing is its ability to be dynamically scaled to meet changes in demand. In many cases this is accomplished by spawning new virtual machine instances containing system components as demand increases and destroying them as demand returns to normal. A system for the cloud needs to be scalable in the same way, which is, simply by adding more nodes. This requires at least linear scalability in the majority of the system to be effective.

These objectives are accomplished with a variety of techniques including attribute based encryption (to accomplish legal compliance, confidentiality of encrypted records, and comprehensive enforcement of access policies), a DOSGi based framework (to provide dynamic discovery and communication between EHR services such that they may be properly scaled in a distributed environment), a role based access policy model (to enable role based access policies on records and services) and a single sign-on protocol (to allow for distributed access control and the confidentiality of user credentials).

1.6 Thesis Layout

This thesis presents four major components which, when combined, create a novel system for securing a potentially untrustworthy public cloud to store and distribute health records. These components include the Health Cloud eXchange (HCX) architecture, the Role Based Access Control as a Service (RBACaaS) model and access control system, the Role Based Single Sign-On (RBSSO) protocol and the Distributed Multi-Authority Ciphertext-Policy Shared Attribute-Based Encryption (DMACPSABE) scheme. The HCX architecture (presented in Chapter 2) provides a distributed OSGi (DOSGi) based architecture for storing and sharing EHRs over a public, private or federated cloud. The RBACaaS model and access control system (presented in Chapter 3) provides a model, service implementation and administration interface for providing role based access control to cloud applications and platforms via webserver or DOSGi calls. The RBSSO protocol (also presented in Chapter 3) provides a light weight and

scalable single sign-on protocol for cloud based applications with support for the RBACaaS RBAC model/system and DMACPABE based encryption policies. Finally, the DMACPSABE encryption scheme (presented in Chapter 4) provides extensions to the Ciphertext-Policy Attribute-Based Encryption model proposed by Benthencourt, et al. (2006) to add multiple distributed authorities which share a subset of attributes without the need for a user to communicate with more than one authority (or any need for inter authority communication). Additionally, a "not equals" operation and authority hierarchy is incorporated.

This thesis is divided into five chapters including this introduction and conclusion. Chapters two, three and four contain an introduction to the subject area covered by the chapter, background information, a review of current and relevant research in the area, and the presentation of at least one of the novel components which comprise our solution. Chapter five details how these components may be combined to produce a full solution to cloud security, discussion of our results, discussion of further work needed in this area and concluding remarks. Chapter summaries are given in Table 1.1.

Chapter	Summary/Contents
1. Introduction	Introduction of "the cloud problem", background information, current approaches to cloud security, research goals and thesis layout.
2. Constructing A Cloud Based Infrastructure for Sharing Health Records (HCX)	Review of existing EHR standards, presentation of the DOSGi based HCX architecture for sharing health records and implementation details for a cloud based environment.
3. Developing a Cloud Based Role Based Access Control and	Review of existing RBAC models, presentation of the RBACaaS model and access control system, review of existing single sign on protocols, presentation of the RBSSO protocol,

Single-Sign-On System	performance evaluation of the RBSSO protocol as compared to SSL and Kerberos.
4. Cloud Privacy With Attribute Based Encryption	Review of existing identity and attribute based encryption schemes, presentation of the DMACPSABE scheme, and performance evaluation of the DMACPSABE scheme as compared to CP-ABE.
5. Conclusions	Details of how the four main components may be combined to create a full system, discussion of results, discussion of future work and concluding remarks.

Table 1.1: Chapter summaries.

Chapter 2

2 Constructing A Cloud Based Infrastructure for Sharing Health Records (HCX)

2.1 EHR Specifications

There are many notable EHR standards for storing, processing and transmitting patient healthcare records such as HL7 CDA (DOLIN, ALSCHULER, BOYER, & BEEBE, 2006), Continuity of Care Record (CCR) (ASTM International, 2005), HL7 Continuity of Care Document (CCD) (Health Level Seven International, 2007), DICOM (ftp://medical.nema.org/medical/dicom/2011/) and openEHR(http://www.openehr.org). The CCR and CCD standards have gained wide acceptance in the healthcare community due in part to the support provided by major EHR vendors including Google (via Google Health), and Microsoft (via Microsoft's HealthVault(http://www.microsoft.com/en-us/healthvault/)). With the growing number of EHR platforms, interoperability is becoming a major issue which the CCR and CCD standards seek to solve through a patient health summary which contains the most commonly used and required information used and stored by EHR systems.

2.1.1 Continuity of Care Record

The Continuity of Care Record (CCR) is an XML based patient health summary containing the "most relevant administrative, demographic, and clinical information facts

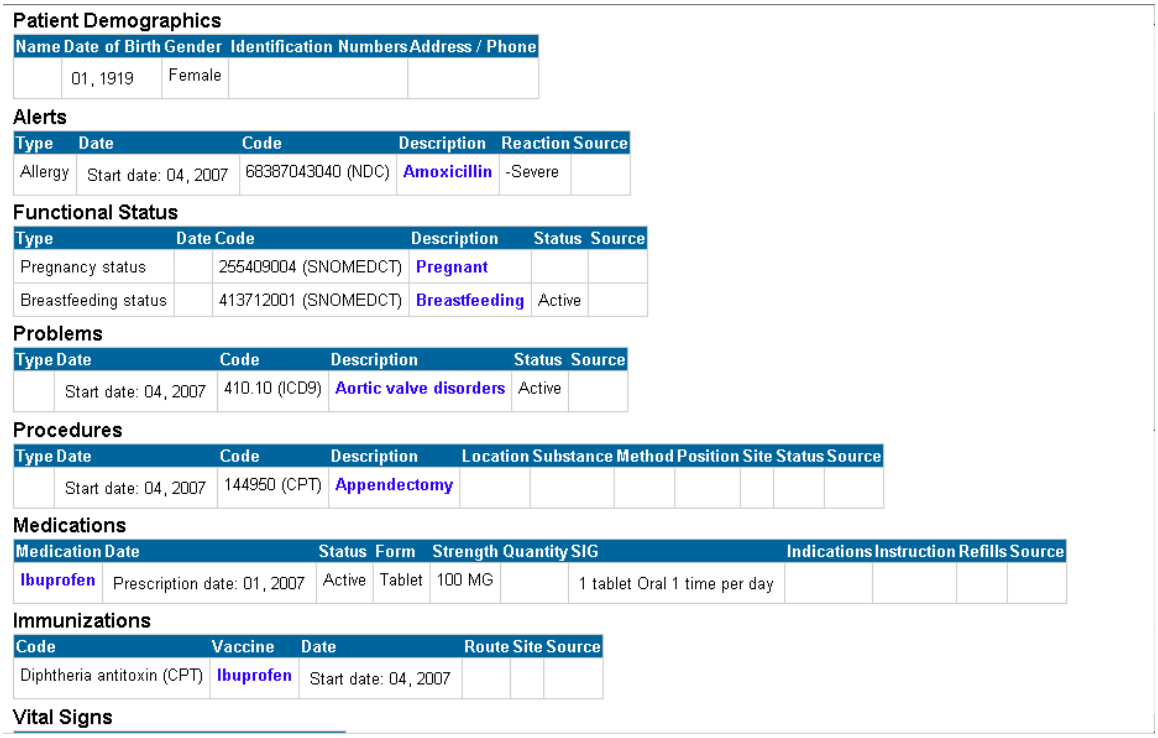
about a patient's healthcare, covering one or more healthcare encounters" (ASTM Subcommittee: E31.25, 2005). The CCR standard was developed by the ASTM International E31.28 subcommittee including supporting members such as the Massachusetts Medical Society, the Healthcare Information and Management Systems Society, the American Academy of Family Physicians (AAFP), the American Academy of Pediatrics, the American Medical Association, the Patient Safety Institute, the American Health Care Association, the National Association for the Support of Long-Term Care, the Mobile Healthcare Alliance, the Medical Group Management Association and the American College of Osteopathic Family Physicians.

The primary propose of the CCR standard is to share a point in time snapshot of a patient's medical and administrative data between health information systems. This interchangeability is accomplished through a human and machine readable XML encoding comprised of three main elements: header, body, and footer. The header contains metadata about the document including the CCR format version, the date the document was created, a unique ID identifying the document and a unique id identifying the patient. The body of the document contains detailed information about procedures, immunizations, family history, insurance information, medications, vital signs, test results, and medical alerts of and relating to the patient. The footer contains a list of actors (persons, organizations and information systems) referenced throughout the document by an actor ID and adds additional information such as name, address, email, etc. Also contained in the footer section is a reference section that allows external documents such as DICOM images to be linked with a CCR based health care record, a comments selection which allows comments to be placed on different CCR elements, and a signatures section for digital signing of elements in a CCR document. An example CCR document is presented in Figure 2.1:

```
<ContinuityOfCareRecord xmlns='urn:astm-org:CCR'>
   <CCRDocumentObjectID>Doc</CCRDocumentObjectID>
   <Language>
      <Text>English</Text>
   </Language>
   <Version>V1.0</Version>
   <DateTime>
      <ExactDateTime>2008</ExactDateTime>
   </DateTime>
   <Patient>
      <ActorID>Patient</ActorID>
   </Patient>
   <Body>
      <VitalSigns>
         <Result>
            <CCRDataObjectID>0001</CCRDataObjectID>
            <Description>
               <Text>Blood Pressure</Text>
            </Description>
            <Test>
               <CCRDataObjectID>0002</CCRDataObjectID>
               <Description>
                  <Text>Systolic</Text>
                  <Code>
                     <Value>163030003</Value>
                     <CodingSystem>SNOMEDCT</CodingSystem>
                  </Code>
               </Description>
               <TestResult>
                  <Value>120</Value>
                  <Units>
                     <Unit>mmHg</Unit>
                  </Units>
               </TestResult>
            </Test>
         </Result>
      </VitalSigns>
   </Body>
   <Actors>
      <Actor>
         <ActorObjectID>Patient</ActorObjectID>
         <Person>
            <Name>
               <CurrentName>
                  <Given>John</Given>
                  <Family>Doe</Family>
               </CurrentName>
           </Name>
         </Person>
      </Actor>
   </Actors>
</ContinuityOfCareRecord>
```

Figure 2.1: Example CCR document for fictional patient John Doe containing the results of a blood pressure test.

The CCR standard was chosen as one of the supported intermediate document formats in the HCX architecture as its XML nature makes it portable, easily implemented and provides the potential for security and privacy extensions, while still being powerful enough to contain most critical patient information and health history. Being XML based also allows CCR documents to be easily transformed into human readable documents using XSL transformations (as seen in Figure 2.2) and increases interoperability between EHR systems. The CCR standard is currently being used by multiple EHR systems including Google Health (https://www.google.com/health) and Microsoft's HealthVault (http://www.healthvault.com/).



Patient Demographics

Name	Date of Birth	Gender	Identification Numbers	Address / Phone
	01, 1919	Female		

Alerts

Type	Date	Code	Description	Reaction	Source
Allergy	Start date: 04, 2007	68387043040 (NDC)	Amoxicillin	-Severe	

Functional Status

Type	Date	Code	Description	Status	Source
Pregnancy status		255409004 (SNOMEDCT)	Pregnant		
Breastfeeding status		413712001 (SNOMEDCT)	Breastfeeding	Active	

Problems

Type	Date	Code	Description	Status	Source
	Start date: 04, 2007	410.10 (ICD9)	Aortic valve disorders	Active	

Procedures

Type	Date	Code	Description	Location	Substance	Method	Position	Site	Status	Source
	Start date: 04, 2007	144950 (CPT)	Appendectomy							

Medications

Medication	Date	Status	Form	Strength	Quantity	SIG	Indications	Instruction	Refills	Source
Ibuprofen	Prescription date: 01, 2007	Active	Tablet	100 MG		1 tablet Oral 1 time per day				

Immunizations

Code	Vaccine	Date	Route	Site	Source
Diphtheria antitoxin (CPT)	Ibuprofen	Start date: 04, 2007			

Vital Signs

Figure 2.2: Example XSL transformed CCR document using XSL transformation from the CCR Acceleration Resources Project (http://sourceforge.net/projects/ccr-resources/).

2.1.2 Continuity of Care Document

The Continuity of Care Document (CCD) is the result of a collaboration between HL7 and ASTM to integrate ASTM's CCR and HL7's Clinical Document Architecture

(CDA). The CCD specification, much like the CCR specification, describes a XML based patient health summary which contains the most critical and commonly needed patient medical and administrative information by modern EHR systems. Also akin to the CCR specification, the XML nature of the CCD specification allows for easy implementation, readability (by both humans and parsers) and interoperability between EHR systems. However, the CCD format has several advantages over the CCR document including supporting additional clinical documents outside of the patient summary (such as Discharge Summary which is out of the scope of the CCR document), enhancements for easy rendering and human readability, support of the Reference Information Model (RIM), and greater acceptance including acceptance on the national level in countries such as Canada, France, Greece, Finland, England, and Argentina as well as efforts in the United States.

The CCD specification was chosen in addition to the CCR specification to increase compatibility with existing EHR systems and to take advantage of the support of additional clinical documents lacking in the CCR format. The XML nature of both formats maintains portability and interoperability while also providing a human readable that match well as an intermediate format for the goals of the HCX Architecture.

2.1.3 Others

There are multiple EHR specifications and formats in existence and used today including HL7 CDA, openEHR, and e-MS Electronic Medical Summary for which details have been omitted for space and complexity reasons. The CCR format is an ideal use case for the research presented as it is simple, human readable, used by existing cloud PHR systems and an open standard. However, in general, if the record can be stored, transmitted and encrypted it may be used with the techniques introduced in the described

systems, models and schemes. In a real world implementation of the systems described in this thesis, it is likely that some standardization in the EHRs shared would be required, but, for simplicity sake it is assumed that the only standards being used are CCR and CCD.

2.2 HCX Architecture

In this section we describe our Health Cloud eXchange (HCX) architecture for both sharing and storing EHRs over a public, private or federated cloud. HCX can act both as the middleware between existing EHR systems as well as an independent cloud based EHR management and storage system with the possibility of web and application based patient portals. Our architecture aims to accomplish the following goals in addition to providing cloud base EHR services:

1. **Modularity:** To accommodate the changing nature of the cloud, with machine instances being created and destroyed based on demand, the system should be able to automatically adapt to HCX services coming and going off line. Also, the consumers should be able to automatically discover and use any HCX service that implements a standard interface.
2. **Interoperability:** HCX should function both as an independent EHR system and as the middleware between existing EHR systems on and off the cloud. This should be accomplished with minimal changes to existing systems through the adoption of widely supported standards such as CCD and CCR.
3. **Loosely Coupled:** Service consumers should be able to use any HCX service implementation assuming it follows a standard interface. From a consumer's stand point, services acting as a middleware between systems should be identical

to those serving records directly from the HCX system (i.e. from a cloud based EHR repository).

4. **Simplicity:** The HCX architecture and service interface should be as easy to implement as possible to allow for new HCX services and clients to be rapidly created that connect existing EHR systems with little effort from developers.
5. **Leverage Cloud Infrastructure:** The system should take advantage of the dynamic scalability of the cloud and automatically adapt to creation and destruction on machine instances that contain HCX services.
6. **Distributed:** The system should be as distributed, with few centralized points of failure. The failing of a single or multiple HCX services should have no effect on consumers beyond making their records temporarily unavailable.
7. **Extendibility:** The HCX architecture should be extendable so that custom or third party authentication, administration, and security modules may be used in implementing systems. Note that HCX itself does not deal with security, authentication or confidentiality and that these issues are dealt with in the proceeding chapters (namely Chapters 3 and 4).

2.2.1 Services

The proposed HCX architecture provides several primitive service interfaces: EHRProvider , EHRManager, EHRPortal, Administative and AuditLog. Any number of services implementing these interfaces may run within the same cloud and are registered upon execution with a central service registry for dynamic service discovery. Multiple instances of the same service may be run simultaneously, balancing the load between them (in cases where they provide the same services or records) and creating a shared

repository of health records (in cases where they provide access to different records). Services are provided from cloud based virtualized machine instances dynamically created and destroyed by a service controller application according to current levels of demand (see Figure 2.3).

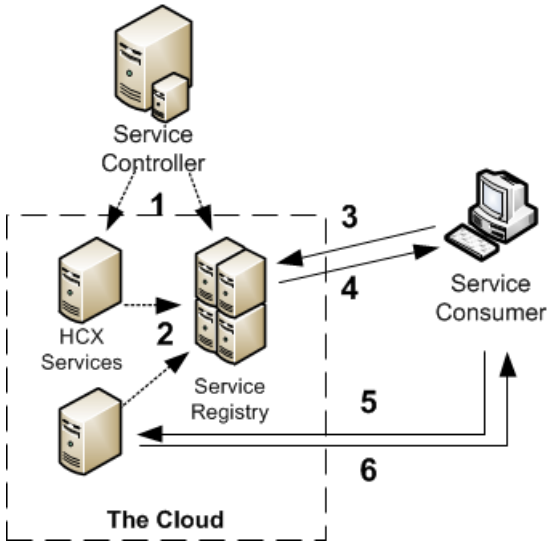


Figure 2.3: Service controller and registry interactions. Dotted arrows lines indicate interactions transparent to service consumers.

Once started the Service Controller spawns and initializes several machine instances to support the HCX architecture (Figure 2.3 part 1). Firstly, instances are created to host the service registry which allows for dynamic service discovery and utilization. Instances to host HCX services are subsequently created and initialized with a set of HCX services they will provide. Once initialized, services are registered with the service registry (Figure 2.3 part 2) and made available to consumers. Consumers may then query the service registry (Figure 2.3 part 3 and 4) for a listing of available HCX services matching set criteria and commence their requests upon the services (Figure 2.3 part 5 and 6).

Service registry entries consist of the following details:

- The service's public location (e.g. a public IP and port).

- The protocol which is being used to communicate with the service (e.g. HTTP, SOAP, etc.).
- The HCX interface which the service implemented (e.g. EHRProvider).
- The interface version being used (for forward support and future backwards compatibility).
- A unique ID for the service.
- An operational ID which is identical for services of the same implementation and operation on the same data store (i.e. clones of services used for load balancing and fail over) but unique to other services. Consumers may use services with the same operational ID interchangeably with the same effect.
- Shared group ID and range. To further load balance services, records may be divided among several services in the same shared group based on a record's unique identifying quality (e.g. a patient's ID) fitting an assigned range. (e.g. all IDs starting with 0-4 may be assigned to one service while 5-9 would be assigned to another).
- Name of the service implementation.
- The mode the HCX service is operating in (CloudEHR or Middleware) in the case of EHRProvider or EHRManager services. In the case of a service operating in "Middleware" mode, the unique name of the external EHR system is also listed.
- The date and time the service was launched into the cloud.
- Minimum set of roles a client must have active in a session to use an operation of this service (see Chapter 3 for details on the RBAC model being used).
- ServiceToken (see Chapter 3 for details on the SSO model being used).

Details on how service registries may be effectively scaled are discussed in the HCX implementation details (section 2.3 HCX Implementation). The proceeding subsections describe each service interface supported by HCX in detail including the standard set of supported operations.

2.2.1.1 EHRProvider

The EHRProvider interface is primarily designed for HCX services which provide read only, partial or full CCR or CCD based EHR records to EHR clients or outside EHR systems. An EHRProvider service may operate in one of two modes, "Middleware" or "CloudEHR". When operating in "Middleware" mode, the service acts as the middleware between an EHRProvider consumer and an existing external (to HCX) EHR system (e.g. Google Health), forwarding consumers requests to the outside system and responding with a CCR or CCD formatted record or listing of records. While operating in "CloudEHR" mode, no external EHR system is contacted and EHRs are made available off scalable cloud storage within the HCX implementation. The mode of operation of the service is transparent to the service consumer (beyond the listed mode of operation in the service registry). The format of consumer's requests and the interface used to access a EHRProvider service running in "Middleware" mode are identical to those in "CloudEHR" mode.

Interface

See appendix A.1.

Use Cases

The following are some potential use cases for EHRProvider based services:

1. **Emergency Patient Health Summaries**: In many cases of medical emergencies a patient will arrive in critical condition and be unable to provide a necessary history. EHRProvider based services would allow for EHR clients (including mobile clients) to be created that may request a readonly limited health record containing the most pertinent patient information (allergies, next of kin, blood type, etc.) to emergency room workers and paramedics (possibly while still on route through the use of mobile EHR clients). Such clients could connect to both an HCX based Cloud EHR system as well as external EHR systems through Middleware EHRProvider services, creating a network of emergency EHR sharing between medial institutions, hospitals, doctors offices and clinics. Limited read-only records reduce the chance of abuse and privacy concerns while still providing emergency access to front line health workers.
2. **Temporary and Limited Patient Records:** In many cases segments of a patient's health record are required to complete some action. For example, a receptionist in a doctor's office may be required to view a patient's insurance information to process a claim but it would be undesired for them to have full access to a patient's health record. EHRProvider based services are ideal in such a case as the receptionist could be authorized to use only the EHRProvider service and access only the insurance segment of a resulting CCR or CCD document. The read-only nature of the EHRProvider service would also limit potential abuse resulting from unauthorized changes to health records.
3. **Sharing Records Between Institutions**: In some cases it may be desired to share a patient's health record between two EHR systems in a read-only fashion. For example, if a patient has moved and is changing family doctors an EHRProvider service could be used as the middleware between their existing EHR systems to

copy the record between systems while leaving an unaffected archival copy in the original system. Another related example would be importing records into personal EHR clients, that are starting to become more popular, so that patients may view their own EHRs.

2.2.1.2 EHRManager

The EHRManager interface provides the same search and retrieve functionality as the EHRProvider interface, however, it has the additional power to edit, append, delete, move (between EHR systems) and create health records stored both on the cloud and in existing outside systems. Much like the EHRProvider services, EHRManager services may be operated in either “CloudEHR” or “Middleware” modes. When operating in “CloudEHR” mode, EHRManager services provide access to health records stored on the cloud which HCX is operating. While operating in “Middleware” mode, EHRManager services are granted access to external EHR systems in accordance to service level agreements between EHR systems. Retrieved records are sent to EHRManager consumers as CCR or CCD formatted documents and changes or updates to records are sent to the service as requests containing the CCR or CCD XML elements that have changed. New records are sent as complete CCR or CCD documents which may optionally include attachments such as DICOM images.

Interface

See appendix A.2.

Use Cases

The following are some potential use cases for EHRManager based services:

1. **Full EHR System:** The primary purpose and main use case of EHRManager services is to operate as a full cloud-based EHR system. In such a setup a client would be created to consume the EHRManager services offered on the cloud and allow medical professionals to access and update the records stored on a public cloud. Such a system would have advantages in terms of cost and scalability, not requiring heavy investment in network infrastructure as services are hosted in a pay per use manner on a public cloud, and being easily scaled when demand or the amount of records increases. The large number of clinical documents covered by the CCD specification, combined with the ability to include attached documents, allows for support of fully featured EHR systems and backwards compatibility with older systems.
2. **EHR Middleware:** The secondary purpose and second use case of EHRManager services is to operate as the middleware between existing EHR systems. A growing number of EHR related endeavours by governments and health care organizations to modernize their management health records, have led to a large number of isolated EHR systems. EHRManager services provide a means to transparently access, update, and attach additional clinical documents to EHRs as if they were part of the HCX cloud-based EHR system. This can greatly reduce time involved in sending clinical documents and full health records between systems as clients will have access to remote records as if they were local (assuming they have the correct permissions).

2.2.1.3 EHRPortal

The EHRPortal service provides a patient portal in both the form of a web service (corresponding to the interface detailed in the proceeding subsection) and web based

cloud application. Patient portals are becoming a popular trend in the healthcare industry (Weingart, Rind, Tofias, & Sands, 2006), allowing patients to securely access their own personal health records over the internet as well as enabling some level of immediate interaction with their health care providers (e.g. messaging their family doctor, correcting their patient history, filling in forms, etc.). Patient portals also allow health providers to easily comply with freedom of information laws present in most countries that require patients to have access to their personal records and the ability to issue corrections.

The EHRPortal service exposes the patient portal as both a web based application and web service so that portal clients may be created which allow greater flexibility including mobile applications. Patients are granted access to the portal via their health care provider (the institution or person considered to be the owner of their health record in the HCX system). EHRPortal services obtain patient records by consuming EHRProvider services on the same cloud. This enables the EHRPortal service to provide portals for not just the patients who have records stored within the HCX system but any external system with middleware (EHRProviders operating as "Middleware") available as well.

Interface

See appendix A.3.

Use Cases

1. **Providing Patient's Access to Their Health Records:** EHRPortal services provide an easy means of allowing patients to view and request corrections to their EHR as well as complying with freedom of information laws (access control maybe based on the RBACaaS model in Chapter 3).

2. **Centralized Patient Portal:** Currently many patient portals are isolated to a single health care provider, leaving patients who frequent multiple providers with multiple portals, each showing an incomplete picture of their health history. EHRPortal services offer a solution to this problem by accessing both the records stored on the cloud as well as the external EHR systems via the middleware provided by EHRProvider services.

2.2.1.4 Administrative

The Administrative interface contains operations relating to the management and administration of the HCX implementation itself (e.g. creating new middleware connections to outside systems, settings relating to load balancing and providing fail over of services, etc.). This is largely left as an optional service and implementation detail dependent on how the other HCX services are configured.

2.2.1.5 AuditLog

The AuditLog service is used to keep and store an uneditable audit log of all actions that have been performed on the EHRs and services, including views, changes, and removal of records. These logs keep a permanent record of user's actions that can be used as evidence in case an abuse of a user's credentials occurs. The AuditLog service is called directly from all HCX services and is not accessible to normal users directly. The interface of the AuditLog has a single operation which takes the user's request details and session information (essentially the AuthToken, RequestToken and summary of the user's request upon the service from section 3.2 Single Sign On). Figure 2.4 shows the interaction between a normal HCX service and the AuditLog service.

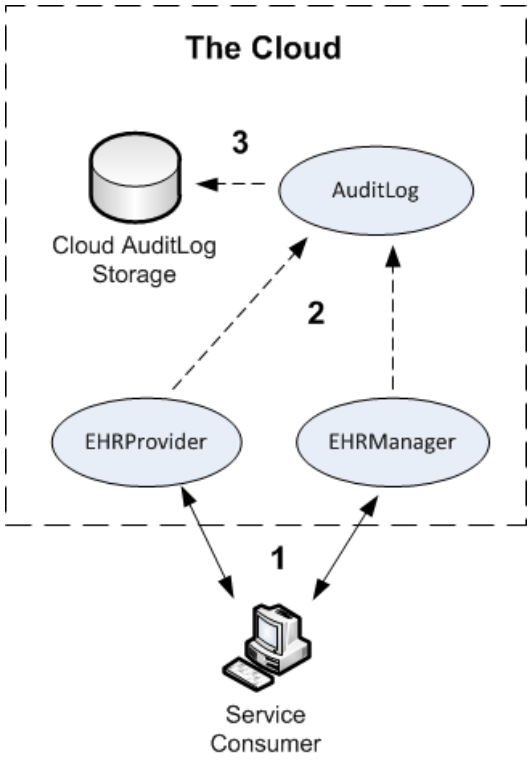


Figure 2.4: AuditLog interactions. 1. Client/Service consumer makes a request on a service. 2. The service sends the RequestToken, AuditToken and request summary to the AuditLog service. 3. The AuditLog service stores a log entry for the request on cloud storage.

Interface

See appendix A.4.

2.2.2 Clients

HCX clients come in three main forms: existing EHR systems which use HCX to share records, patient portals offered through a web based or web service interface, and end user client software designed to act as a local EHR system for a doctor's office, hospital, etc. In all cases (excluding access to a patient portal via a web browser) clients communicate with the HCX services either via DOSGi or web service requests. Service discovery is accomplished through a centralized ZooKeeper cluster (that may be located in the cloud) which clients connect to, to receive an updated listing of available services.

Client connections are load balanced between active HCX services of the same type (e.g. EHRProvider, EHRManager, etc.) to maintain scalability and reliability.

2.3 HCX Implementation

2.3.1 DOSGi Infrastructure

Distributed OSGi (DOSGi) provides a good basis for building the HCX system as its modular service based infrastructure already accomplishes several goals of the system (distributed, loose coupling and modularity). The distributed nature of DOSGi allows for a loose coupling between services and consumers through the use of a service discovery mechanism for finding the location and type of services currently being offered in a given grouping.

Our implementation of HCX utilizes the DOSGi reference implementation, Apache CXF DOSGi as a foundation to build HCX services upon, as well as taking advantage of the DOSGi service registry to fulfill the role of the HCX service registry. Apache CXF DOSGi accomplishes this dynamic service discovery through the use of an Apache ZooKeeper based cluster which enables simple and scalable service look up and discovery while keeping the advantages of a distributed system (e.g. not relying on a single point of failure, see Figure 2.5). Service consumers are notified of new services becoming available or going offline (a common occurrence in a cloud based setting) and are able to automatically use or discontinue use of a given service.

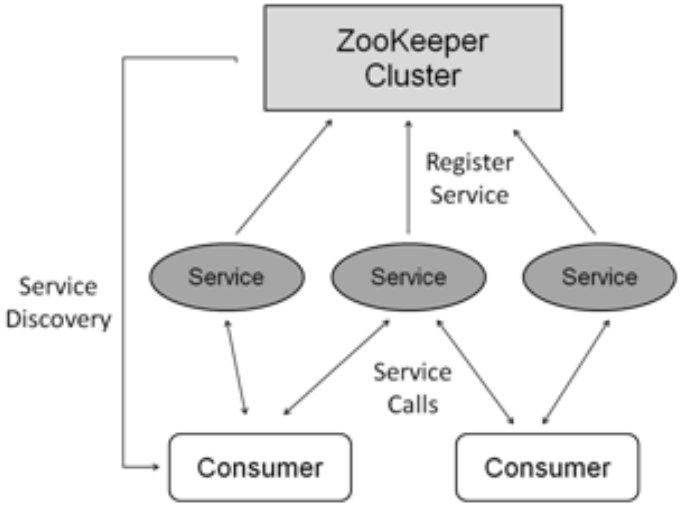


Figure 2.5: The Apache CXF DOSGi Service Discovery.

Several modifications were required to the base Apache CXF DOSGi implementation to support the full HCX service registry specification as well as to provide transmission security between HCX services and consumers. First, the web services automatically created by DOSGi to handle remote method calls were changed from using a plain HTTP connection to requiring transport layer security (HTTPS). Second, the zookeeper directory was modified to also include the service registry entries listed in section 2.2.1, such that HCX clients may obtain additional information about the service and which records it holds.

Adapting DOSGi for use on the cloud required the creation of two Xen based machine images. An image was required to host a standard OSGi implementation (such as Eclipse Equinox, Apache Felix or Knopflerfish) upon which the Apache CXF DOSGi, and HCX bundles would be run to provided HCX's services via the cloud. A second image was required to host ZooKeeper servers for service registry and discovery. As demand increases on a particular service, additional OSGi machine instances may be run to load balance requests between more instances of that service. As demand increases on

the service registry, more ZooKeeper machine instances may be run to add additional ZooKeeper servers to the cluster. This set-up is shown in Figure 2.6 and Figure 2.7.

The OSGi machine image was created with Pax Runner (http://team.ops4j.org/wiki/display/paxrunner/Pax+Runner) (a tool for provisioning OSGi bundles in a range of OSGi frameworks), installed and configured to automatically start an Equinox (http://eclipse.org/equinox/) OSGi console upon booting. Once started, the Apache CFX's DOSGi OSGi bundle and its dependencies were set to be automatically loaded to support HCX services that would be run on this instance. Additionally several custom scripts were installed to deal with the initialization data from the Service Controller, download the appropriate HCX bundles (based on the Service Controller data) and start their execution in Equinox. The ZooKeeper image simply contained an Apache ZooKeeper install configured to join the ZooKeeper cluster and provide registry services to the cloud.

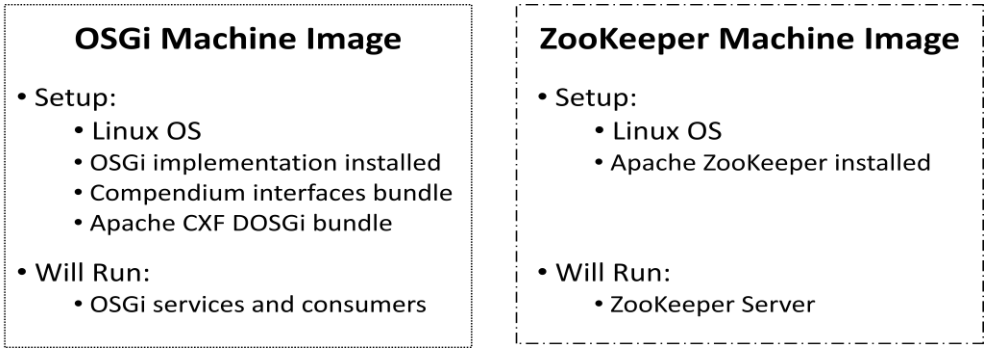


Figure 2.6: Xen based machine images to support DOSGi on the cloud.

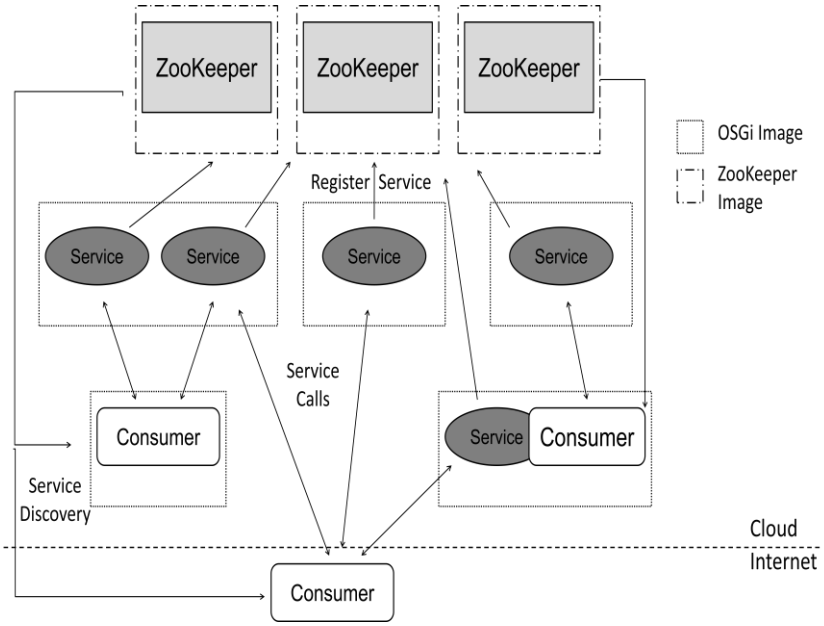


Figure 2.7: Machine Instance Interaction to Support DOSGi on the Cloud.

2.3.2 Cloud Infrastructure

The cloud infrastructure used in our HCX implementation consists of both a private Eucalyptus based private cloud and shared resources on the public Amazon AWS cloud. The hardware infrastructure of the private cloud consisted of 15 identical IBM xSeries rack mounted servers connected to each other via a 1000 Mbit/s switch. Of the 15 servers, 14 were designated as Eucalyptus Node controllers which run the Xen based virtual machine instances, while the Cloud Controller, Walrus (S3 Storage), Storage Controller and Cluster Controller services were installed on the remaining server to provide scheduling, S3 based bucket storage, EBS based storage and a front end for the cloud. This set up is shown in Figure 2.8.

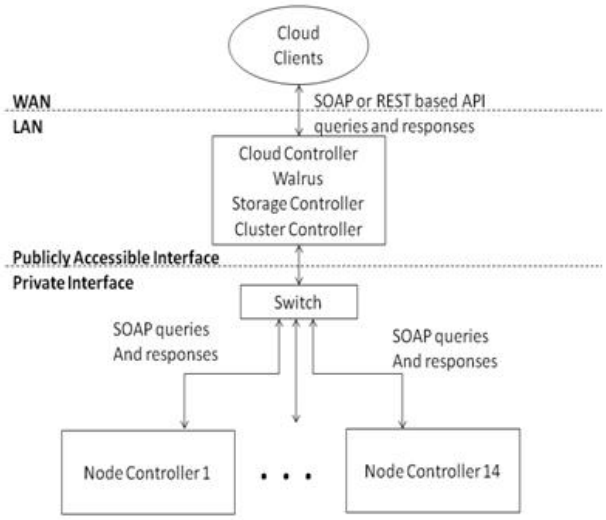


Figure 2.8: HCX Eucalyptus Private Cloud Set-up

Eucalyptus is an open-source software platform that implements IaaS-style cloud computing using the existing Linux-based infrastructure found in the modern data center. Its interface is compatible with and based on the Amazon Web Service (AWS) interface making it possible to move workloads between AWS and a private Eucalyptus based cloud without significant modifications to the code that comprises them. Eucalyptus supports a variety of virtualization technologies including the VMware (http://www.vmware.com/), Xen (http://xen.org/), and KVM (http://www.linux-kvm.org) hypervisors for the creation and management of virtual servers. Compared to other private cloud frameworks, such as Nimbus and abiCloud (http://www.abiquo.com/), Eucalyptus was chosen as it has a stronger community support, larger amount of documentation and comes packaged in the easy to install Ubuntu Enterprise Cloud Linux distribution.

A Service Controller application was created which sits outside of the cloud and manages virtual machine instance creations, destruction and initialization. This is accomplished through the EC2 web service API provided by Amazon AWS for public

cloud instances and through the Eucalyptus EC2 based API for private cloud instances. Further details on the role of the service controller are given in section 3.2.

2.4 Conclusions

While the DOSGi based HCX architecture presented in this chapter does not provide the necessary security or data privacy we desire, it does offer a scalable framework on which a more complex system that enforces role based security policies may be built. We have shown how DOSGi may be adapted to a cloud based environment by distributing services between machine instances and using a similar method for creating a zookeeper cluster for service discovery. We have also described and introduced a set of services for sharing EHRs, creating patient portals, maintaining an audit log and offering administrative functions. The proceeding chapters take the cloud environment and services introduced here and add systems for enforcing role based access policies and data privacy through attribute based encryption.

Chapter 3

3 Developing a Role Based Access Control and Single-Sign-On System for the Cloud

3.1 Role Based Access Control

Traditionally access control has been limited to discretionary access control (DAC) and mandatory access control (MAC) models that use access control lists (ACLs) to rigidly map users and groups to low level data objects. These approaches may perform well for controlling access on simple local systems, such as a standalone computer's file system, however, it becomes increasingly difficult to maintain and manage user permissions when they are applied to more complex and less rigid systems. Enterprise and cloud environments require more flexible models of access control that are able to more closely represent the organizational role a user plays in these environments. Role based access control (RBAC) offers a more general solution that is flexible enough to model the real life roles and responsibilities of the members of most organizations, in fact it is even generic enough to enforce the traditional MAC and DAC access policies if needed (Osborn, Sandhu, & Munawer, 2000).

Users of cloud based applications may require different levels of access to multiple cloud based services, capable of performing various abstract operations on lower level data objects. Managing permissions for accounts spanning services made available via a cloud infrastructure, requires a model that can preserve the security of traditional access control systems while providing a level of abstraction which allows administrators

to implement high level policies that are independent of the low level infrastructure that compose the cloud.

3.1.1 RBAC Related Research

While much work has been done in the area of role based access control (Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001) (Ferraiolo & Kuhn, 1992) (Sandhu, Coyne, Feinstein, & Youman, 1996) (Yao, Moody, & Bacon, 2002) little has been done in terms of adapting this model to the cloud computing paradigm. Based on the identified challenges inherent to cloud computing (see section 1.2) we have identified the following qualities needed in a RBAC model to meet the demands of the cloud:

1. **Scalable:** An RBAC system for the cloud needs to be designed to scale alongside the cloud or the dynamic scalability advantages gained from using cloud computing will be lost. This includes reducing or eliminating potential bottlenecks including connections to systems outside of the cloud and centralized services only offered from a single physical or virtual system.
2. **Distributed**: A cloud based RBAC system should match the distributed nature of the cloud, offering services from multiple virtualized systems rather than a more traditional centralized server setup. A clear namespace for identifying objects, roles, users, etc. among different systems distributed throughout the cloud and client systems are required. Ideally, such a system would be able to handle the joining and parting of different nodes which compose the system (caused by machine instances being created and destroyed to meet demand) with little difficulty and transparently to the RBAC system's end users.

3. **Auditable**: The RBAC systems should be capable of maintaining logs of users' actions and role activations within the system and ensure that no part of the system has been tampered with or compromised by a malicious user or administrator.
4. **Confidential**: A user's identity and personal details should be kept from services using the RBAC system for authentication unless necessary for their function or authentication method. This becomes more critical on a public cloud setting where the cloud provider may not always be trusted.
5. **Straightforward Administration:** Proper administration of an RBAC system is critical for ensuring the security of the systems which utilize it. Administration of roles, users, rules, permissions, etc. should be reasonably straightforward and well understood to RBAC administrators.
6. **Reliable:** To maximize reliability, centralized points of failure should be eliminated or minimalized. Having cloud services dependent on a RBAC system for authentication means any failure or downtime for that system translates to downtime of all cloud services. If a RBAC system relies on a central server or service, there should be some level of failover protection to diminish the effect of downtime on end users and services.

The following section reviews two popular and relevant RBAC models and offers criticism based on the qualities of an ideal cloud based RBAC system identified above.

3.1.1.1 The ANSI RBAC Standard

3.1.1.1.1 Summary

Several role based access control models have been developed in recent years that have expanded on and standardized the core ideas behind RBAC. One of the most notable is the effort by the National Institute of Standards and Technology (NIST) (Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001) to create a standardized template for which the majority of RBAC implementations can be based and expanded upon. The NIST model integrates several previously published RBAC models/frameworks (Sandhu, Coyne, Feinstein, & Youman, 1996) (Ferraiolo & Kuhn, 1992) into the standard for RBAC adopted as ANSI INCITS 359-2004 (InterNational Committee for Information Technology Standards, 2004). This model divides RBAC into four functional components: Core RBAC and three optional components (Hierarchical RBAC, Static Separation of Duty Relations and Dynamic Separation of Duty Relations), which may be combined to create the basis for implementing an RBAC package.

Core RBAC maps together the five basic elements of a role based access control system (users, roles, objects, operations and permissions) to assign users to roles, and roles to permissions, where permissions are in turn mapped between operations and objects. User sessions are also present in the Core RBAC model, allowing users to activate a subset of roles they have been assigned in a given session. Figure 3.1 illustrates the many-to-many mapping between these basic elements.

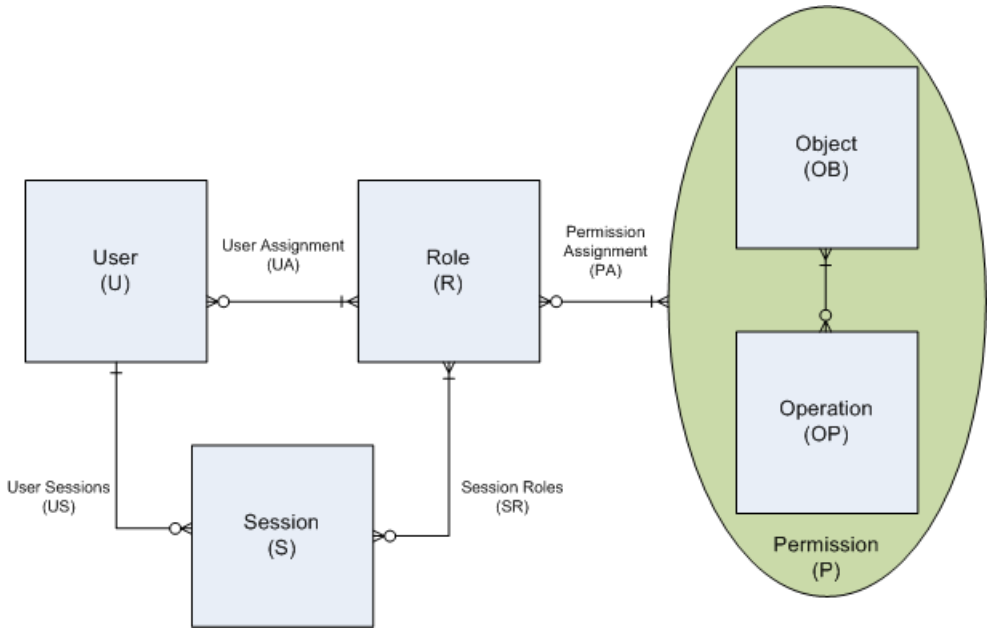


Figure 3.1: ANSI INCITS 359-2004 Core RBAC Model

Hierarchical RBAC extends the Core RBAC model to add a hierarchy of roles which inherit their parent's permissions. Support for both a limited inheritance (roles being limited to one descendent) and a general inheritance (roles with any number of descendents and ascendants) are given in the NIST model. Hierarchical roles allow for simplified management of permission assignments and more closely model the relations between roles in real organizations. Figure 3.2 illustrates this extension to the Core RBAC model.

Static Separation of Duty (SSD) relations extend the Core RBAC model to enforce simple separation of duty policies during user role assignment. Sets of two or more conflicting roles and the maximum cardinality of the intersection of users' roles with such a set are maintained in the system to represent an organization's SSD policy. For example, an organization may create a policy that limits a user to being assigned to at most two of three roles involved in the process of authorizing payments. The NIST model also allows these SSD policies to be applied to Hierarchical RBAC models, by having

SSD constraints inherited alongside role permissions. Figure 3.3 illustrates this extension to the Core RBAC model.

Dynamic Separation of Duty (DSD) relations also extend the core RBAC model to enforce an organization's separation of duty policies. However, unlike SSD, DSD constrains the active permissions a user may be indirectly assigned rather than their role assignment by limiting the roles a user may have active together in a single session. As with SSD, sets of conflicting roles and maximum cardinalities are used to represent the organization's DSD policy. However, in this case the intersection is between the conflicting roles and the user's active roles in a session rather than their overall role assignment. For example, if a user has both the role of patient (allowing a user to view their own health record) and the role of doctor (allowing a user to view their patient's health records and update records to approve a treatment), DSD would not allow such a user to activate both their patient role and doctor role at the same time, preventing them from being able to approve treatments on themselves, while still giving the user the flexibility to view their own record and perform their job in regards to their patient's records. Figure 3.4 illustrates this extension to the Core RBAC model.

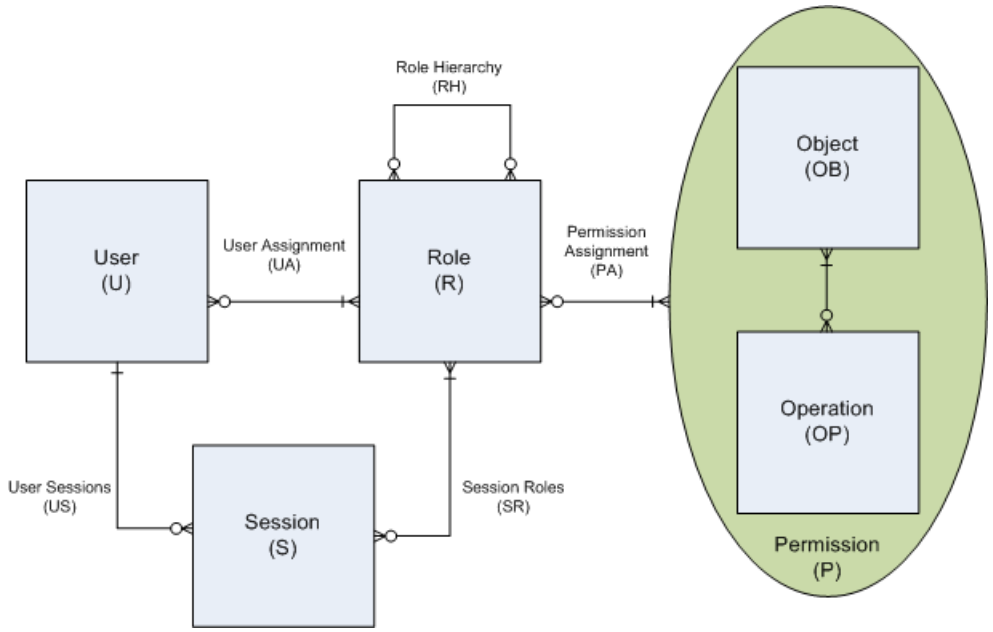


Figure 3.2: General inheritance Hierarchical RBAC

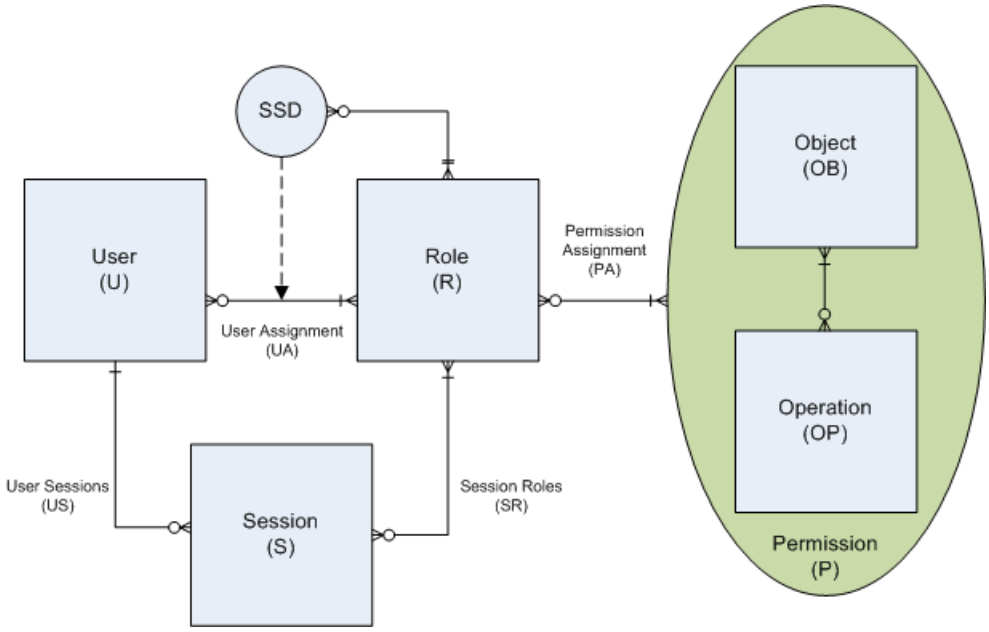


Figure 3.3: SSD RBAC

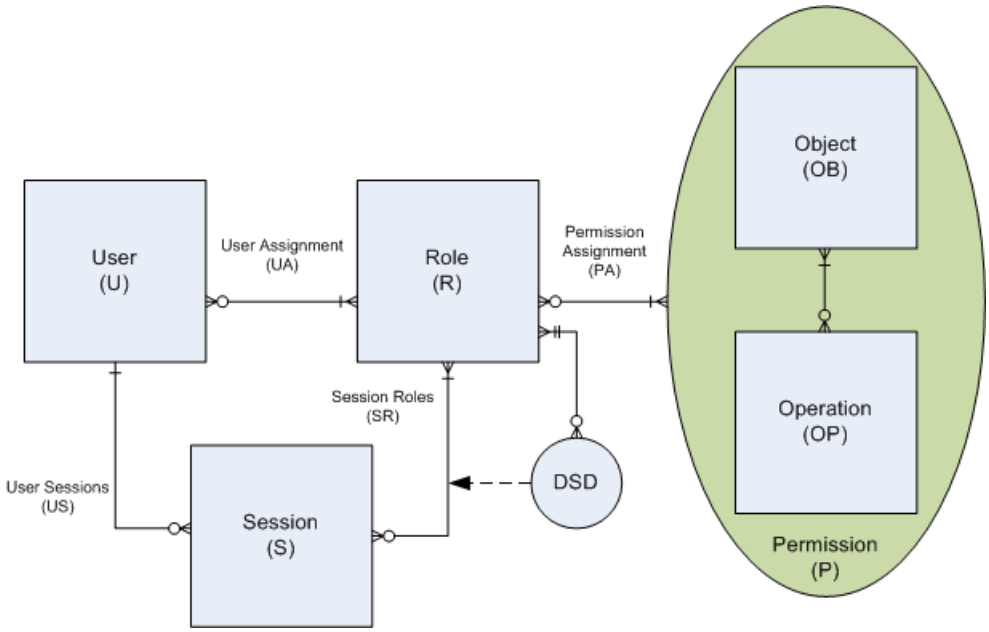


Figure 3.4: DSD RBAC

3.1.1.1.2 Criticisms

While the ANSI model may provide a "consistent and uniform definition of role based access control (RBAC) features" (InterNational Committee for Information Technology Standards, 2004) and a basis for developing RBAC systems, it still contains several issues and limitations. The standard lacks details critical to implementing a working RBAC system, has limitations that affect scalability, fails to be generic enough to apply to all cases where RBAC maybe be used and has several areas where the design can be improved.

Ninghui Li, et al. (2007) offer a critique of the standard which addresses several key issues for which they provide possible solutions. Besides small typos and technical errors, the core criticism centers on the following concerns (Li, Byun, & Bertino, 2007):

- The standard does not allow a system to limit sessions to only allowing a single role to be activated at a time (Single-Role Activation vs. Multi-Role Activation).

- Having Hierarchical RBAC use a partial order creates issues when updating the role hierarchy.
- Ambiguity of the role hierarchy.

Single-Role Activation (SRA), limiting sessions to a single role, provides several advantages over the Multi-Role Activation (MRA) endorsed by the standard. The most apparent being the simplification of enforcing the principle of least privilege (as only one role may be activated, it is not possible to activate conflicting roles simultaneously). Alternatively, MRA requires the implementation and proper configuration of additional mechanisms, such as dynamic separation of duty (as used in the standard), to support the principle. Secondly, SRA requires roles to be explicitly created to allow users to have a given set of permissions active at the same time. With MRA, roles must be explicitly excluded from being activated simultaneously, requiring role administrators to review each combination of roles for conflicts. This essentially boils down to a white list (SRA) vs. black list (MRA) approach to least privilege, placing the standard's use of a black list methodology in conflict with the fail-safe defaults principle of "bas[ing] access decisions on permission rather than exclusion" (Saltzer & Schroeder, 1975).

Ninghui Li, et al. (2007) argue that the use of a partial order to maintain role hierarchies, such as is done in the ANSI and RBAC96 models, negatively effects the excepted outcome of updates to the hierarchy in several cases. For example, in the case of ANSI RBAC, the General Role Hierarchy (RH) is defined as follows (directly from (InterNational Committee for Information Technology Standards, 2004)):

> $RH \subseteq ROLES \times ROLES$ is a partial order on $ROLES$ called the inheritance relation, written as $\succeq$, where $r_1 \succeq r_2$ only if all permissions of r_2 are also permissions of r_1, and all users of r_1 are also users of r_2.

With the addition and deletion of inheritances being defined as:

$$AddInheritance(r\_asc, r\_desc: NAME) \lhd$$
$$r\_asc \in ROLES; r\_desc \in ROLES; \neg(r\_asc >> r\_desc); \neg(r\_desc \geq r\_asc)$$
$$\geq' = \geq \cup \{r, q: ROLES | r \geq r\_asc \wedge r\_desc \geq q \bullet r \mapsto q\} \rhd$$

$$DeleteInheritance(r\_asc, r\_desc: NAME) \lhd$$
$$r\_asc \in ROLES; r\_desc \in ROLES; r\_asc >> r\_desc$$
$$\geq' = (>> \setminus \{r\_asc \mapsto r\_desc\})^{*} \rhd$$

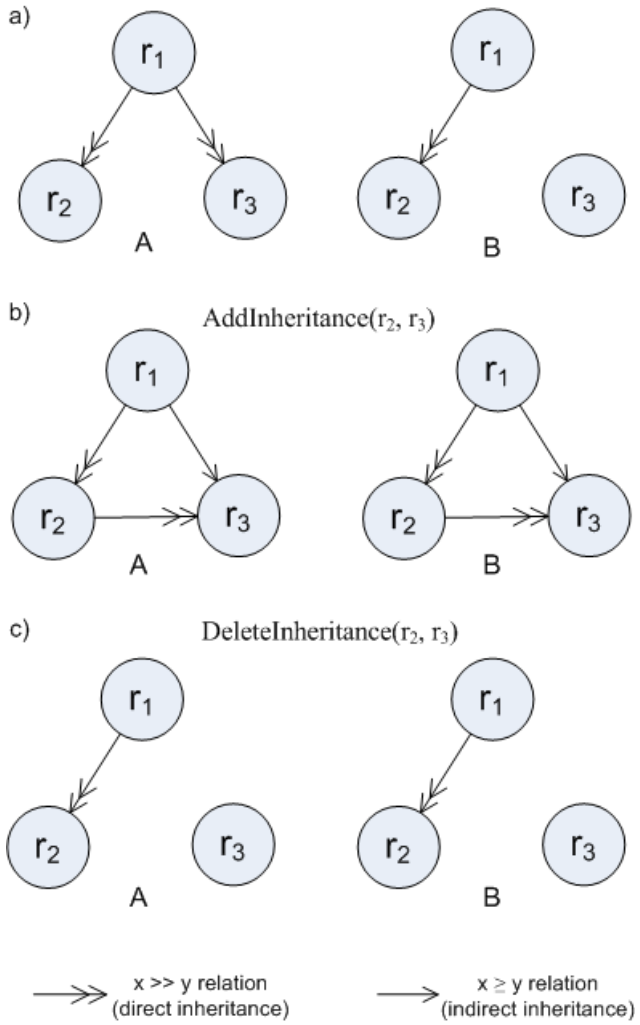


Figure 3.5: ANSI RBAC inheritance operations on role hierarchies A and B.

To demonstrate the issue, consider a role hierarchy A containing the roles r1, r2 and r3 with the relations r1 >> r2 and r1 >> r3 and a role hierarchy B containing the roles r1, r2, r3 with only the relation r1 >> r2 (see figure Figure 3.5a). If the operation AddInheritance(r2, r3) is performed on both A and B, the resulting hierarchies will be

equivalent and represented by the same partial order, with relations r1 >> r2, r2 >> r3 and r1 ≥ r3 (as shown in figure Figure 3.5b). As the original relations that were explicitly created are not persevered for further operations, this can lead to some what counter intuitive results. For example, if the operation DeleteInheritance(r2, r3) is performed on the resulting hierarchy in figure Figure 3.5b, to attempt to undo the last step, the resulting hierarchy in both the cases of A and B will be that shown in figure Figure 3.5c, with only the relation r1 >> r2. This could easily be seen as the excepted result for hierarchy B, however the result for hierarchy A is not equivalent to the hierarchy before the AddInheritance operation was performed (as shown in figure Figure 3.5c). This partial order method for maintaining a role hierarchy fails to handle update operations in a way that a role administrator would intuitively expect in many cases, leading to possible unexpected loss of inheritance relations as was showing in figure Figure 3.5.

The last major issue raised by Ninghui Li, et al. (2007) relates to the ambiguity of the ANSI standard's general and limited role hierarchies. The current standard allows for several different interpretations of the role hierarchy including those identified by Ninghui Li, et al. (2007):

- **User Inheritance (UI):** Users authorized for role r1 are also authorized for role r2 given that r1 >> r2 (i.e. a user may activate any role that is inherited by a role they are assigned).
- **Permission Inheritance (PI):** Role r1 is authorized for all permissions role r2 is authorized for, given that r1 >> r2 (i.e. a role is authorized for all permissions of the roles which it inherits).

- **Activation Inheritance (AI):** If role r1 is activated in a session then role r2 is also activated given that r1 >> r2 (i.e. all roles inherited by an active role are also activated in the given session).

Implementations are left to decide which interpretation (or set of interpretations) to use without any standardization. However, picking the wrong interpretations can have negative consequences on a system's ability to enforce SSD and DSD rules. For example, if PI is used without UI, users may bypass SSD rules excluding the use of roles r1 and r2 by activating a role r3, where r3 >> r1 and r3 >> r2. Ninghui Li, et al.'s (2007) analysis of the issue concludes with the recommendation of "[using] UI and PI at all times and add AI whenever MRA is used.".

In addition to the concerns raised by Ninghui Li, et al.'s (2007) critique, we have identified several supplementary issues with the ANSI model that will have a significant impact on RBAC systems both following this model and a distributed design (such as those implemented for the cloud). These issues fall into the following categories:

1. Permission definition and operation-object mapping.
2. Lack of user groups or rule based groups.
3. Enforcing the principle of least privilege.
4. Issues for distrusted implementations.
5. User sessions.
6. Updating SSD constraints.

Permission Definition and Operation-Object Mapping

The ANSI standard defines a permission as approval to perform a given operation on an object ("…any system resource subject to access control, such as a file, printer, terminal, database record, etc." (InterNational Committee for Information Technology

Standards, 2004)). However, this definition is somewhat simplistic for real world applications. First, limiting an object to system resources would seem to exclude meta structures, such as groupings of resources (e.g. a grouping of files not necessarily contained in the same level of a file system hierarchy or with a common attribute) or roles and permissions stored in the RBAC system, as well as possibly excluding virtualized or remote resources such as virtual drive or a remote file share.

Second, the mapping of operations to objects largely ignores the properties of the object or at a minimum requires many operations and many mappings to cover most common permissions a system would need. For example, many file systems assign an owner and group to files and directories as well as a set of permissible actions. To emulate the same permissions with this operations-objects mapping, a permission for each user/group would need to be created which contains the set of all mappings of operations on files for which that user or group would have some level of access and then mapped to the appropriate roles and users, resulting in many complex relations for RBAC administrators to maintain. Alternatively, additional operations can be created to check if a user meets some requirement of the underlying files system (e.g. that the user is the owner of the file according to the file system), however, this removes the precise knowledge of what resources a given user may have access to in the RBAC system and breaks the operations-objects mapping as the permission only contains a set of operations. Additionally, there may be cases where neither the object nor the local system has knowledge of an object's property for which it may be desired that permissions be built around. For example, a printer in an office building has the physical property of which floor of the building it is located on. It may be desired that a permission be created that limits one role to only printing on a given floor but another role to have full access to all printers. Traditionally, this would be accomplished by

creating a permission for each floor mapping the print operation to every printer on that floor. However, if a RBAC system had the capability to map properties on-to objects and contained more complex permissions, the permission could simply contain the rule that the printing is allowed if the printer contains the property of being on the given floor. This would allow for more natural RBAC administration, where administrators first map properties on to objects and then create permissions by defining rules based on the object's properties and would also allow for greater reuse (e.g. if it was desired that a permission be created to allow a role to stop a print job on a given floor).

The final issue with the standard's permissions is the lack of detail on how implementations will reference operations. The standard defines an operation as "…an executable image of a program, which upon invocation executes some function for the user" (InterNational Committee for Information Technology Standards, 2004) which seems to suggest that the operation in the model's permissions are a reference to a specific executable program or service on the system and may vary for each object type. For example, the edit operation listed for a file would be different from the edit operation for a database. This requires the RBAC model to have some understanding of the underlying system for which it provides access control and would increase the difficulty of generating a list of users that have access to a standard operation such as "read" across several different object types (e.g. a list of users that can view the content of a given set of files and databases) as the operations would differ. A set of standard operations such as "view", "edit", "copy", "move", "delete", etc. with the option of manually adding additional and more specific operations would greatly simplify permission administration.

Lack of User Groups or Rule Based Groups

The next issue with the standard is the limited assignment of roles only to users. Adding user groups to the model would allow for simpler RBAC administration when a set of roles needs to be assigned to the same group of users, or if a group of users needed to be temporarily assigned to a role, or required frequent changes in their assigned role. Furthermore rule based user groups would allow for the assignment of roles based on conditional rules. For example a group could be created whose members are based on an IP address range allowing access to select resources based on a user's IP, allowing a network admin to limit access to critical objects to users on a trusted intranet.

Enforcing the Principle of Least Privilege

While the ANSI model complies with the principle of least privilege through its support of per session role activation, it fails to enforce that the users of an implementing system abide by the principle. Although the SSD and DSD components prevent users from activating potentially conflicting roles, there are no mechanisms within the standard which prevents or discourages users from constantly activating an assigned role with higher than needed privileges for an assigned task. For example, if a user is assigned a role with the permission granting it access to view a database record as well as a role with permission to view and update the record, there is no mechanism to prevent or discourage the user from using the second more powerful role for a task that only requires viewing a record.

Issues for Distributed Implementations

The ANSI standard choses to omit implementation details for how RBAC services might (or should) be provided in differing environments (e.g. distributed vs.

local), presumably to increase applicability of the model. However, many of the administrative functions and formal operations would be extremely costly or difficult to implement in anything but a centralized, server-client or local system. The administrative functions for adding or changing an SSD constraint (CreateSsdSet, AddSsdRoleMember, SetSsdSetCardinality, etc.) for example require that the resulting constraint is satisfied for all related user-role assignments. In a distributed RBAC system it is likely that user and/or roles would be distributed among multiple remote systems and such a check would require querying every system for user-role assignments that may violate the new constraint.

Also lacking in the standard is a standardized namespace for identifying objects, roles, permissions and users across multiple remote systems. Such a standardized namespace would be critical in a distrusted system so that elements of the RBAC could be properly and uniquely identified and referenced, as well as easily located despite not necessarily being local. Existing standards for locating and referencing resources, such as the Uniform Resource Identifier (URI) (RFC 3986), Uniform Resource Locator (URL) (RFC4266 and RFC4248), and Uniform Resource Name (URN)(RFC1737 and RFC2141) could possibly serve this function, however, it may be more appropriate to design or extend an existing naming standard around RBAC.

User sessions

Several of the administrative functions in the standard (including DeleteUser, DeleteRole, AssignUser, DeassignUser, GrantPermission, and RevokePermission) leave the handling of active sessions as implementation specific details. For example, if a user has an active session when DeeleteUser is called, should the session be destroyed or remain active until the user logs out of the system? Leaving these decisions as

implementation details causes several issues. First, this creates a large discrepancy between systems implementing the same standard in terms of consistency when an administrative function is performed, and second, the issue is deserving of further discussion as the implications can be large for a system's security. We have identified three possible methods for dealing with active sessions after a direct (e.g. GrantPermission, etc.) or indirect permission change (e.g. DeleteRole, AssignUser, etc.):

1. Leave all active sessions as they are.
2. Drop all affected user sessions.
3. Update sessions when possible (e.g. GrantPermission, RevokePermission, etc.), drop when not (e.g. DeleteUser, DeassignUser, etc.).

The three options have various advantages and disadvantages in terms of easy to implement, feasibility and security. The first option is the simplest to implement, works in distributed or centralized systems, and is easily scaled, but any administrative function which indirectly removes permissions from a user has the potential to leave an opportunity for abuse if an active session exists for any user for whom the change effects. For example, if a user may never be assigned roles R1 and R2 concurrently due to an SSD restriction and an RBAC administrator changes a user's assigned role from R1 to R2 while the user has an active session using role R1, the user will be able to create a second session using R2 and bypass the SSD restriction as long as their first session remains active. While Single-Role Activation or DSD could be used to prevent this case (assuming all SSD rules were also DSD rules), the user would still have access to the permissions granted to role R1 until the session expires despite the role being unassigned. This could be a massive security issue in distributed RBAC systems where session revocation is not possible or limited, and a malicious or compromised user needs to be removed immediately. The second option removes the security issues of the first but has

the potential to inconvenience users with active sessions if a change is made to a live system. Additionally, in distributed systems, revoking user sessions can be costly to scalability if remote services need to be notified or need to be constantly checking a session's validity with a centralized server. The third option has the advantages of the second while limiting any potential inconvenience users of the system may experience. However, it would also present greater challenges and complexities for distributed systems, requiring updated session information to be synchronised with all services in the system.

3.1.1.2 OASIS Role-Based Access Control

3.1.1.2.1 Summary

OASIS role-based access control (Yao, Moody, & Bacon, 2002) provides an architecture and model for secure service authentication and access with an open distributed environment. Unlike most role based access control models, OASIS does away with the traditional role hierarchy and does not use role delegation but instead an appointment process. Rather than relying on a centralized role administrator to delegate roles, the OASIS model uses a credential-based system for role activation whereby users may activate roles based on the current credentials they possess and conditions relating to the systems environment (e.g. current time, current task a user is performing, etc.). Credentials are granted through appointments initiated by any user who is a member of some role which grants the appointment ability for the given credential. For example, a user may be granted a new credential upon obtaining a professional qualification which will in turn grant access to a new set of roles in the system during role activation.

The OASIS model supports separation of duty constraints at the role activation level (similar to dynamic separation of duty in the ANSI model) as a role activation rule. Additional context based role activation rules beyond credentials and separation of duty constraints are also supported through parameters in the extended model including time based rules (roles only allowed during set dates or times of day), and role prerequisites (a session with role r1 must be active before role r2 may be active). Furthermore, many additional rules are supported through extensions to the basic RBAC model including support for workflow systems, team-based systems, and content-based access control.

W. Yao, et al. (2002) argue that their model of appointment has several advantages over the delegation model including well-defined and controlled privilege propagation, prevention of cascading delegation, and the ability for a user to grant privileges that they do not necessarily have to possess. Additionally, appointment can be viewed as generifying delegation as delegation becomes a special case of appointment in which a user grants a credential which in turn allows activation of the same role as the granting user.

The model provides three methods of credential revocation which a system may implement; appointer-only revocation, appointer-role revocation and system-managed revocation. Appointer-only revocation allows only the appointer of a credential to revoke it from a user; this tends to model how many organizations function in real world scenarios. Appointer-role revocation allows any user with the ability to grant a credential to also revoke it from a user; this is more preferable in cases where the original appointer may not always be available to revoke a credential in cases of emergency (e.g. a malicious user abusing the system). Finally system-managed revocation allows the system to automatically revoke a credential under set conditions. Three possible conditions for system-managed revocation are supported; time-based revocation, task-

based revocation and session-based revocation. Time-based system revocation forces an appointment to expire at a set time, task-based system revocation revokes an appointment once the user has completed some task (normally the task that required the appointment) and session-based system revocation in which appointments are revoked once the user's session ends or when the appointer's session ends.

3.1.1.2.2 Criticisms

The OASIS RBAC model provides a new take on the role based model, replacing direct role delegation with automatic role appointments based on a set of rules, and a user's qualifications. However, we have identified several issues with the OASIS model that would hinder its adoption in the cloud. These issues fall into the following categories:

1. Rejection of the Role Hierarchy
2. Scalability
3. Appointment vs. Delegation
4. Security

Rejection of the Role Hierarchy

Yao, Moody, & Bacon (2002) reject the need for a role hierarchy, viewing them as a violation of the principle of least privilege and questioning their utility in practice, despite their acceptance in many common models (Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001) (Nyanchama & Osborn, 1999) (Sandhu, Bhamidipati, & Munawer, 1999). They base this view mostly on the criticism offered by C. Goh and A. Baldwin (1998) which argues that role hierarchies rarely accurately model the real world roles of

an organization (Goh & Baldwin, 1998). While the role hierarchy does add additional complexities to a RBAC model and can in some cases affect the application of the principle of least privilege, we believe it is critical for several key reasons, including proper support of a distributed cloud RBAC.

First, while introducing a role hierarchy may add additional complexities during the systems implementation, it often simplifies role administration once the system is in use. Take for example the case where a system has a default user role that grants a set of permissions to access various subsystems (such as viewing publicly available documents shared by other users of the system), several other roles needing to contain all permissions of the user role plus additional permissions to various sub systems (such as viewing documents limited to select roles), and an administrator role containing the privileges of all other roles. Without a RBAC hierarchy, an RBAC administer would be left with two choices: either creating each role and manually adding the permissions of the lower role (e.g. each role would manually be given the permissions of the user role and the administrator role would be given the permissions of all other roles) or creating each role missing the permissions of the lower role and requiring users to activate multiple roles. The first choice is problematic for maintaining a role's permission set (i.e. when the user role changes, every other role needs its set updated manually) and the creation of a large number of roles sharing the same subset of permissions is time consuming and error-prone. The second choice, while avoiding issues of updating all role's permission sets when the user role changes, requires a RBAC system to support multiple role activations (which is not always desired) and additionally requires that users of the system activate the lower roles with the higher ones (e.g. the default user role would need to be activated with any more privileged role). If not automated this would

lower the usability of the system, requiring that users know which set of roles need to be activated in conjunction with a given role to perform a task.

Secondly, while the claim that a role hierarchy creates issues for enforcing the principle of least privilege is true for some cases, such as would be the case if all system administrators were assigned the max role (the role which inherits permissions from all others), it is not necessarily the case when the role hierarchy/graph is properly managed. In fact a hierarchy of roles can even aid in the automatic activation and deactivation of roles as needed. Consider the following case where role hierarchy is created such that a minimal role (containing only bare minimum permissions to use the system) is extended/inherited by each subsequent role which is in turn extended/inherited by any role whose permission set contains a subset equal to the permission set of another role until a maximum role is reached that contains the set of all permissions such that there is a path from the minimum role to the maximum role through all roles. In this case there is a clear path that role escalation can follow such that a user may start by activating the least privileged role (the minimum role) and move along the path of roles they are assigned when a higher level of privilege is needed (reversely, roles may be switched with lower privileged roles when the level of access is no longer needed). Proper creation of roles (such that they do not contain unnecessary permissions for tasks of a member of that role) and a mechanism to encourage users to only activate the minimum role required for a given task can counter most violations of the principle of least privilege that may occur from the use of a role hierarchy.

Finally, a lack of a role hierarchy may pose an issue for a distributed RBAC system with equal domains. In some cases it may be desired that a certain domain or entity “own” a role or permission, such that they are the only one authorized to make changes to that role or assign that permission. For example, a hospital may divide their

RBAC system into domains represented by the real departments of the organization such that the administration holds the main sets of permissions and common roles. The administration could then allow certain roles to be extended/inherited by roles of other specified domains such that they may assign their own permission upon it. For example, the administration could create a role called “accounts” which enables the holder to access the hospitals accounting records and grant the accounts department/domain the right to extended it by having a set of roles inherit its permissions. The accounts department could then add their own specific permissions to create fine grained access control to their own department’s roles (this could be accomplished either with negative permissions which remove permissions from a parent role or more likely by having the accounting system require that a user has some subset of permissions from the “accounts” role in addition to some subset of permissions from a child role created by the accounts domain to access or perform an operation on a given resource). This enables the administration domain to have ultimate control over their permissions while allowing other domains to still add fine grade control and add their own roles (Note that we present such a distributed RBAC system in section 3.1.2).

Scalability

Another issue with the OASIS model is the requirement to have a notification system between RBAC systems, user credential database and the systems using their access control services. In theory the notification system provides means to notify services when a user’s credentials or other requirements (which determine a user’s role) change, are removed or new credentials are added. Additionally, this mechanism allows for the immediate revocation of a user’s sessions in the case of a compromised account or malicious behavior. While notifications allow for quicker responses to changes in a user’s

role sets (via changes in their credentials), it creates scalability issues for large scale distributed RBAC systems. In such systems, which might involve thousands of users and RBAC service consumers, where user and credential database updates may trigger notifications to a large set of services and each service needs to maintain a notification channel with the role issuer, scalability may quickly become an issue. As there are currently no large scale OASIS implementations and the notification specification is somewhat vague, it is currently difficult to fully evaluate the model's scalability.

Appointment vs. Delegation

Unlike more traditional RBAC models, OASIS uses a system of appointment rather than role delegation. In the OASIS model any user active in an appointment role may grant other users of the system credentials for which the appointment role authorizes. This allows for cases such as a hospital administrator granting medical credentials to other users (such as doctors) without themself having the given credential (this in opposition to delegation models where a user must have role or permission to further delegate it to another user). OASIS roles are then granted based on a rule set listing the required credentials to activate a role. While this method simplifies role administration (as no direct mapping of users to roles is required) it adds some complexities in terms of calculating a user's possible permission set, preventing accidental role appointments and creating potentially complex rule sets for assigning roles.

In RBAC models such as the ANSI standard, ARBAC'96, etc. calculating the overall possible permission set of a user (i.e. the set of permissions a user may access through role activation) is somewhat trivial; the set of all roles a user may activate are found, and then the set of all permissions those roles are mapped to are found, which

together compose the user's overall permission set. In OASIS, role appointment is based on potentially complex rules involving both the user's credentials and environment variables such as the current date/time. This means that the set of possible permissions a user may access through role activation is not static but is changing based on environment variables that may be different on each system a user may have access to. While the ability to accurately calculate such a set of permissions is not critical to the function of such an RBAC system, it may be important for its administration (i.e. allowing an RBAC administer to view what permissions a user may be granted through role activation).

As no administrator is necessarily responsible for direct role assignment or delegation, it may quickly become confusing as to what credential may indirectly grant what role in large OASIS based RBAC system. A hospital administer with the ability to grant medical based credentials in the system may not have a full understanding of the effect they will have on set of roles a user may activate. In many cases a user of the system may come to such an administer requesting access to a particular permission (e.g. permission to sign off on a lab report while the normal supervisor is away), however, it may not necessarily be clear what credential needs to be appointed to the user to access this permission. This kind of role appointment also is largely dependent on an RBAC administer correctly identifying what credentials and rules should grant every role. For large organizations this may be a daunting task where simple mistakes may grant normally unauthorized users powerful roles. Traditional role delegation requires an RBAC administer to directly assign roles to users reducing the possibility of error and limiting its effect to a single user (or single group if roles may be delegated to groups of users at once).

Security

Recent work by A. Belokosztolszki and D. Eyers (2002) has identified several potential security weaknesses in the OASIS model when applied to a large scale system (Belokosztolszki & Eyers, 2002). A. Belokosztolszki, et al. (2002) suggest that a large scale EHR system may be a potential target for cyber-terrorism and list potential points of attack in the heartbeat based notification system, the threshold-based rule evaluation and bounded session durations (DoS type attacks against OASIS services). They also provided potential changes to the OASIS model to solve most of these issues.

3.1.2 A New Take on RBAC (RBAC as a Service)

3.1.2.1 Introduction

This section presents a new model for role based access control which aims to fulfill the required qualities of an RBAC system for the cloud introduced in section 3.1.1. That is, be scalable, distributed, auditable, enforced confidentiality, provide simple administration and be reliable. This is accomplished by dividing the traditionally centralized RBAC system among multiple system domains. Each domain is enabled to create and assign roles to their users, create and assign their own permissions, and more importantly, extend the roles and permissions of other domains via inheritance in the role and/or permission hierarches.

Additionally, a system for conditional permissions and user groups is introduced. Users activating roles with conditional permissions are only granted the permission if set conditions are met at the time of role activation and the permissions use. Conditional groups only allow membership to a user if they meet a set condition at the time of authentication (e.g. a condition may require that a user be authenticating from a given

network or IP range). The process of user parameterization allows users to be assigned parameters which may be checked in these conditions. For example, a parameter may be created which indicates that a user has been granted some safety certificate and a conditional group may be created to only allow users with the corresponding parameter to activate a given role (e.g. a role which has permissions for accessing and using equipment in a lab).

RBAC systems implementing this model offer access control to cloud services via a scalable web service interface and client API. A namespace is detailed which allows services to distinguish between RBAC elements from different domains and prevent any conflicting identities from being created. A system for enforcing session revocation is also detailed, as are potential use cases for the system.

3.1.2.2 Model Description

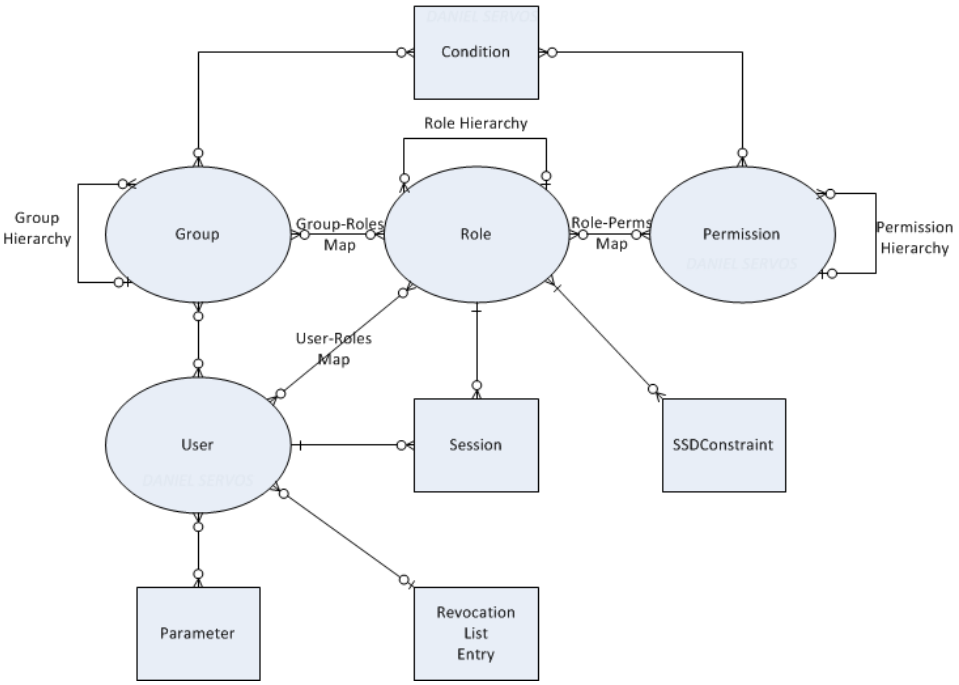


Figure 3.6: RBACaaS Model.

The Role Based Access Control as a Service (RBACaaS) model is based on the NIST standard and aims to resolve several of the issues with the NIST standard and provide distributed role based access control services from the cloud via a web service interface. The core model (as shown in Figure 3.6) is composed of four main elements; Users, Groups, Roles and Permissions. Users represent any actor in a system for which access control may need to be applied (e.g. web services, real persons, third party systems, etc.). Groups represent a subset of users which share the same roles based on their membership in the group. Groups allow for simplified administration when it is common for multiple users to fulfill the same set of roles in a system; our model also enables the conditional mapping of users to roles based on user and system parameters. All groups are part of the group tree (as shown in Figure 3.7) and inherit the roles of their parent group node assuming the set conditions are met.

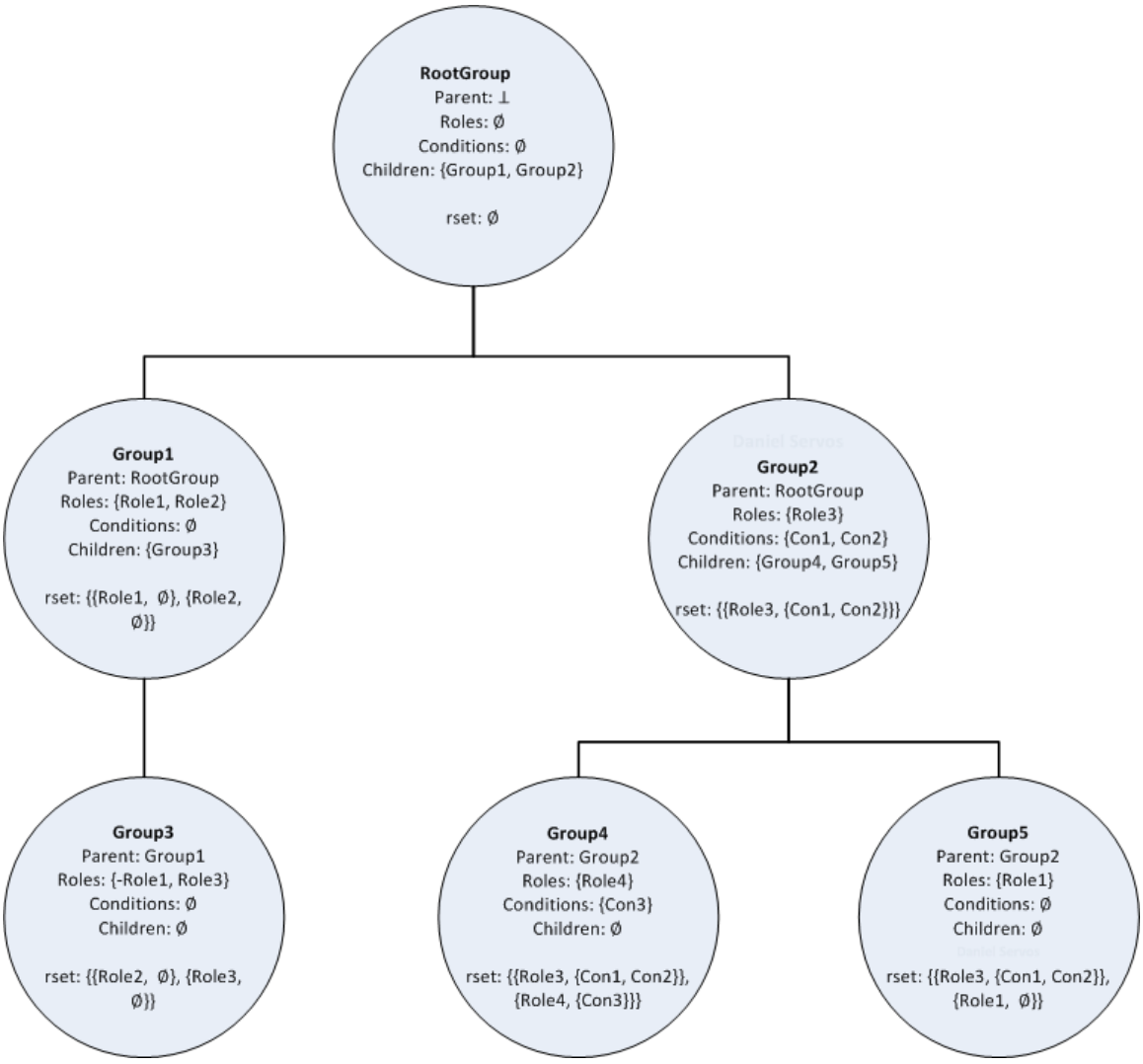


Figure 3.7: Example group tree. All groups descend from the root group which contains no roles or conditions.

Roles provide a mapping between either a group or an individual user to a set of permissions. Like groups, all roles are part of the role tree (as shown in Figure 3.8) and inherit the permissions of their parent role. A permission in our model represents some level of access to a single or group of objects in the implementing system which may be dependent on some set of conditions evaluated at the time of access. An object may be a service, operation, file, physical resource, database, record, or any other physical or logical component to which access control may be applied. The mapping of the logical permission to one or more system objects is left to the implementing entity but is

commonly related to the permissions namespace (more details in subsection 3.1.2.2.1). Like roles and groups, permissions are also hierarchical in nature, however, unlike roles and groups, the root permission node contains all access to a given system and each child node refines and limits that access to a specific set of objects. Also unlike ridged tree data structure used by groups and roles, the permission hierarchy is enforced by the name space rather than the data model (see Figure 3.9 for an example permission hierarchy).

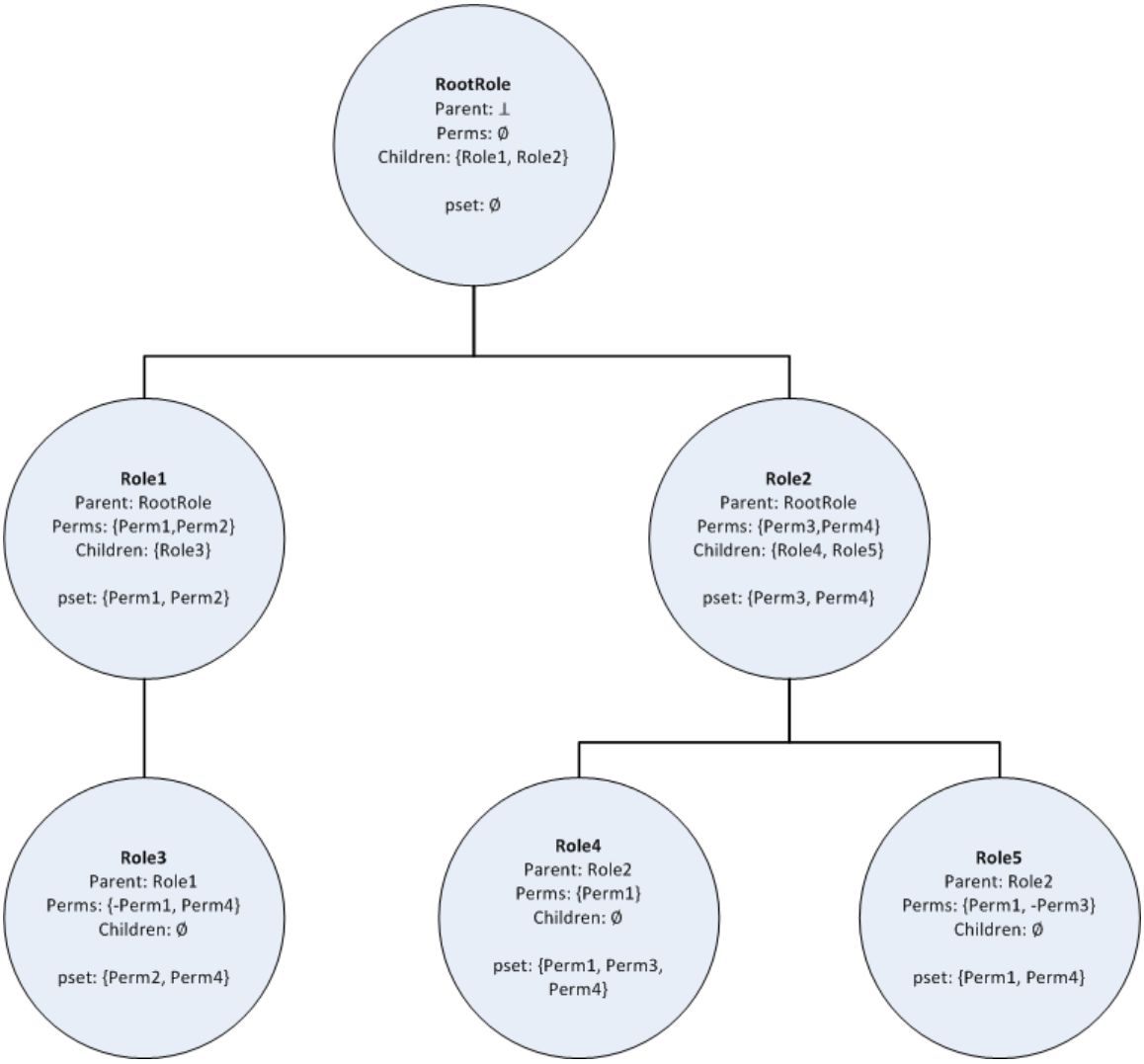


Figure 3.8: Example role tree. All roles descend from the root role which contains no permissions.

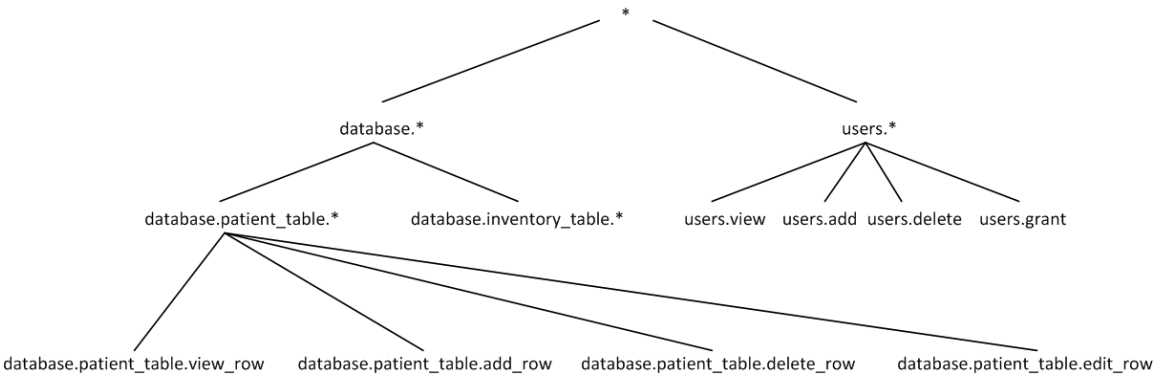


Figure 3.9: Example namespace enforced permissions tree. All permissions descend from the '*' permission node.

3.1.2.2.1 Namespace

The following uniform resourced identifier (URI) based naming scheme is used in the RBACaaS model to uniquely identify members of each model element across multiple distributed systems:

```
rbac_uri            =  "RBAC:" element_types ":" id
                    /  "RBAC:perm:" perm_id


element_types       = "user"
                    / "group"
                    / "role"
                    / "cond"
                    / "const"
                    / "param"

id                  = domain ":" sid

perm_id             = domain ":" perm_sid

domain              = (ALPHA / DIGIT) *( ALPHA / DIGIT / "-" / ".") ["_" port]

port                = ( 1-9 ) *( DIGIT )

sid                 = +( ALPHA / DIGIT / "-" / "." / "*" / "_")

perm_sid            = "*" / ( +( ALPHA / DIGIT / "-" / "_") "." perm_id )
```

Figure 3.10: RBAC URI grammar.

Element Type

Each model element (Users, Groups, Roles, Permissions, Conditions, SSDConstraints, and User Parameters) is assigned an unique type as detailed in Figure 3.10 and used as part of the element members full URI.

Examples: user, group, role, cond, const, parm, perm

Domain

Each system running or storing an RBACaaS component is considered to be a domain of that system and is assigned a unique identifier that corresponds to that system's hostname on the network. Optionally, a port number may be appended to the host name to support multiple domains on the same system or offered on abnormal ports.

Examples: lakeheadu.ca, clutch.lakeheadu.ca, cloud.lakeheadu.ca_3434

ID

Each RBAC element in the system is assigned an identifier that is globally unique for that element type. This ID is a combination of the local system's domain and a locally unique identifier (SID). As it is assumed that all domains are globally unique in a given RBAC system, it follows that all IDs should be globally unique if the SID is locally unique. For permission elements, the same ID rules apply but there are more restrictions placed on the SID.

Examples: lakeheadu.ca:bob, cluch.lakeheadu.ca: alice, cloud.lakeheadu.ca_3434:user.view.*

SID

The simple ID (SID) is a locally unique identifier for a member of an element within that element's namespace. The SID may be used to refer to the member within the local domain, however, a full ID is required to refer to members from distributed systems. For permissions, special restrictions apply to SIDs to create the permission hierarchy such that every permission SID ends with ".*", starts with a letter, digit or is simply a single '*', and contains at least one digit or letter between each set of '.'s.

Examples: bob, alice, user.view.*

3.1.2.2.1 Parameterization and Conditions

The RBACaaS model allows for both a static direct assignment of roles to users and the dynamic assignment of roles to groups of users dependent on set conditions evaluated at the time of session creation. Conditions are simple Boolean expressions involving a constant value, user parameter or system parameter of the following grammar:

```
condition    =  exp [ bool_op condition ]

exp          =  var op var
             /  ["!"] bool_var
             /  ["!"] "(" condition ")"

var          =  const
             /  user_param
             /  system_param

bool_var     = boolean
             / user_param
             / system_param
```

```
op           =  “>” / “<” / “=” / “>=” / “<=” / “!=”

boolvar      = “AND” / “OR”

user_param   =  id

system_param =  “SYSTEM:” sid

const        =  int
             /  float
             /  string

int          =   [“-”] ( 1-9 ) *( DIGIT )
             /   “0”

float        =   int “.” +( DIGIT )

string       =  “\”” *( ALPHA / DIGIT / “-“ / “.” / “*” / “_” / “:”) “\””

boolean      =   “TRUE” / “FALSE”
```

Figure 3.11: Condition grammar.

User parameters are a simple mapping of a parameter name (user_param in the grammar) to a string, integer, boolean or floating point value (more complex types may be built upon these primitives, e.g. a date could be stored as an integer). This parameterization of users allows for RBAC administrators to tag users with values based on their profile in the organization and create dynamic rules granting access to different roles based on the user’s profile. For example, consider the use case of a lab technician at a hospital that is required to complete an online WHMIS safety course before they are granted the access role required to access any of the lab’s systems. They may be automatically granted the parameter “HOSPITAL_DOMAIN:WHMIS_SAFETY” with the value of “TRUE” once the course is completed and once combined with their membership in the LAB_TECHNICIAN group, this parameter may fulfill a condition granting them the role of “HOSPITAL_DOMAIN:LAB_ TECHNICIAN”.

System parameters function similarly to user parameters but have a dynamic value based on the current state of the system rather than being set by an RBAC

administrator. For example the “SYSTEM:TIME_STAMP” system parameter may contain the current date and time as a Unix time stamp (represented as an integer) and allow for the creation of groups which are only granted roles for a limited period of time (i.e. that expire after a set time and/or only become active after a set date). The table below shows the default system parameters that should be present in a given RBACaaS implementation:

Parameter Name	Type	Perm	Description
SYSTEM:TIME_STAMP	Integer	✓	The current date and time as a Unix time stamp.
SYSTEM:TIME_DAY	Integer	✓	A number [1, 31] representing the current day in the current month. Based on gregorian calendar and UTC.
SYSTEM:TIME_HOUR	Integer	✓	A number [0, 23] representing the current hour in UTC.
SYSTEM:TIME_MINUTE	Integer	✓	A number [0, 59] representing the current minute in UTC.
SYSTEM:TIME_SECOND	Integer	✓	A number [0, 59] representing the current second in UTC.
SYSTEM:TIME_WEEK_DAY	Integer	✓	The current week day represented by a number starting at 0 for Sunday and ending at 6 for Saturday. Based on UTC.
SYSTEM:TIME_MONTH	Integer	✓	A number [1, 12] representing the current UTC gregorian calendar month
SYSTEM:TIME_YEAR	Integer	✓	A number representing the current gregorian calendar year in UTC.
SYSTEM:USER_IP	Integer	✓	An integer representation of the user’s version 4 IP at the time they authenticated with the server.
SYSTEM:USER_IP_1	Integer	✓	An integer representation of the first byte of a user’s version 4 IP at the time they authenticated with the server.
SYSTEM:USER_IP_2	Integer	✓	An integer representation of the second byte of a user’s version 4 IP at the time they authenticated with the server.
SYSTEM:USER_IP_3	Integer	✓	An integer representation of the third byte of a user’s version 4 IP at the time they authenticated with the server.
SYSTEM:USER_IP_4	Integer	✓	An integer representation of the fourth byte of a user’s version 4 IP at the time they authenticated with the server.
SYSTEM:USER_HOST	String		A string containing the user’s hostname at the time they authenticated with the server.
SYSTEM:USER_HOST_DOMAIN	String		A string containing the domain part of a user’s hostname at the time they authenticated with the server.
SYSTEM:USER_DOMAIN	String		A string containing the server’s RBACaaS domain name.
SYSTEM:USER_DOMAIN_ID	Integer	✓	The ID assigned to the server’s RBACaaS

			domain.
SYSTEM:USER_ID	String		A string containing the user's RBACaaS ID.
SYSTEM:USER_SID	String		A string containing the user's RBACaaS SID.
SYSTEM:USER_GID	Integer	✓	The user's RBACaaS GID.
SYSTEM:USER_START_DATE	Integer	✓	A unix time stamp containing the date the user's account was activated.
SYSTEM:USER_END_DATE	Integer	✓	A unix time stamp containing the date the user's account will be or was deactivated or "0" if no such date is set.
SYSTEM:SESSION_START	Integer	✓	A unix time stamp containing the date and time the user's session was started.
SYSTEM:SESSION_EXPIRE	Integer	✓	A unix time stamp containing the date and time the user's session will expire.
SYSTEM:CLIENT_VERSION	Integer	✓	An integer representation of the version number of the client software the user used to authenticate with the server.
SYSTEM:SERVER_VERSION	Integer	✓	An integer representation of the version number of the server software being used.
SYSTEM:AUTH_METHOD	Integer	✓	An integer representing the authentication method used to authorize the user.

Table 3.1: Default system parameters.

In addition to applying conditions to group membership, the RBACaaS model also allows conditional permissions. Unlike group conditions that are evaluated when the user activates a role, permission conditions are evaluated when the user tries to access an object protected by the RBACaaS system. Access to encrypted resources is accomplished through the attribute based encryption scheme detailed in Chapter 4, with details on using the encryption scheme with RBACaaS given in subsection 5.1. Access to services and unencrypted resources is accomplished by the protected service implementing the RBACaaS client API and web service (detailed in Appendix B and C).

3.1.2.2.2 Sessions

Sessions in the RBACaaS model are defined as a set containing a role SID, user SID, start date, expiry date, IP address (of the user during authentication), and a RBACaaS domain (which the user authenticated with). Sessions are limited to single role activation as a means to indirectly enforce separation of duty between multiple roles. For

example, if there existed some protected object which required permissions A and B to access, and role 1 granted a user permission A, and role 2 granted a user permission B, a user assigned to both roles 1 and 2 could access the object if they were allowed to activate both roles simultaneously which is likely not the intention of the RBAC administrator. While this issue may be solved to a degree with a dynamic separation of duty system (such as the one described in the NIST model), it requires additional work by RBAC administrators to enforce and provides little benefit to end users. As an alternative, users may start multiple sessions containing different roles but may not combine their permissions (i.e. the user in the last example could not access the projected object but they would still have access to objects only protected with permissions A or B but not both). Only allowing single role activation also helps enforce the principle of least privilege; rather than activating multiple or all available roles simultaneously users may start in their least privileged role and only activate higher roles when the privilege is required.

Sessions are granted by RBACaaS authentication services to users in the same domain upon presenting credentials and role activation. The authentication service issues an auth token (as described in section 3.2) which contains the session set, the set of permissions the role grants, and a digital signature ensuring it was issued by the stated RBACaaS server. The authtoken is then used to authenticate with and share the session with remote services for the stated role and permission set in accordance with the RBSSO protocol (section 3.2).

3.1.2.2.3 Constraints

In addition to the separation of duty protection provided by signal role activation, the RBACaaS model also provides tools for enforcing a static separation of duty (SSD) constraint on what roles a user may be granted. RBAC administrators may create constraints on a set of roles, limiting each user in the system to only holding at most a fixed number of roles in the constraint set. SSD constraints are enforced at the time of role assignment and include roles gained through group membership.

3.1.2.2.4 Negative Permissions and Roles

RBACaaS has limited support for negative permissions and roles. Negative permissions allow RBAC administrators to remove permissions from roles that would otherwise be inherited from a parent role. This allows for simplified role administration as administrators may create roles which have the same permissions as an existing role (by inheriting it) but with some set of permissions removed. Similarly, negative roles allow for the removal of roles from a user group that would otherwise be inherited from a parent group.

3.1.2.2.5 Revocation

While the RBACaaS authentication service for each domain keeps an updated database of users and the required credentials to authenticate them, the distributed nature of the system would still allow an active session to be used until the expiry date is met. As it may be required for sessions to be terminated sooner when sensitive data is involved, a revocation list is provided to list sessions which have become invalidated. This is accomplished through each domain publishing a public list of active session IDs

which correspond to sessions which should be treated as expired (despite not yet reaching the expiry date). The revocation of user's attribute encryption keys is a more complex issue detailed in section 4.3.2.9; more details on user sessions are given in section 3.2.

3.1.2.2.6 Distributed Function

To provide scalable RBAC services to remote systems and to allow for multiple parties to control their own user credentials and access rights, the RBACaaS system uses multiple distributed components. These components include the domain authentication service, the domain RBAC service, the domain administrative service, RBAC clients, and the user clients. Each organization or party with an independent set of users, services and resources they wish to protect is considered to be a unique "domain" within the system. For example, in a system for sharing health records a single hospital may be considered a domain, as would a doctor's office, clinic or research group. Every domain is assigned a unique numeric ID and name string (as detailed in Figure 3.10 and normally corresponding to the hostname of the domains RBAC service) at the time of creation (the initial setup of the domain's authentication and RBAC services).

Authentication Service

Each domain operates at least one authentication service that is responsible for managing user records, credentials and user authentication within that domain. Each authentication service handles user authentication requests (with the RBSSO protocol detailed in section 3.2.2) based on matching user's presented credentials with existing user records in an organization's database. The only requirements imposed by the authentication service on the underlining user database is that each user be assigned a

unique numeric ID and RBAC URI (as detailed in Figure 3.10) within the domain. Upon receiving a request for user authentication and role activation, the service first validates the user's credentials, and then connects to the domain's RBAC service to verify that the user possesses access to that role (and that all conditions are met if the role is available only through a group) and retrieve the set of all permissions the role grants the user and their conditions, as well as the set of the user's parameters and their values. Finally, if all group conditions and verifications are met the service starts a user session by issuing the user an "auth token" containing the list of permissions, the list of parameters and a DMACPSABE key (section 4.3).

Multiple authentication services may be run within the same domain to ensure scalability and reliability so long as the underlining user database used is properly synchronized within the domain (e.g. MySQL master/slave setup where services read from different slaves and writes are only done to the master) or the same database is used for all service instances.

RBAC Service

The RBAC service is a web service that provides the core RBAC operations for a given domain in an RBACaaS system. The RBAC service stores the RBACaaS model (Figure 3.6) data being used for the domain (i.e. roles, groups, conditions, permissions, sessions, SSD constraints, user parameters and their maps to each other and users of the domain) and responds to requests from both the domain's authentication service and systems implementing the RBACaaS API for protecting a resource, service or other object. RBAC services are also responsible for requesting information from and responding to requests from other domain's RBAC services, for example each RBAC service contains a mapping of parameter and permission RBAC URIs to DMACPSABE

attribute names (see section 4.3 and 4.3.2.8) that is made available to other RBAC services upon request.

RBAC services are linked together in a hierarchical method similar to that used by the Domain Name System (DNS). Each RBAC service may have a parent for which it may extend any roles, groups or permissions (by creating new roles, groups, etc. which inherit a role, group, etc. owned by the parent RBAC service) and assign users to groups, roles and parameters owned by both itself and its ancestors. Similarly, each service may also have 0 or more child services. Each domain may have multiple RBAC services (to balance load, and increase readability) so long as they all descend from a signal RBAC service also within that domain (as show in Figure 3.12). Each service keeps a list of approved children that will receive notifications when an update is made to any RBAC element and the permission and role cache need updating. Child RBAC services may also directly request a listing of RBAC elements in their relations from their parent as well as their parent's ancestors.

For more details on the interface provided by RBAC services see Appendix B.

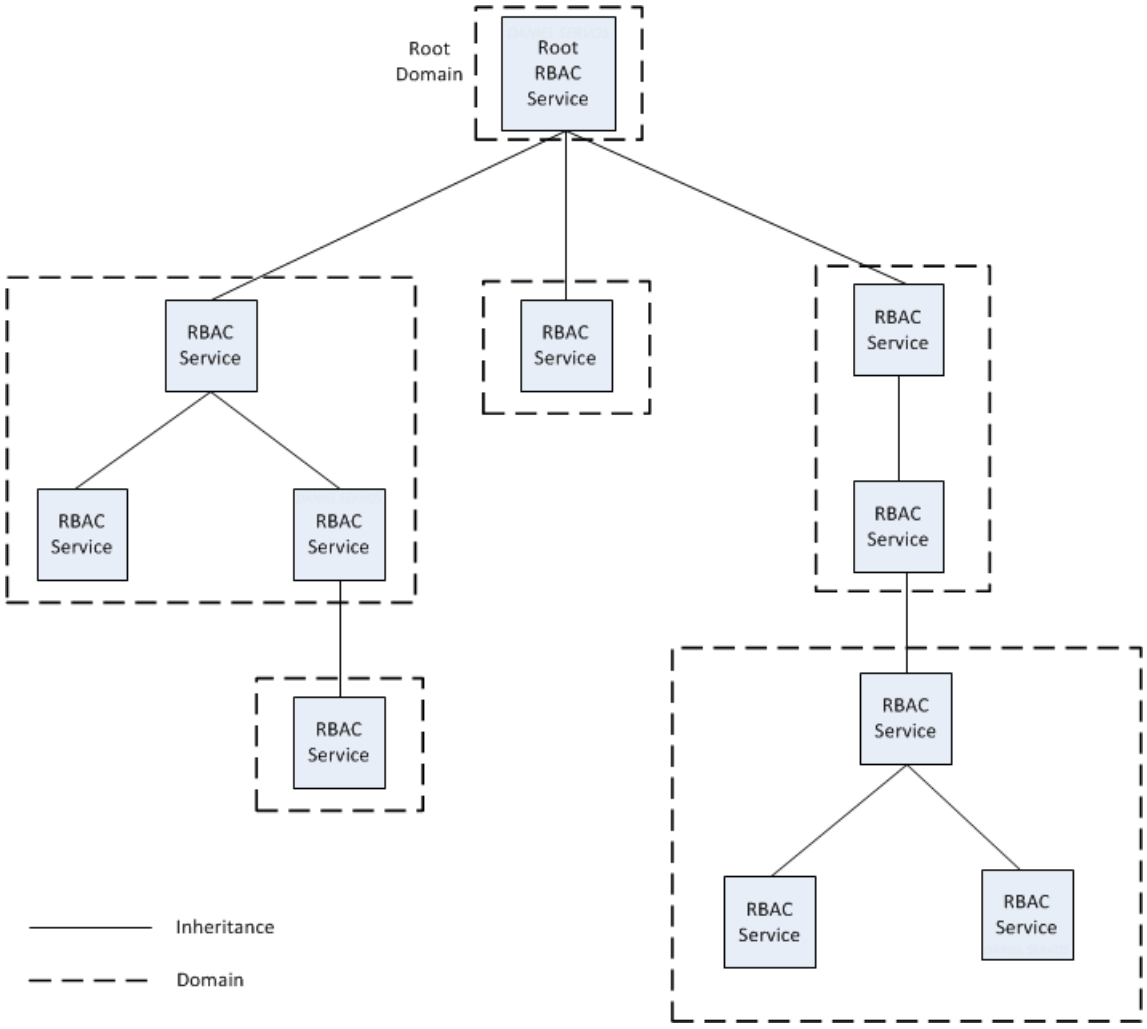


Figure 3.12: Example RBAC service hierarchy.

Administrative Service

The administrative service is a web service paired with the RBAC service that offers administrative functions for the data (RBAC elements and relations) severed by the RBAC service. The administrative service itself is protected by the same RBACaaS system that it administers (permissions for administrative functions are listed in Appendix B.2 and exist in the system by default for each domain). The administrative service interface is also further detailed in Appendix B.2 and functions listed in Appendix D.5.

RBAC Clients and API

RBACaaS provides an API for RBAC Clients (the systems using RBACaaS to protect a resource, service or object) to authenticate users (based on their provided auth token), validate that they should have access to a given resource based on a simple Boolean statement involving permissions and encrypt documents using the DMACPSABE scheme presented in Chapter 4. The most notable part of the API is the *hasPermssion* method which takes a Boolean statement (for which the grammar is given in Figure 3.13) involving one or more RBACaaS permissions with "AND" or "OR" operations. If *hasPermssion* returns true the user has passed the permission requirements in the Boolean statement which is determined based on the contents of the user's auth token. As the auth token contains the set of permission/condition pairs for the activated role and the set of the user's parameter/value pairs, the method is able to check that the user's permission set meets the requirements of the statement and that if the permission is conditional the conditions are met by the user's parameter/value set. Additionally the *hasPermssion* method may check the session ID against the last copy of the revocation list the client has obtained from the RBAC service.

```
condition    =  exp [op condition ]

exp          =  perm
             /  "(" condition ")"

op           = "AND" / "OR"

perm         = "RBAC:perm:" perm_id
```

Figure 3.13: Grammar for *hasPermission* Boolean statement. Note that *perm_id* is from Figure 3.10.

Encrypting documents using a similar method as *hasPermission* (similar in that they both take the same Boolean statement), *encryptWithPermissions* allows data to be protected with the same RBAC model, permissions and conditions in offline

environments which may be isolated from the RBAC service for long periods of time or even indefinitely. Rather than an active service which handles user authentication, the access policy is embedded in the ciphertext and only decryptable once the user is given the proper “attributes” in their DMACPSABE key which meet access policy (this is accomplished with the ciphertext policy attribute based encryption scheme presented in chapter 4 and details for its use and integration with RBACaaS are given in section 5.1). The *encryptWithPermissions* function is responsible for translating the given Boolean statement using permissions into a proper DMACPSABE access policy using attribute names (which may require a request to the RBAC service to lookup). Additional details on the Client API are given in Appendix C.

3.1.2.2.7 Web Service Interfaces, Client API and Formal Description

Appendix B details the RBAC web service and administrative interfaces for RBACaaS. Appendix C gives details on the client API services use to enable RBACaaS access controls. Appendix D gives a simplified formal description of the RBACaaS model which omits the distributed function.

3.1.2.2.8 Permissions Set and Role List Caching

As the model in Figure 3.6 has multiple many-to-many relations between RBAC elements, several performance improvements are required to make the model useable and scalable. The first of these improvements is the permissions set cache (*pset*), which stores an updated set of permissions/condition pairs calculated using *comp_role_pset* (see Appendix D.4) when there has been an update to a role. The *pset* cache allows for a quick look up of permissions for a given role and their corresponding conditions during role

activation and the creation of an auth token. The second cache based improvement is the role list cache (*rset*), which stores an updated set of role/condition pairs, calculated using *comp_group_roles* (see Appendix D.4) when there has been an update to a group. The *rset* cache allows for quick look ups of roles granted by a group and the conditions that must be met for them to be activated by a user.

3.1.2.2.9 Example Use Case

This section introduces a health care related use case for intrahospital EHR protection using the RBACaaS system. In this case it is assumed that all initialization and setup steps have been performed (e.g. creation of user credentials, set of the RBAC and authentication services, DMACPSABE authority and master key generation, etc.) and the health records in question have already been created with the policy stated in the case.

Intrahospital Protection of EHRs

For this case we assume a simplified view of a hospital which is divided into three departments; medical (consisting of doctors seeing patients), lab (consisting of lab techs doing work ordered by doctors) and billing/insurance (consisting of accounting clerks processing insurance claims, sending invoices to patients, etc.). The goal is to provide doctors in the medical department with access to all medical information in a given EHR (including lab results) while limiting their access to insurance and billing information; to allow lab technicians in the lab department to only view lab related parts of an EHR and no identifying information, billing information or unneeded medical information, and to allow accounting clerks to only view billing and insurance related information. Additionally, we want to restrict the clerks to only accessing records during business

hours (9am to 5pm) and doctors to only viewing records while authenticating from the hospital's network.

The first step to accomplishing these goals is the creation of the permissions which enable access to the various parts of a health record. It is assumed that the EHR format being used is divided in to 4 parts: identification information (contact details, and general information about the patient), medical history (detailed medical history and notes, not including lab reports), lab results (results of lab work done on the patient), and insurance/billing information. The required permissions are displayed in the following table (note that the system parameters in the conditions column are from Table 5.1):

Permission Name (SID)	Conditions	Description
`EHR.*`		All access rights to EHR documents.
`EHR.view.*`		Access to view any part of an EHR.
`EHR.edit.*`		Access to edit any part of an EHR.
`EHR.view.ident.*`		Access to view the identification information part of an EHR.
`EHR.view.medical.*`		Access to view the medical history part of an EHR.
`EHR.view.lab.*`		Access to view the lab results part of an EHR.
`EHR.view.insurace.*`		Access to view the insurance information part of an EHR.
`EHR.edit.ident.*`		Access to edit the identification information part of an EHR.
`EHR.edit.medical.*`		Access to edit the medical history part of an EHR.
`EHR.edit.lab.*`		Access to edit the lab results part of an EHR.
`EHR.edit.insurace.*`		Access to edit the insurance information part of an EHR.
`EHR.view.ident.intranet`	`SYSTEM:USER_IP_1 == 192 AND SYSTEM:USER_IP_2 == 168 AND (SYSTEM:USER_IP_3 == 100 OR SYSTEM:USER_IP_3 == 110)`	Access to view the identification information part of an EHR but only from the 192.168.100.* or 192.168.110.* subnets.
`EHR.view.medical.intranet`	`SYSTEM:USER_IP_1 == 192 AND SYSTEM:USER_IP_2 == 168 AND (SYSTEM:USER_IP_3 == 100 OR SYSTEM:USER_IP_3 == 110)`	Access to view the medical history part of an EHR but only from the 192.168.100.* or 192.168.110.* subnets.

EHR.view.medical.intranet	SYSTEM:USER_IP_1 == 192 AND SYSTEM:USER_IP_2 == 168 AND (SYSTEM:USER_IP_3 == 100 OR SYSTEM:USER_IP_3 == 110)	Access to view the lab results part of an EHR but only from the 192.168.100.* or 192.168.110.* subnets.
EHR.view.insurace.bizhours	SYSTEM:TIME_HOUR >= 9 AND SYSTEM:TIME_HOUR <= 17	Access to view the insurance information part of an EHR but only between 9am and 5pm.
EHR.edit.medical.intranet	SYSTEM:USER_IP_1 == 192 AND SYSTEM:USER_IP_2 == 168 AND (SYSTEM:USER_IP_3 == 100 OR SYSTEM:USER_IP_3 == 110)	Access to edit the medical history part of an EHR but only from the 192.168.100.* or 192.168.110.* subnets.
EHR.eidt.lab.intranet	SYSTEM:USER_IP_1 == 192 AND SYSTEM:USER_IP_2 == 168 AND (SYSTEM:USER_IP_3 == 100 OR SYSTEM:USER_IP_3 == 110)	Access to edit the medical history part of an EHR but only from the 192.168.100.* or 192.168.110.* subnets.

Table 3.2: Table of permissions required for 1st RBACaaS use case.

Next, roles are created for the doctors, lab technicians, and insurance clerks and permissions are mapped to the roles to grant access to EHRs:

Role Name (SID)	Permissions	Description
Doctor	EHR.view.ident.intranet EHR.view.medical.intranet EHR.view.lab.intranet EHR.edit.medical.intranet EHR.eidt.lab.intranet	Doctor role with permission to view an EHRs identification, medical, and lab parts, and permission to edit the medical and lab parts. Permissions are only valid from hospital intranet (due to conditions on permissions).
Technician	EHR.view.lab.* EHR.edit.lab.*	Technician role with permission to edit and view the lab portion of an EHR.
Clerk	EHR.view.insurace.bizhours	Clerk role with permission to view an EHRs insurance information but only during business hours.

Table 3.3: Table of roles required for 1st RBACaaS use case.

Finally, the roles are mapped appropriately to each user of the department who needs EHR access: users in the medical department being granted the Doctor role, users in the lab department being mapped the Technician role and users of the billing/insurance department being mapped the Clerk role.

Once the described roles, permissions and conditions have been created, the EHRs in the system may be encrypted using the *encryptWithPermission* function in the RBACaaS client API (see Appendix C) as follows:

EHR Section	Encryption Policy
Identification Information	`EHR.* OR EHR.view.* OR EHR.view.ident.* OR EHR.view.ident.intranet`
Medical History	`EHR.* OR EHR.view.* OR EHR.view.medical.* OR EHR.view.medical.intranet`
Lab Reports	`EHR.* OR EHR.view.* OR EHR.view.lab.* OR EHR.view.lab.intranet`
Insurance/Billing Information	`EHR.* OR EHR.view.* OR EHR.view.insurance.* OR EHR.view.insurace.bizhours`

Table 3.4: Table of encryption polices for 1st RBACaaS use case.

The *encryptWithPermission* function (for which more details are given in section 5.1.1) replaces permissions with their corresponding DMACPSABE attributes and conditional permissions with a statement involving the condition. For example, the encryption policy for the insurance/billing section becomes:

```
EHR.* OR EHR.view.* OR EHR.view.insurance.* OR (EHR.view.insurace.bizhours AND
(SYSTEM:TIME_HOUR >= 9 AND SYSTEM:TIME_HOUR <= 17))
```

Additionally, the rules from Table 5.2 are appended to the policy to enforce system wide polices such as key expiration dates, minimum client versions, acceptable authentication methods, etc.

Once protected, the EHRs may be safely moved to cloud based storage and made available with cloud based services such as HCX from Chapter 2. Such services enforce the edit permissions using the *hasPermission* function from the RBACaaS client API to check if a requesting user has the proper permissions to update a given section of a file (the service gets proof of a user's permissions granted by an active role from the authtoken described in section 3.2.1). The user sends the service an updated ciphertext for

a given section of the EHR and the service runs *hasPermission* to check for compliance with the following polices:

EHR Section	Edit Policy
Identification Information	`EHR.* OR EHR.edit.* OR EHR.edit.ident.*`
Medical History	`EHR.* OR EHR.edit.* OR EHR.edit.medical.* OR EHR.edit.medical.intranet`
Lab Reports	`EHR.* OR EHR.edit.* OR EHR.edit.lab.* OR EHR.edit.lab.intranet`
Insurance/Billing Information	`EHR.* OR EHR.edit.* OR EHR.edit.insurance.*`

Table 3.5: Table of edit polices for the 1st RBACaaS use case.

As with the encryption policies and the *encryptWithPermission* function, conditional permissions are appended with their condition and all policies are appended with the rules from Table 5.2.

Hospital users of all departments may access EHRs (for which they have access) by authenticating with the hospital's local authentication service using the RBSSO protocol (detailed in section 3.2.1) and activating a single role. Once the user is authenticated, the authentication service issues the user a secret DMACPSABE key (containing the user's attributes) and an authtoken containing the permissions for the activated role, the user's parameter name/value set, additional details described in 3.2.1 and a digital signature proving the token came from the authentication service and has not been edited. To request an EHR or update a section of an EHR, the user creates a requesttoken and sends the request, requesttoken and authtoken to the EHR service. If all tokens are valid and the request meets the access policy, the EHR service either updates the EHR or sends the encrypted EHR to the user (depending on the request type). Users may decrypt sections of the EHR using the secret DMACPSABE key they received from the authentication service assuming their attribute set meets the policy (this is made possible with the DMACPSABE scheme presented in Chapter 4).

3.2 Single Sign On

A critical component for a distributed authentication system not covered by our RBAC as a Service model is the protocol and mechanism by which user sessions are authorized and securely propagated to remote services. Centralizing this task as a single authentication server or role server would create new bottle necks in the system and limit the scalability gain from using a distributed model. To solve issues relating to sessions in our disturbed RBAC model we have created an accompanying Single Sign On (SSO) model, protocol and prototype called Role Based Single Sign On (RBSSO).

3.2.1 RBSSO Description

The RBSSO protocol attempts to accomplish the following goals in its design:

1. **Distributed**: a SSO system for the cloud should ideally be distributed rather than centralized to match the distributed computing potential of most cloud computing infrastructure. The systems overall functionality should be unaffected by nodes coming and going on/offline at random intervals and scaled by simply adding additional nodes. No or few centralized points of failure should be present in the system.
2. **Isolated**: User credentials and personal details should be isolated from the public and potently untrustworthy cloud. Cloud based services should only be granted the minimum amount of information to authenticate a user and grant access to a service.
3. **Scalable**: The SSO system should be scalable simply by adding additional nodes to a public or private cloud. Costly operations such as communications between

virtual cloud resources and between users and cloud resources should be minimized to prevent network bottle necks.

4. **Secure**: The SSO system should be secure enough to comply with data privacy laws such as PIPEDA, HIPA and HIPAA, as well as provide a reasonable level of assurance to users that their accounts are secure even when operating on a public cloud.
5. **Convenient**: The system should provide maximum convenience and usability to both the systems users and administrators. E.g. not requiring user to sign in to each cloud based service individually.
6. **Compatibility**: Be compatible with most common cloud computing infrastructure (i.e. Amazon web services and Eucalyptus) and take full advantage of the RBACaaS mode described before.

The RBSSO model defines the following major components necessary for client single sign on authentication with cloud based services:

1. **Authentication Servers (AuthServers)**: Servers or nodes which handle user authentication requests and issue AuthTokens. AuthServers are hosted on the trusted network for an organization who wishes to access cloud services.
2. **RBAC Service**: RBACaaS RBAC service which stores the roles and relations for the RBACaaS system. May be combined with an AuthServer.
3. **Cloud Based Services**: Services offered on a potentially untrusted cloud and service clients of the RBACaaS system wishing to secure a resource.
4. **Service Controllers**: Systems located on a trusted network that are responsible for spawning new machine instances on an untrusted cloud which run cloud base services and initialize them with their initial data.

5. **End User Clients**: Clients of the system and their software and hardware components.

3.2.1.1 Authentication Servers

To distribute the load of user authentication, isolate user credentials to their organization and trusted network and keep administration of user accounts within an organization authority, authentication servers are distributed among the organizations that require access to the publicly hosted cloud based services and run on the organization's presumably trusted network. Using this model, organizations are made responsible for their own user accounts and the scalability of their authentication services. For example, if a set of cloud based services were created to share electronic health records between hospital, clinics, doctors' offices and emergency medical services, each would host their own authentication server on their own network (see Figure 3.14).

Before use, Authentication Servers are first initialized with two public/private key pairs, (AKsigpub, AKsigpri) and (AKencpub, AKencpri) which they will use through the future course of their operation. Also before use, the keys AKsigpub and AKencpub must be registered with the Service Controller network as a trusted AuthServer through a secure channel. The key pair (AKsigpub, AKsigpri) is used for signing user AuthTokens while the pair (AKencpub, AKencpri) is used as part of the encrypted communications with the client during an AuthRequest. Before authenticating with an AuthServer, clients must first obtain the keys AKsigpub and AKencpub from the service controller network. Once initialized, both the AuthServer and Client need not perform these steps again unless the AuthServer's keypairs are compromised and revoked.

Authentication servers may serve as a front end to existing credential stores for an organization (e.g. LDAP, Kerberos, MySQL database, etc.) to provide authentication

using existing user credentials within the organisation or contain an isolated database of user credentials for use with only cloud based services. To further enhance scalability for large systems AuthServers may be setup in a master-slave configuration where user credentials are accessed from the master and replicated to slaves periodically through notifications of changes to user accounts (see Figure 3.14). In this case the slaves would contain a database containing a user's ID, credentials and assigned RBACaaS roles updated based on notifications from the master which in turn obtains the details from a backend credential store. Both the slaves and master must have access to and use the same key pairs. Authentication requests are distributed among the functioning slaves in a round robin fashion.

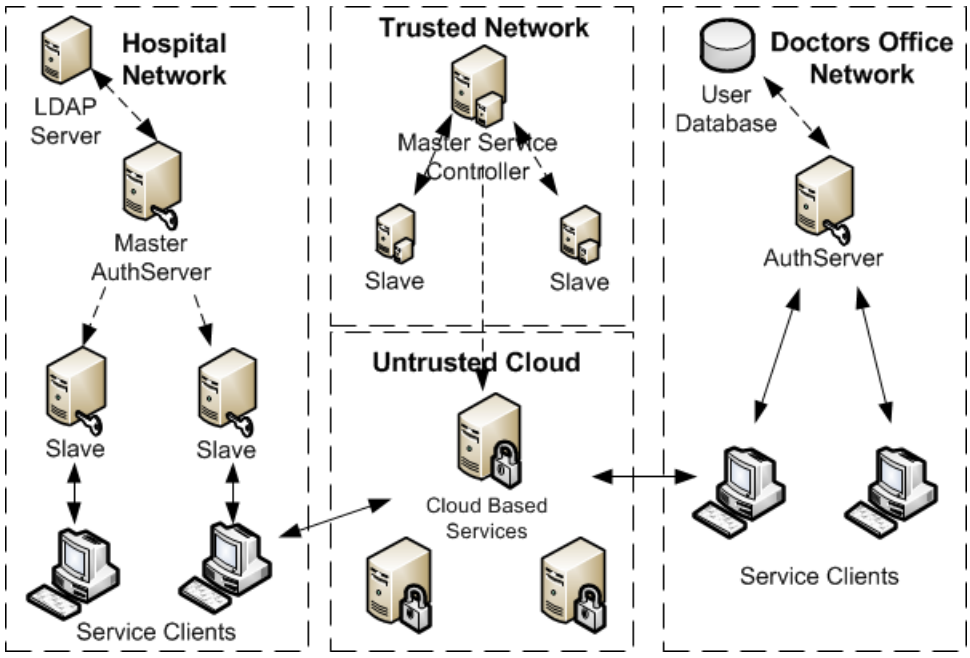


Figure 3.14: Example RBSSO system layout sharing several cloud based services on a public cloud between a hospital and doctors office. Note that the trusted network could also be located in the doctor's office or hospital network.

3.2.1.2 Service Controllers

Like AuthServers, Service Controllers are initialized with a public/private key pair (SCpri, SCpub) for signing ServiceTokens. The key SCpub is shared and stored on

all clients which access the cloud based services. This key is included in the client's software and only changed in the case of a compromised SCpri. Service Controllers sit outside the cloud on a trusted third party's network and are responsible for interfacing with the public cloud's infrastructure to control the creation and destruction of virtualized machine instances which run the cloud based services being provided. Additionally Service Controllers initialize the machine instances with SKpri (the instances private key), a list of all trusted Authentication Servers and their public signing keys, a revocation list of users and sessions, as well as a ServiceToken containing a list of services the instance will run and SKpub (the instances public key). Service Controllers may also be set up in a master-slave configuration on the trusted third party network for redundancy and failover protection where updated revocation lists, AuthServer lists and sets of services to be run are synchronized with the master. When run in this configuration all service controllers use the same key pair and the master controls the cloud. In the event of a failure on the master the next slave in line is promoted to master and continues the work of the master.

3.2.1.3 Cloud Based Services

Cloud based services are services contained in virtualized machine instances executed on a potentially untrustworthy cloud which use RBACaaS and RBSSO to authenticate requests. Once created, a machine instance is initialized with a ServiceToken as described in the above section and accepts requests directly from authorized clients. Machine instances are created and destroyed dynamically by service controllers based on current levels of demand. Cloud services periodically provide updated usage statistics to Service Controllers when it is not available or possible to obtain from the cloud provider (i.e. for cloud providers that do not offer services such as AWS's CloudWatch

(http://aws.amazon.com/cloudwatch/) service). When updated revocation or AuthServer lists are available from the Service Controller, a notification is sent to each machine instance containing the changes to each list.

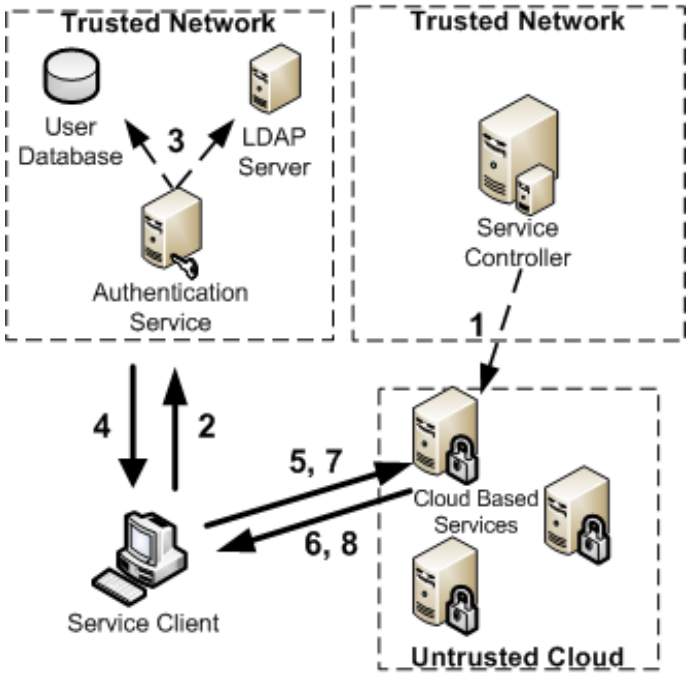


Figure 3.15: RBSSO protocol sequence.

3.2.1.4 Protocol

Figure 3.15 displays the interactions involved in the RBSSO protocol. Each client is assumed to be provided with the public signing and encryption keys (AKsigpub , AKencpub) for their organizations authentication server, as well as the public signing key for the service controller (SCKsigpub). The protocol for RBSSO follows the proceeding steps, as shown in Figure 3.15:

1. The service controller initializes machine instances with a ServiceToken (see Figure 3.16), a list of cloud services the instance will provide, a list of trusted

authentication servers and their set of public keys, a list of globally black listed users and the instances private key, SKpri.

2. The service client authenticates with their organization's authentication server by generating a secret key CKsec and an AuthRequest (see Figure 3.17). The AuthRequest, containing the user's credentials, the RBACaaS role they wish to activate and a public client key from the client public/private key pair created when the client program is initialized, is then transmitted to the authentication server.

3. The authentication server decrypts the AuthRequest using AKencpri and CKsec, validates the user's credentials, and checks that the time stamp and request ID are acceptable. Credentials may be validated against a local database of user credentials or existing authentication infrastructure on the same trusted network (eg. LDAP).

4. The authentication server then makes a request on the domain's RBAC service to validate that the user may activate the requested role, obtain the set of permission/conditions pairs, obtain the set of parameter name/value pairs and start an RBACaaS session.

5. Once the user is validated, the authentication server issues and signs an AuthToken (see Figure 3.18), containing the permission and parameter sets, with AKsigpri for the client's session with the cloud services. This transmission is appended with the DMACPSABE (see section 4.3) key for the user's current

attributes and encrypted with CKsec to protect the user's privacy (i.e. so the user may not be identified by outside observers).

6. Before the service consumer makes a normal request upon a service it first extracts the DMACPSABE key from the end of the AuthToken and requests the service's ServiceToken from the instance on which it resides. The service consumer then validates the service controller's signature using SCKpub and ensures that the service is listed in the service listing and is connecting from the stated IP or hostname.

7. The consumer may now authenticate and make a request upon any cloud service on the instance by generating the secret session key SEKsec and using it to encrypt its AuthToken, the request and a newly generated RequestToken (see Figure 3.20) together. SEKsec is appended with a delimiter and random number and encrypted with SKpub (obtained from the ServiceToken) .The ciphertexts are appended and transmitted to the service (see Figure 3.19).

8. The service decrypts SEKsec using SKpri and decrypts the request, RequestToken and AuthToken using SEKsec. The service then proceeds to validate the signatures contained in AuthToken and RequestToken using AKsigpub and CKpub (from the AuthToken) and validate the fields they contain (time stamp has not expired, etc.). If valid, SEKsec and the AuthToken are temporarily stored for future requests with the instance until the session expires.

9. If the user has a role active which allows the request to be performed on the service, the service complies with the request and provides the appropriate response. All further communications between the consumer and service for the length of the session will be encrypted using SEKsec. Subsequent requests on any service on the instance need only to provide a RequestToken.

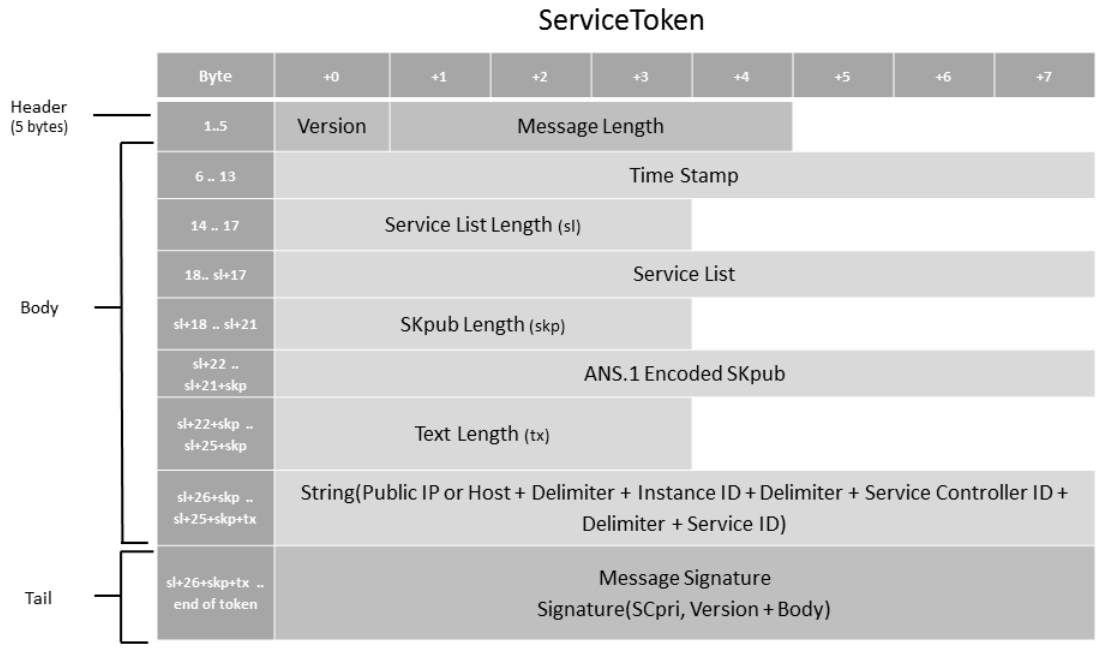


Figure 3.16: ServiceToken protocol diagram

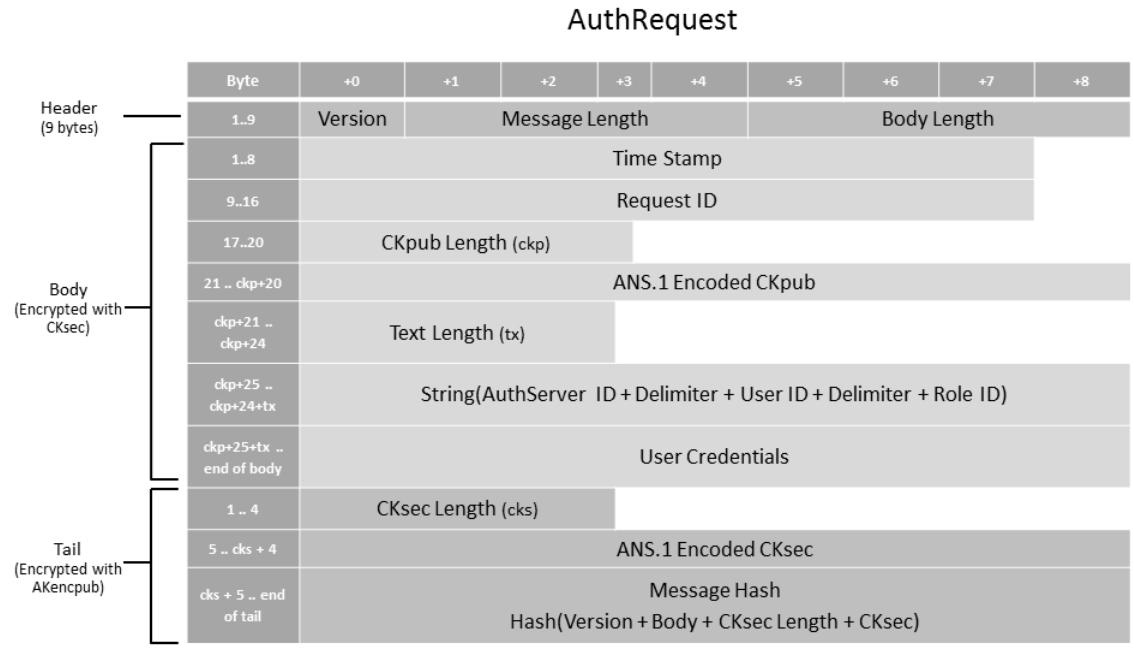


Figure 3.17: AuthRequest protocol diagram.

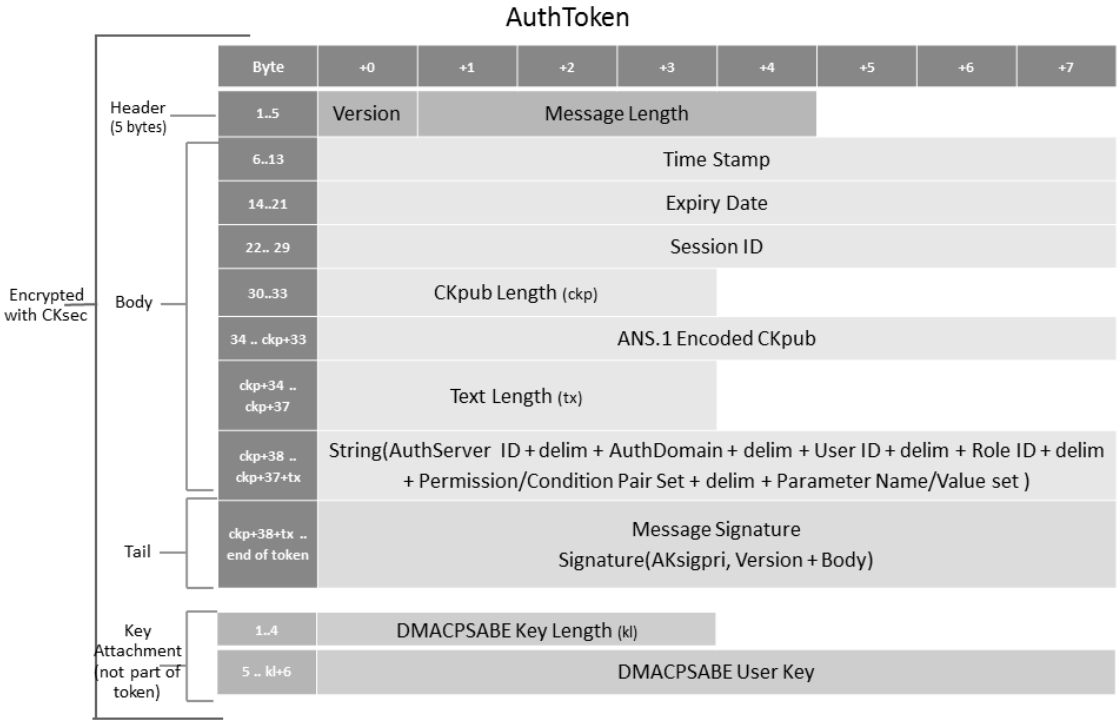


Figure 3.18: AuthToken protocol diagram.

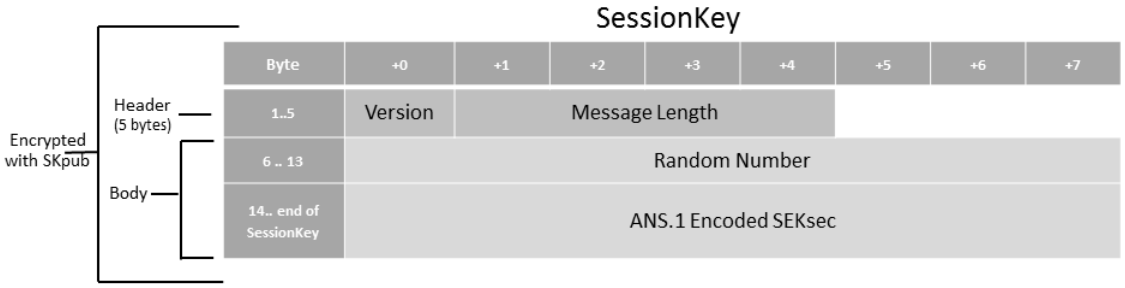


Figure 3.19: SessionKey protocol diagram.

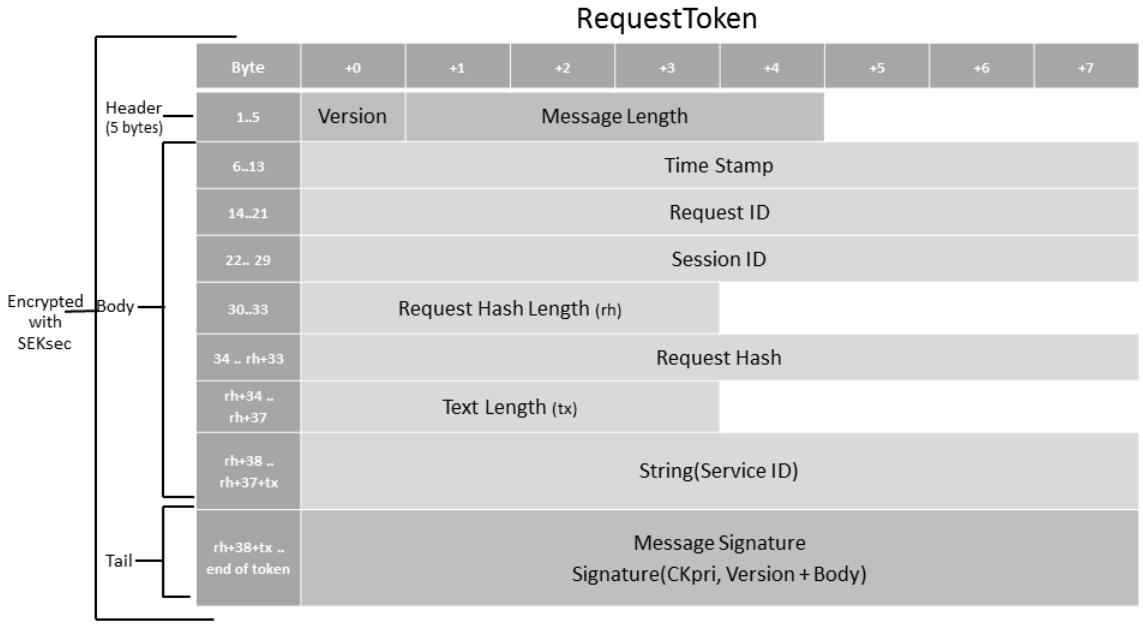


Figure 3.20: RequestToken protocol diagram

3.2.2 Performance Evaluation

To evaluate the performance of the RBSSO protocol a prototype of the Authentication Server and Client where created using standard Java TCP sockets. 128bit AES encryption was used for the symmetric encryption of the AuthRequest body and AuthToken body. 3072bit RSA encryption was used for the asymmetric encryption of the AuthRequest tail and the signature on the AuthToken. SHA-256 was used for generating hashes for the AuthRequest.

Two controls, a simple SSL based connection and Kerberos (http://web.mit.edu/kerberos/) (a popular SSO system), where tested under the same conditions for a basis of comparison. For the first control, an authentication server was created that replaced the encryption of the body and signature of the AuthRequest with an SSL connection (the tail containing CKsec and the token hash were removed from the SSL implementation). Secondly the RBSSO protocol was also compared against the performance of a Java based Kerberos client and the MIT Kerberos 5 implementation which retrieved a ticket granting ticket and a service ticket (somewhat equivalent to an AuthToken in RBSSO). The performance of all three protocols (measured in average time per request) was measured on both a private isolated low latency local area network and over a higher latency and more noisy wide area connection. Each protocol was tested with 10,000 authentication requests for each network in sequential runs of 1000 requests. The results on these tests are shown in Figure 3.21, Figure 3.22 and Figure 3.23.

The RBSSO protocol performed approximately 38% faster on average than the SSL implementation on the LAN and 66% faster over the WAN connection. This is likely a result of the decreased number of requests involved in the RBSSO protocol (no handshake is required and only a single request is made containing the AuthRequest) and explains the difference between the LAN and WAN connections (the cost per request being higher on the connection with increased latency). Similarly RBSSO performed 25% faster than Kerberos over an WAN connection but performed 21% slower over a LAN connection. This is also likely a result of the number of requests, Kerberos requiring a connection to both to a Kerberos authentication server and a ticket granting server before it can make a request on a service.

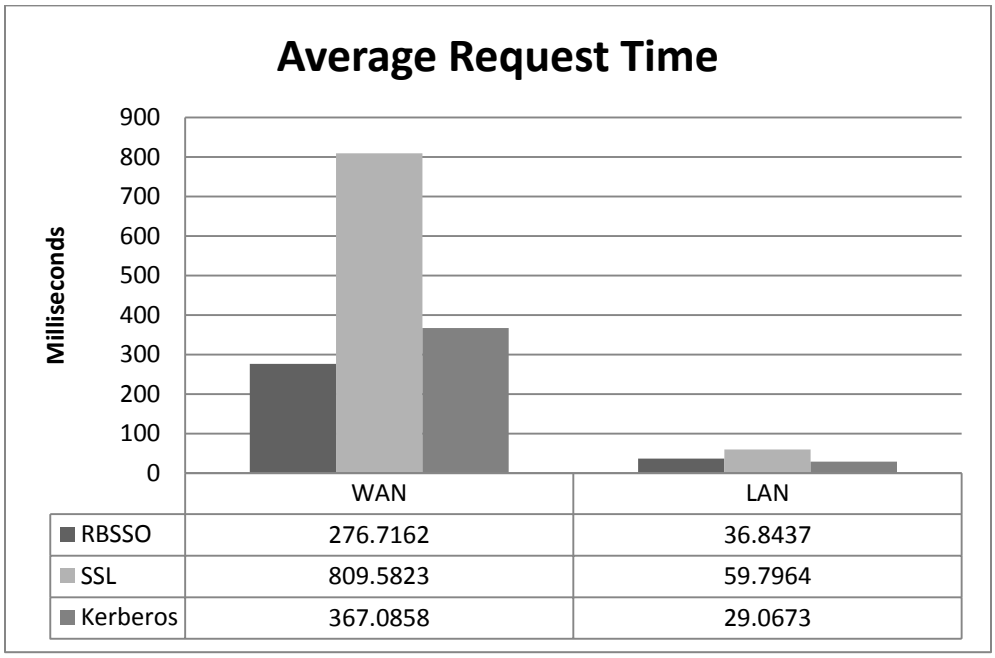


Figure 3.21: Average time (in milliseconds) required to complete and verify an authentication request using each protocol. Based on 10,000 requests.

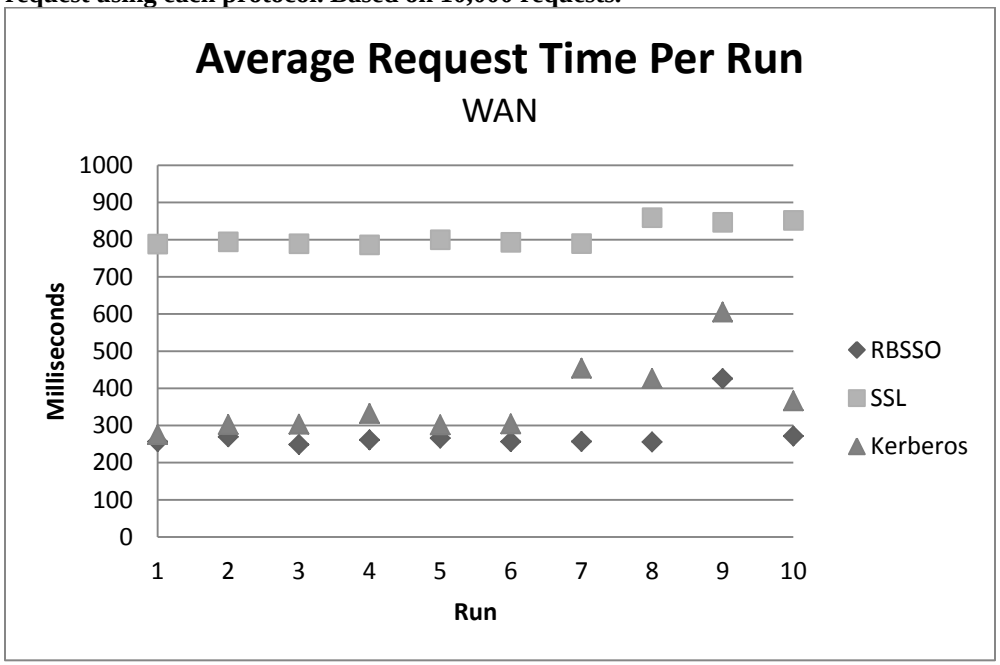


Figure 3.22: Average time (in milliseconds) required to complete and verify an authentication request over the WAN connection. Based on 1000 requests per run.

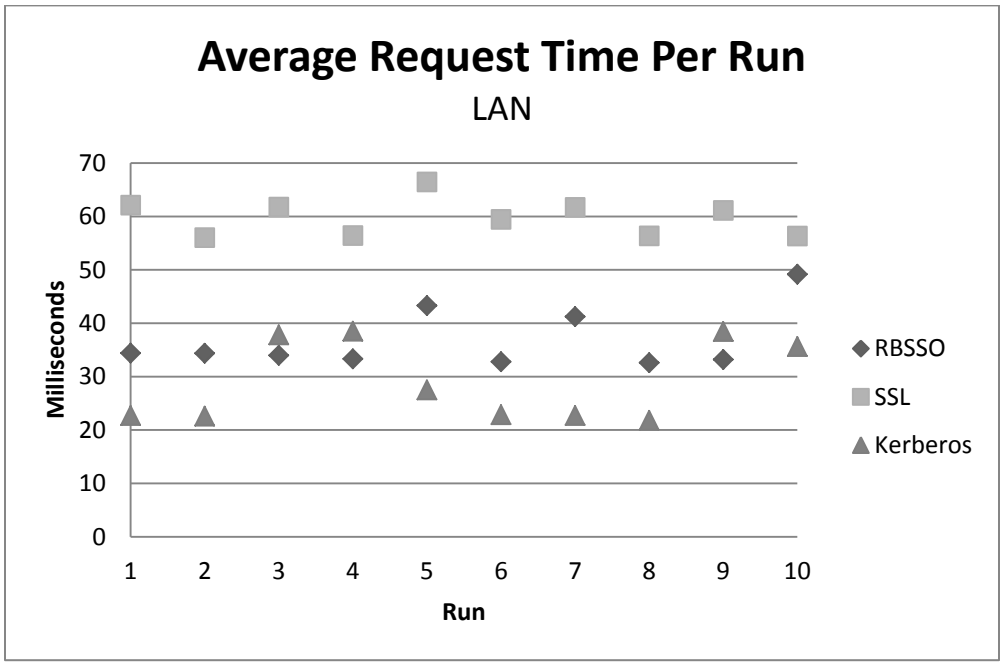


Figure 3.23: Average time (in milliseconds) required to complete and verify an authentication request over the LAN connection. Based on 1000 requests per run.

3.3 Conclusions

This chapter introduced the RBACaaS model and RBSSO protocol which enables conditional role based policies to be enforced in a distributed environment. Organizations are granted their own domain and control all user authentication, credentials, RBAC entities (Groups, Roles, Permissions, etc.) and access policies within that domain. However, they are also able to share permissions, roles and groups by authorizing an external domain to extend the role, group or permissions in their respective hierarchy. For large domains, RBACaaS services may be scaled by running multiple RABC services in the same domain and balancing requests between them (as show in part in Figure 3.12).

Testing of the RBSSO protocol's performance over a wide area network showed average request times which surpassed that of the Kerberos SSO protocol and SSL based methods. Testing on a low latency, high speed local area network still showed

performance gains over the SSL based method and only a minor disadvantage compared to Kerberos. Additional details on integrating RBACaaS and RBSSO with the HCX services described in Chapter 2 and the DMACPSAE encryption scheme of Chapter 4 are given in section 5.1. Future work, new areas of research and possible improvements are detailed in section 5.2.

Chapter 4

4 Cloud Privacy Through Attribute Based Encryption

4.1 Introduction

4.1.1 Data Privacy on the Cloud

Ensuring data privacy on a potentially untrustworthy public cloud is still one of the open research problems in cloud computing (Zhang, Cheng, & Boutaba, 2010), (Armbrust, et al., 2009). Common data privacy methods amounting to "throwing encryption at the problem" are ineffective on the cloud platform and many current research efforts require additional trust computing or cryptographic coprocessors hardware (Itani, Kayssi, & Chehab, 2009), (Chow, et al., 2009) not yet offered by any public cloud provider.

Traditional public and symmetric key encryption methods quickly run into problems when an untrusted third party (such as a cloud provider) is given control of all hardware and network resources, leaving cloud application developers to either use the cloud purely as a semi-public hard drive for storing encrypted data (losing most scalability advantages of the cloud and limiting cloud applications to simply retrieving an encrypted file) or handing over some level of trust and control to the cloud provider to enable their cloud based applications to process potentially sensitive data. Even when information on persistent cloud storage (such as the S3 or EBS services offered by Amazon's AWS) is encrypted, cloud based applications which process and rely on the data may be vulnerable when run on hardware or virtual instances operated by an

untrustworthy cloud provider. It would be trivial for such a provider to extract sensitive data (including the encryption keys themselves from a virtual instance's hard drive, memory or network connections. Additionally, man-in-the-middle type attacks would be trivial for the cloud provider as they operate both the network, hardware and IP ranges for the virtualized services.

This chapter outlines a novel take on attribute encryption for protecting records both on and off the cloud. Several improvements over traditional ABE schemes are added, including distributed attribute authorities with shared subsets of attributes. Subsections 4.1.2 and 4.1.3 provide a background on the concepts involved in attribute based encryption while subsections 4.2 details current research related to attribute based encryption and cloud privacy. Subsection 4.3 and 4.4 detail our attribute encryption system, implementation and evaluation, and subsection 4.5 outlines how it may be used with RBACaaS, RBSSO and HCX.

4.1.2 Pairing-Based Cryptography

Definition 4.1: Bilinear Map

A bilinear map from the cyclic groups of the same order $G_1 \times G_2$ to a cyclic group of the same order G_t is the function:

$$e: G_1 \times G_2 \rightarrow G_t$$

Such that:

$$\forall u \in G_1, \forall v \in G_2, \forall a, b \in \mathbb{Z}: e(u^a, v^b) = e(u, v)^{ab}$$

Definition 4.2: Admissible Bilinear Map

A bilinear map, e, is considered to be admissible if for two generators g_1 and g_2 of groups G_1 and G_2:

$$G_1 \times G_2 \rightarrow G_t \text{ and } e(g_1, g_2) = G_t$$

and e is efficiently computable.

Definition 4.3: Symmetric Pairing

A pairing of two groups G_1 and G_2 is considered to be symmetric if:

$$G_1 = G_2 = G$$

such that:

$$G \times G = G_t$$

Pairing-base cryptography is a relatively new development in cryptography research (popularized by (Boneh & Franklin, 2001)‘s 2001 Identity Based Encryption paper) which uses a pairing between elements of multiple cryptographic groups to create new cryptographic systems. In most schemes this pairing takes the form of an admissible bilinear map (Definition 4.1, Definition 4.2) between a symmetric pairing (Definition 4.3) of a cyclic group of prime order with itself to a second cyclic group of the same

order. Such pairings make it possible to reduce the Decisional Diffie-Hellman (DDH) problem in polynomial time (Boer, 1996), (Maurer & Wolf, 1999) to the discrete logarithm problem (DLP) making it "easy" for one group. However, the Computational Diffie-Hellman (CDH) is still considered "hard" in G (G_1 or G_2) and gives rise to several new cytological problems on which the security of most pairing-based cryptosystems is based:

- **Bilinear Diffie-Hellman problem:** Given g, g^a, g^b, g^c compute $e(g,g)^{abc}$
- **Gap Diffie-Hellman problem:** Solve CDH in G.
- **k-Bilinear Diffie-Hellman Inversion problem:** Given $g, g^y, g^{y^2}, \dots, g^{y^k}$, compute $e(g,g)^{\frac{1}{y}}$.
- **k-Decisional Bilinear Diffie-Hellman Inversion problem:** Distinguish $g, g^y, g^{y^2}, \dots, g^{y^k}, e(g,g)^{\frac{1}{y}}$ from $g, g^y, g^{y^2}, \dots, g^{y^k}, e(g,g)^z$.

That is, the security of the crypto system is based on the complexity of one of the problems (or its correspondent co-problems) for some group G (or the pair G_1 and G_2). In most cases the bilinear map chosen for cytological protocols is the elliptic curve based Weil (Miller V. , 2004) or Tate (Galbraith, Harrison, & Soldera, 2002) pairings computed with Miller's algorithm (Miller, Short programs for functions on curves, 1986) (Blake, Murty, & Xu, 2006).

4.1.3 Identity Based and Attribute Based Encryption

Identity based encryption (IBE) is a type of public-key encryption scheme using pair-based cryptography (though some schemes exist which use other methods such as quadratic residues (Cocks, 2001)) which uses a plain text public key such as an e-mail address or domain name. Ideally a trusted third party, referred to as the Private Key

Generator (PKG), would be tasked with generating and securely distributing private keys to their respective owners. For example, a PKG might be assigned to delegating private keys corresponding to a public key consisting of a user's e-mail address upon request.

Boneh and Franklin (2001) proposed a fully functional identity-based encryption scheme built on pair-based cryptography using a bilinear map (using Weil pairing) (Boneh & Franklin, 2001). Boneh and Franklin's construction consists of four randomized functions: Setup, Extract, Encrypt and Decrypt. The Setup function takes a security parameter $k \in \mathbb{Z}^+$ and returns a set of system parameters, P, (which includes the finite message space M and the finite ciphertext space C) and the master key K_m. The Extract function takes the P, K_m and an arbitrary string $ID \in \{0,1\}^*$ as input and returns a private key d for the given ID. The Encrypt function takes P, ID, and $m \in M$ and returns the ciphertext $c \in C$. Finally, the Decrypt function takes P, c, and d as input and returns m. The expected use of these functions is shown in Figure 4.1 and must follow the standard consistency constraint:

$$\forall m \in M : Decrypt(P, c, d) = m \text{ where } c = Encrypt(P, ID, m)$$

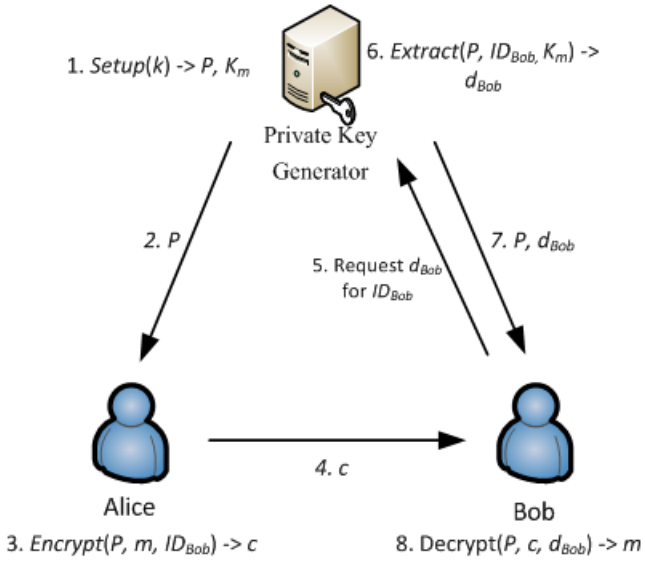


Figure 4.1: Identity-Based Encryption cryptologic protocol.

Like many other pairing-based ciphers, identity-based encryption's security is dependent on the "hardness" of the Bilinear Diffie-Hellman Problem and has been proven semantically secure under the Bilinear Diffie-Hellman assumption (Boneh & Franklin, 2001). Additionally, Boneh and Franklin prove how the technique from Fujiaski and Okamoto (1999) can be used to convert their construct to provide a chosen ciphertext secure IBE system in the random oracle model.

Several cryptosystems have been built on the concept of IBE including the Attribute Based Encryption (ABE) scheme first introduced by Sahai and Waters (2005) as part of their Fuzzy Identity-Based Encryption cryptosystem (Sahai & Waters, 2005). ABE allows an entity to encrypt a document such that only users with a specific set of attributes may decrypt the document. For example, a hospital may wish to limit access to a document to employees with the set of attributes {"doctor", "ethics-committee", "staff"}. This is made possible through ABE by issuing a private key (their "identity") to each employee composed partially of their set of assigned attributes in such a way that collusion between multiple employees does not grant a key containing a larger or combined set of attributes. Employees are then limited to decrypting only messages encrypted with some subset of their attributes. For the cloud, and other untrusted storage environments, ABE is a significant development as it allows for the enforcement of access policies via the encryption used on the document rather than the system holding the documents. Additionally, ABE ensures that documents are protected with the same access policies and same level of security both on and offline, offering the potential for documents to be moved seamlessly from an online storage environment (e.g. a cloud storage service) to an offline storage environment without compromising their security and still allowing access to users matching the set access policy.

Recent research in ABE has led to several improved schemes which enhance the complexity possible in ABE access policies including; enabling a limited form of role based access control. Key-Policy Attribute-Based Encryption (KP-ABE) (Goyal, Pandey, Sahai, & Waters, 2006) enables attribute based policies to be embedded in the user's private key, allowing them to decrypt documents encrypted with attributes matching their key's policy. Ciphertext-Policy Attribute-Based Encryption (CP-ABE) expands on ABE to add variable attributes (attributes which may be assigned a value) and access policies embedded in the cihpertext which support fuzzy Boolean operations including greater than, less than, less than or equals, and greater than or equals, as well as other Boolean statements (equals, x of set of Boolean statements are true, AND, OR, etc.). For example, one user may be assigned the attribute "room = 5020" corresponding to their office number, while another user "room = 4005" and a document may then be encrypted with the policy "room $\geq$ 5000 AND room < 6000" to allow only users on the 5^{th} floor (assuming room numbers start with a floor number) to decrypt the document. Expanded descriptions of these cryptosystems and technical details are provided in the literature review in section 4.2.

4.2 Attribute Based Encryption Related Research

4.2.1 Fuzzy Identity-Based Encryption (Sahai & Waters, 2005)

4.2.1.1 Summary

Unlike traditional IBE schemes which use a string of characters as a user's ID (or pubic key), Fuzzy Identity-Based Encryption (FIBE) (Sahai & Waters, 2005) views a user's identity as a set of descriptive attributes. Users with an assigned a set of attributes which composes their "identity", *w*, may decrypt a given ciphertext encrypted with the

public key *w'* only if *w* and *w'* are within a certain distance from each other in a set threshold. This threshold allows for an amount of error-tolerance that allows for less precise attributes (such as biometric data) to be used as a user's identity. As with most IBE schemes, FIBE requires a central trusted authority assigned to generating and delegating secret keys to users based on a given public identity.

The following constructs are used in FIBE, where identities are restricted to a length of *n* (i.e. the number of attributes in an identity), *e* is the bilinear map for $G \times G \rightarrow G_t$ where g is the generator of *G*, *d* is the threshold (how many components must be matched to perform decryption), *N* will be the set of attributes of size *n* in $\mathbb{Z}_p^*$ created with a collision resistant hash function *H*, and $\Delta i, S$ is the Lagrange coefficient for $i \in \mathbb{Z}_p^*$ and *S* is a set of elements in $\mathbb{Z}_p$, defined as:

$$\Delta i, S(x) = \prod_{j \in S,\ j \neq i} \frac{x - j}{i - j}$$

$PubKey, PrivKey = Setup(n, d)$:
choose: $g_1 = g^y$ for some y
choose: $g_2 \in G$
choose randomly: $t_1, \dots, t_{n+1} \in G$
$PubKey = (n, d, g_1, g_2, t_1, \dots, t_{n+1})$
$PrivKey = y$

Equation 4.1: FIBE Setup function

$SK = KeyGeneration(PubKey, PrivKey, ID)$:
choose randomly: A $d - 1$degree polynomial q where $q(0) = y$
$FOR\ i \in ID$:
$D_i = g_2^{q(i)} \cdot \left(g_2^{i^n} \prod_{k=1}^{n+1} t_k^{\Delta k, N(i)} \right)$ $where\ N\ is\ the\ set\ \{1, \dots, n+1\}$
$r_i = random\ number\ in\ \mathbb{Z}_p$
$d_i = g^{r_i}$
$SK = (D, d)$

Equation 4.2: FIBE KeyGeneration function

$C = Encryption(PubKey, w', M \in G_t)$:

choose randomly: $s \in \mathbb{Z}_p$

$E' = M \cdot e(g_1, g_2)^s$

$E'' = g^s$

$FOR\ i \in w'$:

$$E_i = \left(g_2^{i^n} \prod_{k=1}^{n+1} t_k^{\Delta k, N(i)} \right)^s$$

$C = (w', E', E'', E)$

Equation 4.3: FIBE Encryption function

$M = Decryption(PubKey, SK, C)$:

choose: an arbitrary d element subset S of $w \cap w'$

$$M = E' \prod_{i \in S} \left(\frac{e(d_i, E_i)}{e(D_i, E'')}\right)^{\Delta i, S(0)}$$

Equation 4.4: FIBE Decryption function

Sahai and Waters (2005) prove the security of their cryptosystem by showing that in the Selective-ID model the "hardness" of breaking their encryption reduces to that of the Bilinear Diffie-Hellman problem (See pages 469 to 472 of (Sahai & Waters, 2005) for their proof).

4.2.1.2 Criticisms

While Sahai and Waters FIBE scheme provided an important step forward for identity and attribute based encryption, it lacks many of the features that would be required of an encryption scheme for the cloud. Generation and distribution of a user's secret key and authentication of their identity is limited to a single trusted authority which imposes both scalability and trust issues. If the central authority or its private key should become compromised, the attacker would have the ability to decrypt any document in the system as well as create any identity for themselves (which could be problematic if the

system is used for creating signatures or proving a user's identity). A central authority also significantly limits scalability in systems that require a large number of user keys generated (for example a system which creates a new user key every session or has keys set to expire at a regular interval). Copying the master private key to multiple systems will increase scalability (by distributing user secret key generation requests among them) at the cost of severely compromising security (if any of the multiple key generation systems are compromised the whole system is compromised as the same master key is used).

An additional complication with the security in FIBE, is the lack of a revocation mechanism. If a user's secret key is compromised, there is no easy way of revoking their key or notifying users of the system that the user's identity has been compromised. This is made worse by the fact that a user's identity may not be easily changed (e.g. if biometric data is used) and would forever be compromised unless every key in the system is disregarded and a new master private key and set of secret user keys is created for every user. The use of biometric data as a public key (as suggested in the paper) is also worrisome. The FIBE scheme may only ensure that a user with a given biometric identity may possesses it's corresponding secret key, however, it still discloses that biometric identity in the form of a public key which may affect the security of other systems that rely on the secrecy of such data that is unchangeable (as it is physically part of the user).

Another issue with FIBE is the lack of fine grained access control. FIBE offers only a simple *d* attributes out of *n* based policy for encrypting documents. In real life such a simplistic access policy cannot fully represent organizational security policies or conditional role based access control. For example, a hospital may wish to encrypt a health record such that a patient (to whom the record belongs), a doctor who is both an active employee of the hospital and has a current medical licenses, a lab technician with

recent certification and no one in a set of persons the patient has specified, have access. Unless an extremely large number of attributes is created (at least one for every patient and possible requirement) this sort of access policy is not possible in FIBE. While simplistic role based access control is possible with FIBE, where each role or permission is simply mapped to an attribute and documents are encrypted based roles which should have access to the file. More modern RBAC systems which have conditional or more complex mappings of permissions to roles or roles to users (for example a user may only activate one role at a time, SSD and DSD constraints or other conditions a user must pass before activating a role) are not possible with FIBE.

Finally FIBE uses a fixed value of d, the threshold in $|w \cap w'| \geq d$ (how many components in the identity must be matched to allow decryption), which limits the access policies that maybe used. The solution to this issues presented by Sahai and Waters is limited to creating multiple master private keys and sets of secret keys for each user or adding a very large amount of "dummy" attributes that would be assigned to every user in the system (thus vastly increasing the size of every user's secret key and the time to decrypt and encrypt a given message).

4.2.2 Attribute-Based Encryption for Fine-Grained Access Control of Encrypted Data (Goyal, Pandey, Sahai, & Waters, 2006)

4.2.2.1 Summary

Key-Policy Attribute-Based Encryption (KP-ABE) (Goyal, Pandey, Sahai, & Waters, 2006) is an ABE scheme which embeds access control policies in the user's key rather than incorporating them into the ciphertext during encryption. KP-ABE builds upon the attribute encryption applications of FIBE and replaces the simplistic "*d* of *n* attributes" threshold access policy with a tree access structure consisting of AND and OR

threshold gates as nodes, and leaves are associated with attributes. Threshold gates can be seen as equivalent to the threshold requirement from FIBE, where an OR node consists of a 1 of 2 threshold and an AND gate consists of a 2 of 2 threshold. Goyal, et al. (2006) defines a given access tree, *τ*, with root node *r* as being satisfied when:

$$\tau_r(\gamma) = \ 1$$

Where τ_x is a subtree of τ at node x, γ is the set of attributes a given ciphertext is encrypted with and $\tau_x(\gamma)$ is computed recursively as follows: If x is a non-leaf node compute $\tau_{x'}(\gamma)$ for all children, x' of x. $\tau_x(\gamma)$ returns 1 if 1 of 2 children return 1 for an OR node or 2 of 2 children return 1 for an AND node. If x is a leaf node then $\tau_x(\gamma)$ returns 1 if $x \in \gamma$.

Goyal, et al. (2006) present the following constructions in their paper to enable key generation, encryption and decryption (which are used similarly to the constructions from FIBE). For the following functions, *G* is a bilinear group of prime order *p*, *g* is a generator of *G*, *e* is a bilinear map for $G \times G \rightarrow G_t$, *k* is the size of the groups *G* and G_t, $\Delta i, S$ is the Lagrange coefficient (defined the same as in subsection 4.2.1.1), γ is the set of size *n* elements from $\mathbb{Z}_p^*$ that represent the set of attributes for which a ciphertext is encrypted, and Setup is done in the same manner as in Equation 4.1 to produce a master public key, *PubKey*, containing $(n, g_{1,}, g_2, t_1, \ldots, t_{n+1})$, and a master private key, *PrivKey*, consisting of the value of *y* from $g_1 = g^y$ where $y \in \mathbb{Z}_p$.

$C = Encryption(PubKey, \gamma, m \in G_t)$:
choose randomly: $s \in \mathbb{Z}_p$
$E' = m \cdot e(g_1, g_2)^s$
$E'' = g^s$
$FOR\ i \in \gamma$:

$$E_i = \left(g_2^{i^n} \prod_{k=1}^{n+1} t_k^{\Delta k, N(i)} \right)^s$$

$$C = (\gamma, E', E'', E)$$

Equation 4.5: KP-ABE Encryption function.

$$SK = KeyGeneration(\tau, PrivKey, PubKey):$$
$$q = CreatePolynomials(\tau, y)$$
$$FOR\ \forall leaf\ node\ x\ \in\ \tau:$$
$$r_x = random\ number\ in\ \mathbb{Z}_p$$
$$D_x = g_2^{q_x(0)} \cdot \left(g_2^{i^n} \prod_{k=1}^{n+1} t_k^{\Delta k, N(i)} \right)^{r_x} \quad where\ N\ is\ the\ set\ \{1, \dots, n+1\},$$
$$i\ = attribute\ for\ x$$
$$R_x = g^{r_x}$$
$$SK = (\tau, D, R)$$

Equation 4.6: KP-ABE KeyGeneration function.

$q = CreatePolynomials(\tau, y)$:

"For each node x in the tree, set the degree dx of the polynomial q_x to be one less than the threshold value k_x of that node, that is, $d_x = k_x - 1$. Now for the root node r, set $q_r(0) = y$ and d_r other points of the polynomial q_r randomly to define it completely. For any other node x, set $q_x(0) = q_{\text{parent}}(\text{x})$ ($index(x)$) and choose d_x other points randomly to completely define q_x." (Goyal, Pandey, Sahai, & Waters, 2006)

$$m = Decryption(C, SK):$$
$$A = DecryptNode(C, SK, \tau_r)$$
$$IF\ A\ \neq\ \perp:$$
$$m = \frac{E'}{A}$$
$$ELSE:$$
$$m = \perp$$

Equation 4.7: KP-ABE Decryption function.

$$A = DecryptNode(C, SK, x):$$
$$IF\ x\ is\ a\ leaf\ node:$$
$$i = att(x)$$
$$IF\ i\ \in\ \gamma:$$
$$A = \frac{e(D_x, E'')}{e(R_x, E_t)}$$
$$ELSE:$$

$$A = \perp$$

$$ELSE:$$

$$\forall z\ child\ of\ x:\ F_z = DECRYPTNODE(C, SK, z)$$

$$S_x = \forall z\ child\ of\ x\ and\ F_z \neq \perp$$

$$IF\ S_x \neq \emptyset:$$

$$F_x = \prod_{z \in S_x} F_z^{\Delta i, S'_x(0)} \qquad where^{i=index(z)}_{S'_x=\{index(z):z\in S_x\}}$$

$$A = F_x$$

$$ELSE:$$

$$A = \perp$$

Equation 4.8: KP-ABE recursive DecryptNode function.

Goyal, et al. (2006) also presents a means of delegating user secret keys which was absent from FIBE. This allows users to delegate further secret keys off their current key based on any access tree more restrictive than the one used in the parent key. This allows users to grant access to a subset of documents they may decrypt to others without having to share their own secret key or their full access tree. This process is detailed in section 6 of Goyal, et, al, (2006) and involves several operations for adding new threshold gates, manipulating existing threshold gates and re-randomizing the obtained key.

As with FIBE, the security of the KP-ABE scheme is proven via the hardness of the Bilinear Diffie-Hellman problem (proof maybe found in section 4.3 of Goyal, et al. (2006)). Goyal, et al. also detail how changes to their encryption and decryption functions may allow for CCA-Security to be achieved.

4.2.2.2 Criticisms

KP-ABE provides a needed improvement to FIBE by extending the simple access policy structure to a policy tree which may include both AND and OR threshold gates. This allows for more complex and realistic policies to be implemented which more

closely resemble organizational policies in the real world. However, as KP-ABE is closely based on FIBE it shares many of the criticisms noted of FIBE. A single central trusted authority is still required for user key creation, which acts as both a scalability and trust bottle neck. Again there is no easy means of revocation for user keys; in fact the issue is made worse by enabling a user to further delegate their keys (a compromised key could make an unlimited number of new keys for the same or more restrictive access policy).

Having the access policy embedded in the key rather than the ciphertext also has some potential issues. Encrypting documents with a set of attributes may inadvertently leak potentially sensitive information about the document. For example, if a hospital wished to encrypt some sensitive medical document about a patient's chemotherapy treatment such that only that patient, doctors belonging to the hospital staff, or a technician/nurse who gives the chemotherapy treatments, they may encrypt the document with the following set of attributes {"staff", "patient:john doe", "doctor", "technician:chemo"}. While such attributes maybe necessary to enforce the policies in the user keys (for example a chemo technician in the hospital may have the policy amounting to "technician:chemo AND staff", a doctor may have "staff AND doctor", and the patient John Doe may have "patient:john doe") it also leaks the sensitive information that the document details records about John Doe involving chemotherapy (or at least involving a chemotherapy technician).

Additionally, the key policy based access policy also has potential issues when designing the access policies for a system. During the encryption of documents, the encryptor is required to have a good understanding of all policies currently assigned to users to determine the set of attributes that should be used. Even assuming the encryptor has a list of all attributes used in all key policies, they are left adding all possible

attributes that may be relevant and hoping for the best. In the alterative, a ciphertext policy based system, the encryptor would set the access policy on each message it encrypts and is only left trusting that the authority has correctly assigned attributes to users. It stands to reason that the encryptor would have a better understanding of what access policy is needed at the time of encryption than the key generator, possibly months, if not years, in advance.

Finally, while KP-ABE greatly increases the possible complexity of the access policies used over FIBE, it is still not a complete solution. KP-ABE introduces the use of AND and OR gates, allowing policies such as "is_teacher OR (is_student AND has_ departmental_approval_to_use_lab)" but it is still incapable of policies that require variable attributes (attributes that may be assigned a value rather than a user merely having them) and compressions between them, for example "is_teacher OR (is_student AND year_level = 4 AND credits > 20)". Variable attributes and the Boolean comparisons between them allow for even more complex policies which come even closer to modeling policies of real world organizations.

4.2.3 Ciphertext-policy attribute-based encryption (Bethencourt, Sahai, & Waters, 2007)

4.2.3.1 Summary

Ciphertext-policy attribute-based encryption (CP-ABE) (Bethencourt, Sahai, & Waters, 2007) offers a new encryption scheme which continues the work on attribute based encryption to enable a complex tree based access policy to be embedded in the ciphertext rather than the key as with KP-ABE. CP-ABE also introduces "variable attributes" which use a set of traditional attributes to represent a value that can be evaluated with more complex operations (including >, <, $\leq$. $\geq$ and =). This is

accomplished as follows; for a given decimal integer between 0 and some system defined maximum, first, the value is converted into binary and then an attribute is created for each bit. For example, if the variable attribute "access_level" was to be assigned to a user for the value 5, the following traditional attributes would be assigned:

access_level_flexint_0xxx
access_level_flexint_x1xx
access_level_flexint_xx0x
access_level_flexint_xxx1

The value of each traditional attribute may then be evaluated in an access policy similarly to KP-ABE. For example, "≥ 5" could be enforced with a policy such as "access_level _flexint_1xxx OR (access_level _flexint_x1xx AND (access_level _flexint_xx1x OR access_level _flexint_xxx1))" which creates the following access tree:

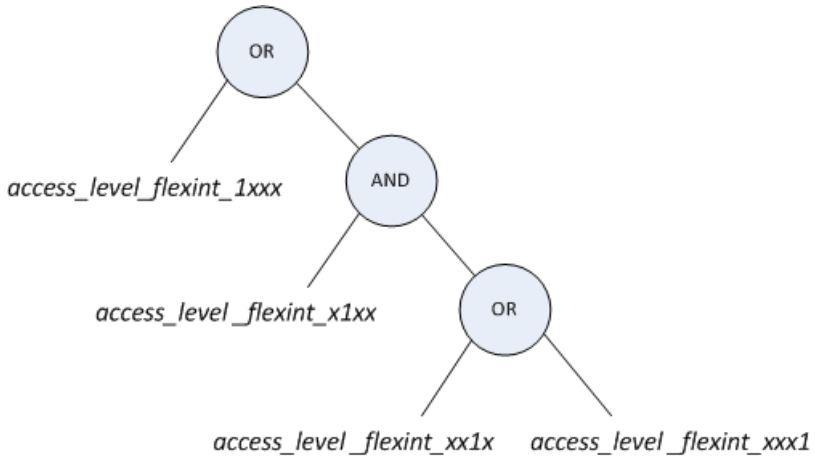


Figure 4.2: CP-ABE policy tree f or access_level ≥ 5

Access trees are created similarly to those in KP-ABE, where each non-leaf node consists of a threshold gate requiring 1 of n children to pass (for an OR gate) or n of n children to pass (for an AND gate) and leaf nodes of the tree represent a required attribute. Bethencourt, et al. (2007) define the following functions on the tree; parent(x) denotes the parent of node x, att(x) returns the attribute associated with the leaf node x,

and index(*x*) returns the index of the leaf node x (leaf nodes are assigned an index, 1 .. *n*, where n is the number of children the parent node of *x* contains). Access trees containing variable attributes are parsed and converted to a traditional access tree as described in the last paragraph.

Bethencourt, et al. (2007) present their constructions for setup, encryption, decryption and user key generation which have the same use and function as the other ABE schemes presented. For the following functions; G_0 and G_1 are the groups in the bilinear map *e* such that $e: G_0 \times G_0 \rightarrow G_1$, *k* is the size of the groups, g is the generator of G_0, $\Delta i, S$ is the Lagrange coefficient (defined the same as in subsection 4.2.1.1), *H* is a collision resistant hash function $H : \{0,1\}^* \rightarrow G_0$ which maps any string to a "random" group element, τ is the access tree for which a ciphertext is being encrypted and τ_r is the root node of that tree and *S* is the set of attributes for which a user key is created.

$$PK, MK = SETUP():$$
choose: G_0 *of prime order p with generator g*
choose randomly: $\alpha, \beta \in \mathbb{Z}_p$
$$PK = \left(G_0, g, h = g^{\beta}, e(g,g)^{\alpha}, f = g^{\frac{1}{\beta}}\right)$$
$$MK = (\beta, g^{\alpha})$$

Equation 4.9: Setup Function

$$CT = ENCRYPT(PK, M, \tau):$$
chose randomly: $s \in \mathbb{Z}_p$
$$q = CreatePolynomials(\tau_r, s)$$
$$Y = \forall leaf\ nodes \in \tau$$
$$CT = (\tau, \tilde{C} = Me(g,g)^{\alpha s}, C = h^s,$$
$$\forall y \in Y: C_y = g^{q_y(0)}, C'_y = H\left(att(y)\right)^{q_y(0)})$$

Equation 4.10: Encrypt Function

$$q = CreatePolynomials(x, s):$$

"Starting with the root node [τ_r] the algorithm sets q_r (0) = s. Then, it chooses d_r other points of the polynomial q_r randomly to define it completely. For any other node x, it sets $q_x(0) = q_{parent}(x)(index(x))$ and chooses d_x other points randomly to completely define q_x." (Bethencourt, Sahai, & Waters, 2007).

$$
\begin{aligned}
&SK = KEYGEN(MK, S, PK):\\
&\quad \text{choose randomly: } r \in \mathbb{Z}_p\\
&\quad D = g^{(\alpha+r)/\beta}\\
&\quad FOR\ \forall j \in S:\\
&\quad\quad \text{choose randomly: } r_j \in \mathbb{Z}_p\\
&\quad\quad D''_j = g^r \cdot H(j)^{r_j}\\
&\quad\quad D'_j = g^{r_j}\\
&\quad SK = (D, D'', D')
\end{aligned}
$$

Equation 4.11: KeyGen Function

$$
\begin{aligned}
&M = DECRYPT(CT, SK, PK):\\
&\quad A = DECRYPTNODE(CT, SK, PK, root(\tau))\\
&\quad IF\ A \neq \perp:\\
&\quad\quad M = \frac{\tilde{C}}{\frac{e(C,D)}{A}}\\
&\quad ELSE:\\
&\quad\quad M = \perp
\end{aligned}
$$

Equation 4.12: Decryption Function

$$
\begin{aligned}
&A = DECRYPTNODE(CT, SK, PK, x):\\
&\quad IF\ x\ is\ a\ leaf\ node:\\
&\quad\quad i = att(x)\\
&\quad\quad IF\ i \in S:\\
&\quad\quad\quad A = \frac{e(D''_i, C_x)}{e(D'_i, C'_x)}\\
&\quad\quad ELSE:\\
&\quad\quad\quad A = \perp\\
&\quad ELSE:\\
&\quad\quad \forall z\ child\ of\ x:\ F_z = DECRYPTNODE(CT, SK, PK, z)\\
&\quad\quad S_x = \forall z\ child\ of\ x\ and\ F_z \neq \perp\\
&\quad\quad IF\ S_x = \emptyset:\\
&\quad\quad\quad A = \perp\\
&\quad\quad ELSE:\\
&\quad\quad\quad A = \prod_{z \in S_x} F_z^{\Delta_{i,S'_x}(0)} \quad where^{i=index(z)}_{S'_x=\{index(z):z\in S_x\}}
\end{aligned}
$$

Equation 4.13: Recursive DecryptNode Function

As with KP-ABE, Bethencourt, et al. (2007) provide a means of delegating new user keys from a subset of attributes in an existing user key. Like KP-ABE, the newly delegated key must be as or more restrictive than the parent key. This is made possible by the value of *f* in the master public key:

$$\widetilde{SK} = DELEGATE(SK, \tilde{S}, PK):$$
$$\text{choose randomly: } \tilde{r} \in \mathbb{Z}_p$$
$$\widetilde{D} = Df^{\tilde{r}}$$
$$FOR\ \forall k \in \tilde{S}:$$
$$\text{choose randomly: } \tilde{r}_k \in \mathbb{Z}_p$$
$$\widetilde{D''}_k = D_k g^{\tilde{r}} H(k)^{\tilde{r}_k}$$
$$\widetilde{D'}_k = D'_k g^{\tilde{r}_k}$$
$$\widetilde{SK} = (\widetilde{D}, \widetilde{D''}_k, \widetilde{D'}_k)$$

Equation 4.14: Delegate Function

Bethencourt, et al. (2007) prove the security of their scheme under the generic bilinear group model (Boneh, Boyen, & Goh, 2005) and is shown in appendix A of Bethencourt, et al. (2007). As with Boneh and Franklin (2007)'s IBE scheme, CP-ABE can be efficiently extended to be secure against a chosen ciphertext attack by applying the technique from Fujisaki and Okamoto (1999).

4.2.3.2 Criticisms

As with KP-ABE and FIBE, CP-ABE shares the same issues from using a single central authority for user key generation (the central authority being both a scalability and trust bottle neck). Also, like KP-ABE, CP-ABE can potentially expose some information about the contents of the document being decrypted; however, this is somewhat less than in the case of KP-ABE. Rather than a set of attributes which potentially describes the contents of the message, CP-ABE encrypts the message with an access tree that holds

potentially less sensitive information in some cases. For example, the case used in section 4.2.2.2; a hospital wishing to encrypt some sensitive medical document about a patient's chemotherapy treatment such that only doctors belonging to the hospital staff or a technician/nurse who gives the chemotherapy treatments, may encrypt the document with the following access policy:

" (staff AND (doctor OR (technician AND department $\geq$ 120 AND department < 125))) OR (patient AND user_id = 304831)"

In this case only the patient's user_id and the fact that technicians from departments 120 to 124 may access the document is disclosed. In some cases this may still be too much information and it may be possible to map the user_id back to a full name.

Another improvement on KP-ABE and FIBE is the possibility of User Key revocation which is made possible in CP-ABE through the use of variable attributes. A user key may be created with an expiry date (e.g. "expire = 1278176400" the unix time stamp for July 3rd, 2010 at noon) and files may be encrypted with an access tree structure containing a limit on the expiry date (e.g. "expire $\geq$ 1310187600", time stamp for July 9th 2011 at midnight). If a CP-ABE based system is made to set this limit to the current date and time of the file's encryption and the key issuer creates user keys with an expiry attribute at a set time in the future, it would limit users of the system to only decrypting documents created before the expiry date. After the expiry date, a user would be forced to obtain a new key or be unable to access any future documents in the system.

While CP-ABE adds new operations to the access tree, including greater than, less than, greater than or equals, less than or equals, and equals, it does not provide a not equals operation. Such an operation may seem unnecessary, as an attribute in a user's key may simply be omitted to limit their access to a file. However, there are cases where such functionality is required. For example, many privacy laws (as detailed in section 1.2)

require that a person be able to limit access to who has access to their sensitive information (e.g. a patient may wish to prevent a particular doctor from accessing their health record which he/she would otherwise have access to). A not equals operation would enable this and allow for the creation of access policies such as “is_staff AND is_doctor AND user_id ≠ 81037”.

Finally, the security of CP-ABE has only been proven with the generic group model. Meaning that if any security vulnerability exists in the scheme, it would have to exploit the cryptographic hash functions used or a mathematical property of elliptic curve groups used in the scheme (see appendix A of Bethencourt, et al. (2007) for more details). Recent work in ciphertext policy based ABE has resulted in CP-ABE schemes proven secure under more common assumptions (Waters, 2011) without significantly impacting the efficiency of the system.

4.2.4 Self-Protecting Electronic Medical Records Using Attribute-Based Encryption (Akinyele, Lehmann, Green, Pagano, Peterson, & Rubin, 2010)

4.2.4.1 Summary

J. Akinyele et al. (2010) present one of the first attempts at using CP-ABE for protecting electronic health records in their 2010 technical report “Self- Protecting Electronic Medical Records Using Attribute-Based Encryption”. Their approach uses the somewhat naive method of directly applying an existing KP-ABE or CP-ABE scheme to XML formatted health records (specifically the CCR and CCD format). The novel contribution comes in the form of automated policy generation and visualization of EHRs for a KP-ABE system and extending the CCR and CCD formats to support ABE based encryption. J. Akinyele et al.’s (2010) policy engine is initialized with configuration options determining the ABE scheme to be used and a rule set dictating a high level view

of the encryption policies to be applied to records based on the contents. As records are passed to the engine, ABE policies are chosen based on the contents of each node in the XML record and encrypted with the specified scheme if the records' contents are deemed sensitive.

User key generation and assignment is done through an entity entitled the "ABE master controller". The ABE master controller is essentially an offline version of the user key generator required by most ABE schemes, in which an authorized user manually generates and distributes keys to hospital patients and staff. In cases where the rule set used by the policy engine requires both KP-ABE and CP-ABE encryption policies, multiple keys may be distributed to each user by the ABE master controller.

J. Akinyele et al. (2010) also detail how their system may be used with a mobile platform for decrypting and using ABE encrypted CCR/CCD health records. A python based implementation of their policy engine and an implementation of their iPhone "iHealthEMR" client is presented. Finally, it is suggested that this system could be used with cloud based services such as Google Health for safe online record storage.

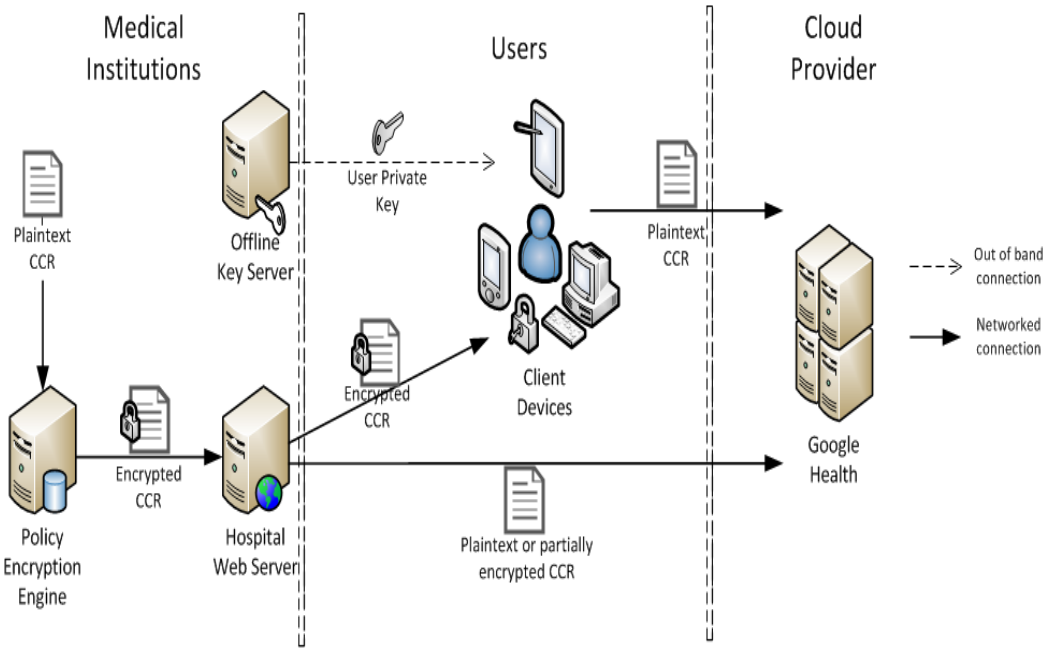


Figure 4.3: Diagram of components from **(Akinyele, Lehmann, Green, Pagano, Peterson, & Rubin, 2010)**.

4.2.4.2 Criticisms

While the ABE EHR system presented by J. Akinyele et al. (2010) offers a good solution to automatic ABE policy creation, it falls short in many other areas. Most notably, the offline ABE master control imposes significant limitations on the system. As with other ABE schemes that rely on a single trusted authority for user key generation, J. Akinyele et al.'s (2010) system suffers from the significant bottle neck of constraining key generation to one server/system. Keeping the master controller offline would seem to negate trust issues with a single entity controlling the master key (as the report suggests) however, the long term issues of this decision may present a larger security vulnerability. Since key distribution is performed primarily offline, requiring the patient or staff member to be given their key in person, it quickly becomes unreasonable to frequently issue new keys to users of the system, leading to longer (if any) key expiry times. This means that in the event that a user key is compromised, it could take a significant amount

of time or effort to revoke it. As it is expected that user keys will be stored on mobile devices in this system that can be easily lost or stolen, it seems likely that it would be more probable that a user key could become compromised than a secured ABE master controller system.

Additionally, an offline ABE master controller also constrains the usefulness of the system. It seems unlikely that all patients would be able to meet with the person in charge of the ABE master controller in person or have the necessary knowledge to utilize the raw key. In an online system, a patient could download a client and supply personal details to be authorized for the creation and delegation of a user key over a secure channel (such as SSL). Such systems already exist and are used frequently which store and process highly confidential information over the internet such as online banking and tax filing software, so it would seem reasonable that with the proper security measures any risk an online system possesses could be minimized. Furthermore, J. Akinyele et al.'s (2010) system lacks any means for outside health providers to share encrypted health records. In many cases doctors' offices, hospitals, specialists, researchers and outside labs need to communicate sensitive health information. The presented system has no means to enable this without in-person key delegation and is largely localized to a single institution.

While an effort is made to secure the ABE master controller from compromise by limiting it to an offline system, little thought is given to the online policy engine system. In many ways the policy engine is just as vulnerable to tampering as all health records are processed, encrypted and sent from this system. An attacker who obtained access to the policy engine could easily change the rules set being used, to create a "back door" attribute requirement (e.g. "OR user_id = 12345" where 12345 is the attackers user_id) in all future ciphertexts. Additionally, an attacker with access to the policy engine system

could simply eavesdrop on all records sent to the policy engine as they are sent in their plain text CCR/CCD format. In effect, the potential vulnerabilities of a compromised ABE master controller are simply shifted to the policy engine system, further undermining the advantage of placing the controller offline.

Finally, the suggested use of GoogleHealth and other cloud services falls short as it would amount to being solely an online storage system with no processing or viewing capabilities when the records are encrypted and lose all privacy protections when the records are sent unencrypted. Even when the records are stored fully encrypted on the cloud there is still the potential of unintentional information leakage depending on the attributes or policy used to encrypt the record. As shown with KP-ABE and CP-ABE (in sections 4.2.3.2 and 4.2.2.2), attributes and access trees embedded in the cihpertext may reveal some information about the contents of the file (e.g. if the name of the patient was used as an attribute to encrypt the file in KP-ABE and attribute names were public).

4.3 Distributed Multi-Authority Ciphertext-Policy Shared Attribute-Based Encryption (DMACPSABE)

4.3.1 Introduction

We present a distributed multi-authority ciphertext-policy shared attribute-based encryption (DMACPSABE) scheme built on the work of Bethencourt, et al.'s (2007) Ciphertext-policy Attribute-Based Encryption (CP-ABE). Our scheme adds support for multiple distributed attribute authorities, capable of generating user keys, which share some given subset of attributes for which they are authorized. We introduce a new hierarchal authorization data structure (section 4.3.2.1) for attribute authorities which dictate the private and shared set of constant and variable attributes a given authority will have permission to delegate to users. A new not equals operation (section 4.3.2.6) for CP-

ABE is detailed and its implications described, performance improvements (section 4.4.2) are discussed and tested, and a means for creating policies based on a user's origin (to which attribute authority they belong) is detailed (section 4.3.2.7). Additionally, our scheme provides a natural layer of anonymization for the attributes used in the access trees embedded in the ciphertext (an issue with traditional CP-ABE and KP-ABE) (section 4.3.2.8).

We present an implementation of our scheme (section 4.4.1) and evaluate its performance against Bethencourt, et al.'s (2007) CP-ABE implementation. A security evaluation and discussion is also presented in section 4.4.4.

4.3.2 Constructions

Our DMACPSABE encryption scheme extends the SETUP (Equation 4.9), ENCRYPT (Equation 4.10), DECRYPT (Equation 4.12), DELEGATE (Equation 4.14) and KEYGEN (Equation 4.11) functions from J. Bethencourt, et al.'s (2007) Ciphertext-policy attribute-based encryption model to enable multi-authority user key assignment and delegation. Each user authority is delegated a set of attributes for which it has authority over (power to further delegate the attributes to users) from an offline master authority. The master authority is only required during the initial creation of a new user authority or attribute.

The following sub-sections outline the extensions to each function. As with the J. Bethencourt, et al.'s (2007) constructions presented in 4.2.3, $G_0$is a bilinear group of prime order p and size k for which g is the generator of G_0 and $e: G_0 \times G_0 \rightarrow G_1$ denotes the bilinear map.

4.3.2.1 Authority Hierarchy

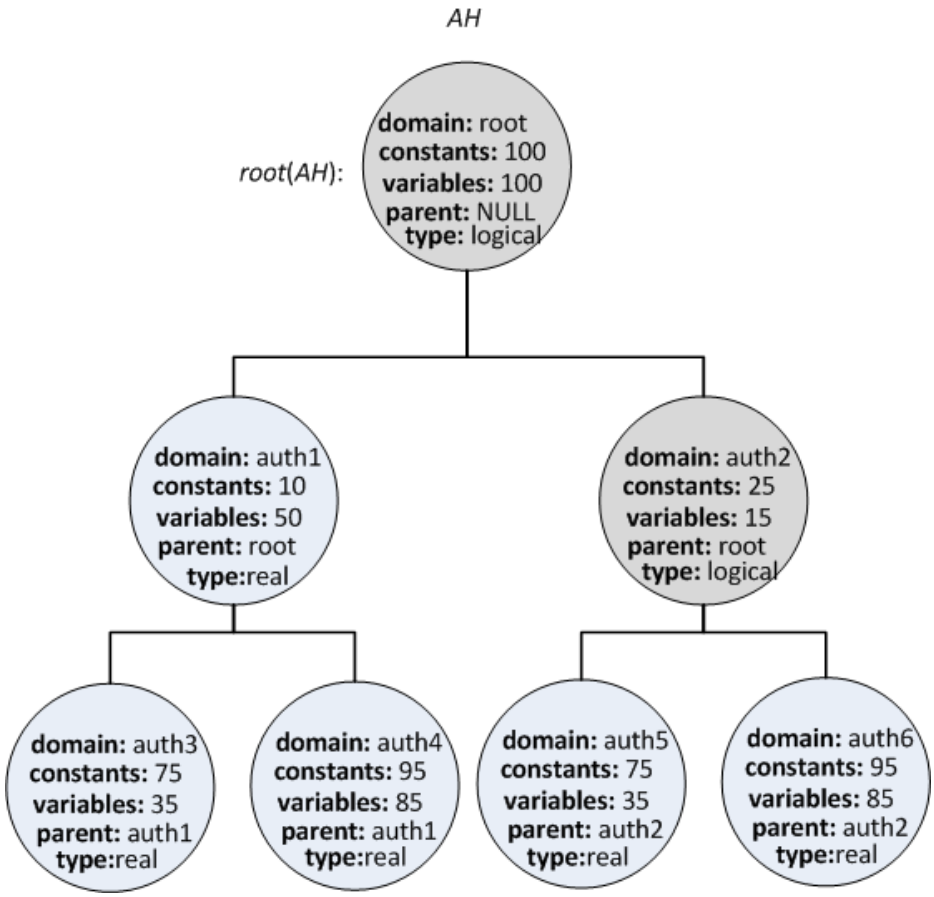


Figure 4.4: Example authority hierarchy with logical authorities root, and auth2, and real authorities auth1, auth3 .. auth6.

Unlike CP-ABE's single master authority model which places a single entity responsible for user attribute delegation and key creation, our scheme allows for multiple authorities to be created and assigned a subset of attributes for which they are granted the power to further delegate to users. Which subset of attributes an authority is granted is determined by the authority hierarchy. The authority hierarchy is a logical layout of all attribute authorities in the system and their parent/child relationships to each other. A child authority is granted all attributes of its parent and ancestors up to the root authority. Thus the root authority contains the subset of attributes shared by all authorities in the hierarchy. An example hierarchy is shown in Figure 4.4.

The authority hierarchy data structure can be seen as a tree (*AH*) with root node *root*(*AH*) representing the root authority. Decedents of the root node represent authorities authorized to assign both attributes assigned to their ancestors (up to the root authority/node) and attributes from a private set available only to that authority and it's decedents in the hierarchy. Each node, *x*, in the hierarchy tree contains a unique name referred to as a domain (*domain*(*x*)), the number of constant attributes (*constants*(*x*)) assigned to the authority, the number of variable attributes (*variables*(*x*)) assigned to the authority, the parent of the authority (*parent*(*x*)) and a type of "real" or "logical" (*type*(*x*)). Nodes of type "logical" are considered to only be place holders for attributes shared among their decedents. A logical authority is not granted an authority key and exists only in the representation of the hierarchy *AS*. For example, the authority "root" in Figure 4.4 will cause the creation of 100 constant attributes and 100 variable attributes which will be shared with all descendants but will not be issued an authority key. Authority "auth1" will be assigned 10 constant and 50 variable attributes and will inherit all 200 attributes from the root authority. Similar "auth3" and "auth4" will be assigned their designated number of attributes and inherit all attributes from "auth1" (their parent) and the root authority (auth1's parent). Like the root authority, auth2 is logical and will not be granted an authority key but will share it's attributes with its descendants auth5 and auth6 (which also inherit attributes from the root authority via auth2).

4.3.2.2 Setup

Our setup function (Equation 4.15) takes the authority hierarchy tree (*AH*) and begins as CP-ABE does, using the same master key (*MK*) and public (*PK*) definitions (only differing in excluding *f* from *PK* and referring to it as the delegation key) but adds the generation of the set of attribute authority keys (*ASK*) based on the attribute set

returned by the AuthAttSet function (Equation 4.16) for each authority in the given hierarchy. As with Equation 4.9, $G_0$is a chosen bilinear group of prime order p and $\propto, \beta$ are randomly generated integers in $\mathbb{Z}_p$. We define *auth_index*(*x*) as a function which returns an arbitrary but always unique integer greater than 0 and less than INT_MAX for a given authority hierarchy node *x*.

$PK, MK, f, ASK = Setup(AH)$:
choose: $G_0\ of\ prime\ order\ p\ with\ generator\ g$
choose randomly: $\alpha, \beta\ \in \mathbb{Z}_p$
$PK = \left(G_0, g, h = g^{\beta}, e(g,g)^{\alpha}\right)$
$f = g^{\frac{1}{\beta}}$
$MK = (\beta, g^{\alpha})$
$AS = AuthAttSet(root(AH), \emptyset)$
$ASK = \ \forall S \in AS:\ \ ASK_s = KEYGEN(MK, S, PK)$

Equation 4.15: DMACPSABE Setup Function

$AS = AuthAttSet(x, parentset)$:
$FOR\ 1\ ..\ constants(x)\ as\ i$:
$S_i = \ string(domain(x) + \text{"\_c"} + \text{i})$

$FOR\ 1\ ..\ (variables(x) * 2)\ by\ 2\ as\ k$:
$S_{constants(x)+k} = string(domain(x) + \text{"\_v"} + i + \text{" = 0"})$
$S_{constants(x)+k+1} = string(domain(x) + \text{"\_v"} + i + \text{" = "} + INT\_MAX)$

$S_{constants(x)+(variables(x)*2)+1} = string(\text{"auth\_key = "} + \text{auth\_index(x)})$
$S = ConvertAtts(S)$
$P = ConvertAtts(\{string(\text{auth\_key = } +\ \text{auth\_index(parent(x))})\})$
$S = S\ \cup (parentset \setminus \text{P})$

$IF\ type(x) = real$:
$AS = \{S\}\ \cup \forall z\ child\ of\ x:\ \ AuthAttSet(z, S)$
$ELSE$:
$AS = \ \forall z\ child\ of\ x:\ \ AuthAttSet(z, S)$

Equation 4.16: Recursive DMACPSABE AuthAttSet Function

In addition to creating the master and public keys, the *Setup* function calls the recursive function *AuthAttSet* (Equation 4.16) to obtain the set (*AS*) containing sets for

each authority containing the attributes to be assigned to the respective authority. An authority's attribute set is determined by recursively descending the authority hierarchy and creating a set of attribute names for each node (with attribute sets for descendants of that node being unioned with the parent node). Next the auth_key attribute is added (explained further in section 4.3.2.6, 4.3.2.7, and 4.3.2.9), the variable attributes are converted to constant attributes (via *ConvertAtts*(*S*)), the set is added to *AS*, and *AuthAttSet* is called on all children of the node. With the set of attribute sets complete, the *Setup* function is able to compute the set of secret keys (*ASK*) for each authority using the *KEYGEN* function.

As attributes may not be initially assigned a particular meaning or purpose in the system, a generic attribute name is created which may be later mapped to a more appropriate human readable name (see section 4.3.2.8). Constant attribute names are created by appending the authority's domain, the string "_c" and a number (1 through *constants*(*x*) inclusively). Variable attributes are named similarly (by appending the domain, string "_v" and a number) but are also given the value of 0 and INT_MAX (INT_MAX being equal to 2^b - 1 and b being the number of bits allowed in the attribute values).

To satisfy the policy tree during decryption, variable attributes are split into multiple constant attributes each representing a possible value of a single bit of the variable's value (see Table 4.1). Thus assigning the same variable attribute to an authority with a value of 0 and INT_MAX is equivalent to assigning it the constant variable's for every possible value of a bit, making up the variable attribute's value. This allows an authority to assign any value for a variable attribute to a user (by delegating the subset of constant attributes which make up the correct value in bits for the delegated value) while only having to hold a key containing *b * 2* constant attributes (where b is the

number of bits in a variable's value). An example of this can be seen in Table 4.1 where an authority with the variable attributes "auth1_v0 = 0" and "auth1_v0 = 15" also contains the subset of constant attributes for "auth1_v0 = 10".

Variable Attributes	**Constant Attributes**
auth1_v0 = 10	auth1_v0_ flexint_1xxx auth1_v0_ flexint_x0xx auth1_v0_ flexint_xx1x auth1_v0_ flexint_xxx0
auth1_v0 = 0 auth1_v0 = 15	auth1_v0_ flexint_1xxx auth1_v0_ flexint_0xxx auth1_v0_ flexint_x0xx auth1_v0_ flexint_x1xx auth1_v0_ flexint_xx1x auth1_v0_ flexint_xx0x auth1_v0_ flexint_xxx0 auth1_v0_ flexint_xxx1

Table 4.1: Table showing the equivalent constant attributes for a given set of variable attributes. Assuming INT_MAX of 15 (i.e. 4 bit variable values).

4.3.2.3 User Keygen

Unlike in CP-ABE, a user's key is not generated via the *KEYGEN* function but delegated off an attribute authority's key. This process (detailed in Equation 4.17, where function *H* is a hash function, $\tilde{r}$, and $\tilde{r}_k$ are random numbers and *US* is the set of attributes to be assigned to the user) is the same as the *DELEGATE* function from CP-ABE but includes the delegation key, *f*, since it is no longer included in the public key due to the changes in the *Setup* function. Also, unlike attribute delegation in CP-ABE, where a key owner may only delegate the value of an attribute variable for which they were assigned, an attribute authority is able to assign any value of for an assigned variable attribute. This is made possible due to the way variable attributes are assigned in our *Setup* function and explained at the end of section 4.3.2.2 (i.e. via the attribute

authority being assigned constant attributes for all possible values of bits in a variable attribute's value).

$$USK = UserKeyGen(ASK_i, US, PK, f):$$
choose randomly: $\tilde{r} \in \mathbb{Z}_p$
$\widetilde{D} = Df^{\tilde{r}}$
$FOR\ \forall k \in US:$
choose randomly: $\tilde{r}_k \in \mathbb{Z}_p$
$\widetilde{D''}_k = D_k g^{\tilde{r}} H(k)^{\tilde{r}_k}$
$\widetilde{D'}_k = D'_k g^{\tilde{r}_k}$
$USK = (\widetilde{D}, \widetilde{D''}_k, \widetilde{D'}_k)$

Equation 4.17: DMACPSABE UserKeyGen Function

Further delegation of attributes at the user level is controlled by limiting access to the delegation key. A user with the delegation key may further delegate their attributes into a new key using the same *UserKeyGen* function with their key and a subset of attributes from the set they were assigned, but may never add more attributes, change attribute values or combine the attributes with another users (the security and source of this protection is discussed in section 4.4.4). Allowing users to further delegate their attributes is no more insecure than the possibility of users sharing a key or the information which it decrypts but has the advantage of enabling users to share only parts of their key (some subset of their assigned attributes) when necessary.

4.3.2.4 Encryption and Decryption

Encryption and decryption proceed the same as in CP-ABE but with a key difference from the CP-ABE implementation. As one of the performance enhancements presented in the CP-ABE implementation (Bethencourt, Sahai, & Waters, 2007), an additional constant attribute is added for each variable attribute containing the decimal value of the variable. For example, for the variable attribute "auth1_v0 = 10" the constant

attribute “auth1_v0_10” would be added. This allows for a performance increase when the policy tree contains an equals requirement on a variable attribute (e.g. requiring that auth1_v0 being equal to 10). As this would require each authority being assigned a constant attribute for each possible value from 0 to INT_MAX (adding significantly to the time to generate and the size of an authority key) we have omitted this enhancement and a policy tree is created which requires all attributes that make up the value in binary to be present (e.g. requiring that a key contains attributes for auth_flexint_1xxx, auth_flexint_x0xx, flexint_xx1x and flexint_xxx0 rather than just the attribute auth1_v0_10 being present).

4.3.2.5 Adding/Removing Authorities and Attribute Sets

New attribute authorities may be added to the hierarchy simply by using the master authority to create the new attribute authority key containing the appropriate set of constant and variable attributes. It is expected that this operation would be performed offline manually and the new key would be installed on the new attribute authority through a secure channel. Similarly, adding attributes or making additive changes to the authority hierarchy may be performed by generating new attribute authority keys for the affected authorities. As this is a costly operation (and time consuming if done manually and offline) it is recommended that a large set of attributes be initially assigned to each authority to avoid the need to frequently create new attributes. If the changes to an authority’s key are purely additive (only adding new attributes and not remove any existing attributes in the key) all current user keys and encrypted documents are still fully functional and backwards compatible with the new authority key.

In an ideal environment, removing attributes from an authority would be done in a similar manner (by issuing a new key) and removing an authority would simply involve

shutting it down. However, removing attributes and authorities poses more of a challenge when the attribute authority may not be trusted. In such a case there is no simple way to guarantee that the authority will discard the old key and only use the new attribute set it is assigned. We do however, provide a means for revoking the old authority key (as explained in 4.3.2.9) for all future encrypted documents and a new authority key and identity (domain name) may be assigned if we wish to only replace the set of attributes. Revoking the authority's key has the side effect of invalidating all user keys for which it delegated for future documents and is reliant on clients performing the encrypting having access to an updated revocation list.

4.3.2.6 Not Equals

As detailed in section 4.2.3.2, the CP-ABE scheme presented by Bethencourt, et al. (2007) lacks a not equals operation. Such an operation is important for at least two cases; the first being excluding a particular user based on an attribute that most or all users possess some value for. For example if we assign every user in the system the variable attribute "user_id" for some unique value to that user (e.g. "user_id = 4727236"), not equals would then allow us to exclude a particular user from decrypting a file by creating an access policy such as "user_id ≠ 9833344". This is important, as many privacy laws require that a person be able to exclude a specified person form viewing their personal information stored by an organization. The second case is for using the operation in user and authority key revocation. As with the first case, a policy like "user_id ≠ 9833344" could be added to all encrypted documents to block a known-to-be-compromised key from accessing the file. Similarly, a statement like "auth_key ≠ 2" could be used to revoke access to a whole authority's user base in the case that the given authority becomes compromised.

For our proposes we may define “not equals” as “equal to any valid value but”, meaning that a user must both have the given variable attribute and it must not be equal to the given value to pass the access policy (users missing the attribute completely would also be rejected). We may construct such an access tree as follows (for the example of “user_id ≠ 4” and an INT_MAX of 15):

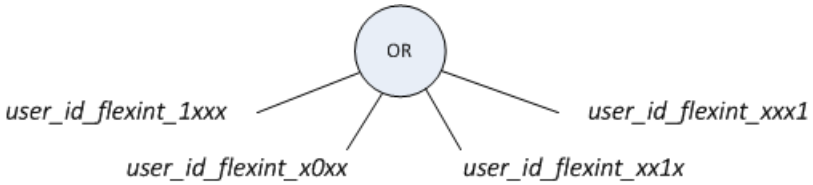


Figure 4.5: Access tree for user_id ≠ 4

That is essentially by converting the value to binary, “0100”, inverting the 1s and 0s, “1011”, and requiring the attribute for each bit. E.g. “1 of (user_id_flexint_1xxx, user_id_flexint_x0xx, user_id_flexint_xx1x, user_id_flexint_xxx1)”.

4.3.2.7 User Origin

Our scheme provides a means of creating access policies based on a given user’s origin (in this case to which attribute authority they belong) via the “auth_key” attribute added to every authority key in the *AuthAttSet* function (Equation 4.16). Every authority in the hierarchy is assigned a unique value of auth_key during authority key creation. It is expected that each attribute authority includes this attribute in each user’s attribute set. However, even if a dishonest authority or user (via delegation of a subset of their key) omitted the attribute they would still fail to pass access policies requiring or excluding a given auth_key value (as the not equals operation requires the attribute be present and have at least some value).

As attribute authorities likely represent different institutions or departments in the system, this feature is useful for limiting access to or from a given institution/department when all other required attributes are shared and no existing attribute performs a similar role. Additionally, the “auth_key” attribute is used as part of our revocation system for revoking compromised authority keys (see section 4.3.2.9).

4.3.2.8 Human Readable Attributes

Unlike traditional CP-ABE and KP-ABE schemes which use a hash function to map descriptive attribute names to attributes, our scheme delegates sets of attributes before their purpose is known. The result is somewhat obscured attribute names/identifiers being assigned to users and used in access trees such as “auth1_v1” or “root_c5”. This actually may be seen as a security feature as it adds a level of anonymity to attributes and helps prevent the information leakage possible in CP-ABE and KP-ABE. However, this also presents a potential problem for the encryptors of documents as they lack the details to determine which attributes to use in their policy.

The following are several potential solutions to this issue which provide, varying levels of attribute anonymity:

Public Mapping of Attribute Names:

In this case an authority keeps an updated map of attribute names to identifiers and publicly publishes it. Users of the system would download a copy of the map periodically (possibly with each key request) and use it for creating access trees when encrypting documents. This case would provide no attribute anonymity but would easily allow for creating encrypted messages.

Private Mapping of Attribute Names:

In this case an authority keeps an updated map of attribute names to identifiers but would only provide it to users who are granted the right to create new documents in the system. Users only re-encrypting documents to make modifications would only need to use the same access tree as for which the document was encrypted (which is embedded in the ciphertext and no knowledge of the attributes is needed to use it). This case would provide attribute anonymity so long as the subset of users who may add documents can be trusted.

Automatic Policy Generation

In this case, a policy engine such as that presented by Akinyele, et al. (2010) is used to automate policy creation during document encryption. Such an engine would be initialized with a rule set containing the high level institutional policies and raw anonymized attribute identifiers and create access tree policies based on the contents of the record being encrypted. This case would help ensure the anonymity of attributes as well as greatly simplify access tree creation, so long as a proper and reliable rule set could be created.

Each attribute authority in the system and the organization/ institution/department it represents may independently choose to implement a different method which best matches their requirements as no one method of attribute name mapping is required to be imposed on all authorities.

4.3.2.9 Revocation and Expiration

User Key Revocation and Expiration

As with the CP-ABE scheme presented by Bethencourt, et al. (2007), user keys may be set to expire by including a variable attribute, an expiry date and ensuring that all encrypted documents contain a policy requiring that attribute to be greater than the current date. This would effectively limit expired user keys to decrypting documents encrypted before the key expired (which may already have been decrypted/compromised by the user). Revoking the user key then becomes simply a case of not renewing the key. Additionally in cases where users have no need to view documents past a set date, a lower limit may be placed on the expiry attribute to limit access to old documents.

As our scheme adds a not equals operation we are also given the option of revoking access to a user by excluding an attribute value unique to that user. For example, if all users are given a unique value for the variable attribute "user_id" one may simply exclude a given user by adding a policy such as "user_id ≠ 123456" to deny a user with the id 123456 the ability to decrypt the document. Even if the user removed the "user_id" attribute from their key, they would still fail to pass the access policy due to the way not equals is defined (see section 4.3.2.6).

Attribute Authority Revocation and Expiration

The addition of the "auth_key" attribute in *AuthAttSet* function (Equation 4.16) allows us to deny access to users whose key was generated by a set authority (i.e. their origin, see section 4.3.2.7) as we could an individual user via a "user_id" attribute. If an attribute authority were to become compromised, a notice could be posted in a public revocation list and future documents could be encrypted with the requirement that "auth_key ≠ 5" for example, if the authority with an auth_index of 5was compromised.

This would effectively prevent any user from that authority from decrypting future documents.

As with user keys, attribute authority keys could also be created with a set expiry attribute which it would in turn delegate on to its users. However, unlike the user key expiry date, which maybe set to only days or hours in the future an authority key would have to be set to expire significantly longer in the future (possibly months or a year) as the process for creating authority keys is more costly and involves some level of manual intervention by a system administrator.

4.3.3 Protocol

The following sub-sections outline the cytological protocol and processes involved in the setup of the master authority (labelled Trent), distribution of authority keys (to attribute authorities labelled auth1, auth2, auth3 and auth4), distribution of user keys (to users labelled Alice and Bob) and message encryption/decryption. The same authority hierarchy shown in Figure 4.4 is assumed to be used in all given examples.

4.3.3.1 Master Initialization

Trent (the master authority) creates an authority hierarchy containing all attribute authorities (in this case auth1, auth2, auth3, and auth4), the initial number of constant and variable attributes for each authority and the parent/child relations between each. In this case Trent creates the hierarchy (*AH*) from Figure 4.4 and assigns 1 variable and 1 constant attribute to each node which results in the following authority attribute sets for

$ASK_{auth1} = \{root\_c1, root\_v1, auth1\_c1, auth1\_v1, auth1\_key\}$

$ASK_{auth6} = \{root\_c1, root\_v1, auth2\_c1, auth2\_v1, auth6\_c1, auth6\_v1, auth6\_key\}$

Trent proceeds to create the public key (*PK*), master key (*MK*), delegation key (*f*) and set of authority keys (*ASK*) by running the *Setup* function (Equation 4.15) with *AH*:

$$PK, MK, f, ASK = Setup(AH)$$

Trent publishes *PK* publicly and stores *MK* offline in a secure location (only needed for further authority and attribute creation). Trent sends each real authority in the hierarchy their respective authority key ASK_i and the delegation key *f* via a secure channel (e.g. SSL tunnel, in person, via another secure communication system).

4.3.3.2 Authority User Key Delegation

Attribute authorities auth1, auth3, auth4, auth5, and auth6 receive ASK_i and *f* from Trent via the secure channel. Bob, a user of authority auth1, and Alice, a user of authority auth6, are delegated user keys as follows:

$Auth1$:

$$USK_{Bob} = UserKeyGen(ASK_{auth1}, US_{Bob}, PK, f)$$

$Auth6$:

$$USK_{Alice} = UserKeyGen(ASK_{auth6}, US_{Alice}, PK, f)$$

For this case we will assume the following attribute sets are assigned to each user:

$US_{Bob} = \{auth\_key = 1, root\_v1 = 5, root\_c1, auth1\_v1 = 7\}$

$US_{Alice} = \{auth\_key = 6, root\_v1 = 11, root\_c1, auth6\_c1, auth2\_v1 = 3\}$

auth1 and auth6 responds to Bob and Alice's request by sending their respective user keys, USK_{Bob} and USK_{Alice}, over the same secure channel.

4.3.3.3 Encryption

A person (here after referred to as Charlie) wishing to send a message, *M*, to any user who matches a given policy tree, *τ*, first obtains the public key of the master authority, *PK*, and creates a policy tree based on a boolean statement involving constant and variable attributes. For example Charlie may wish to create a policy tree to only allow users who have a value for the variable attribute root_v1 greater than or equal to 5:

$$root\_v1 \geq 5$$

Which expands to the following boolean statement using constant variables:

root_v1_flexint_1xxx OR (*root_v1_flexint_x1xx* AND (*root_v1_flexint_xx1x* OR *root_v1_flexint_xxx1*))

For which he creates the following policy tree:

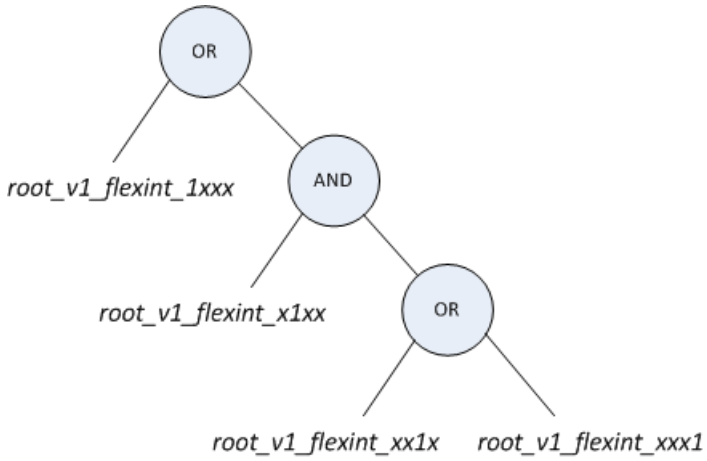


Figure 4.6: Policy tree for root_v1 ≥ 5.

and precedes to compute the cypher text, *CT*, using the same encryption function from Bethencourt, et al. (2007):

$$CT = ENCRYPT(PK, M, \tau)$$

Charlie may now transmit *CT* to the intended users (in this case Alice and Bob) over an unsecure open channel or even publish the cypher text publicly.

4.3.3.4 Decryption

Users Alice, Bob and eavesdropping user Eve who contains the attribute set:

$$US_{Eve} = \{auth\_key\ = 4, root\_v1\ = 4, root\_c1, auth1\_v1\ = 7\}$$

obtain CT from Charlie and attempt to decrypt the message using their user key.

Alice:

Alice decrypts CT using the decryption function from Bethencourt, et al. (2007):

$$M = DECRYPT(CT, USK_{Alice}, PK)$$

This is possible since Alice's key contains the attributes for root_v1 = 11:

root_v1_flexint_1xxx
root_v1_flexint_x0xx
root_v1_flexint_xx1x
root_v1_flexint_xxx1

which satisfy the policy tree τ (Figure 4.6) used by Charlie to encrypt *M*:

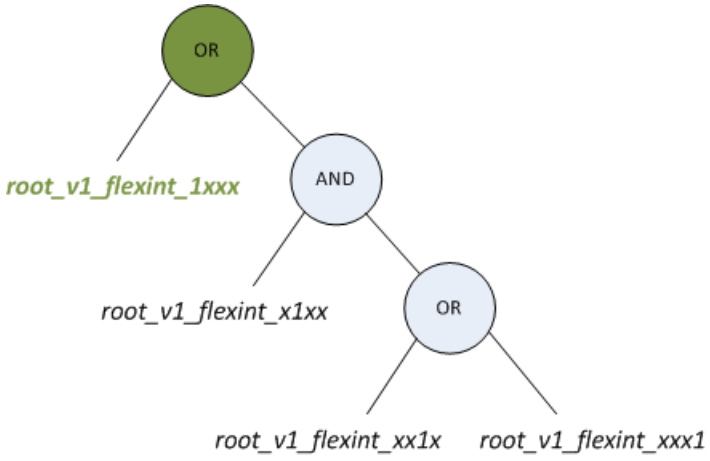


Figure 4.7: Policy tree requirement met by USK_{Alice}.

Bob:

Similarly Bob is able to decrypt the cypher text received from Charlie using the decryption function:

$$M = DECRYPT(CT, USK_{Bob}, PK)$$

As USK_{Bob} contains the attributes for root_v1 = 5:

root_v1_flexint_0xxx
root_v1_flexint_x1xx
root_v1_flexint_xx0x
root_v1_flexint_xxx1

which satisfy the policy tree τ (Figure 4.6) used by Charlie to encrypt *M*:

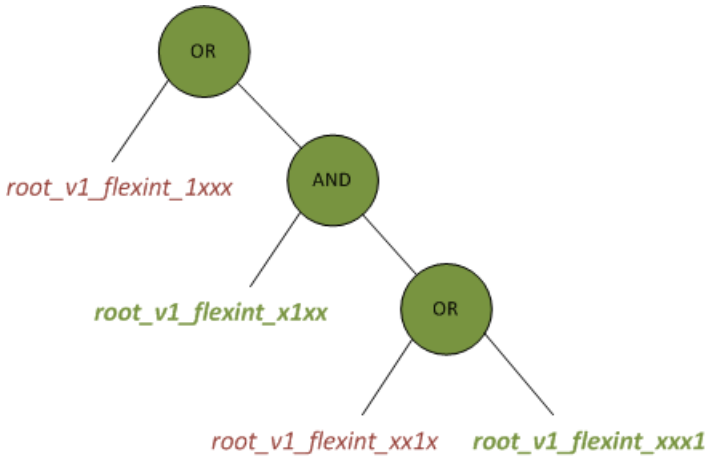


Figure 4.8: Policy tree requirement met by USK_{Bob}.

Eve:

Eve obtains *CT*, from eavesdropping on the communication between Charlie and Bob/Alice or through the location where Charlie publicly published the ciphertext. While Eve may obtain *CT*, *PK*, the decryption function and her own user key, which in this case contains the attributes for root_v1 = 4:

root_v1_flexint_0xxx
root_v1_flexint_x1xx

root_v1_flexint_xx0x
root_v1_flexint_xxx0

she is unable to decrypt the message as she fails to satisfy the policy tree used to encrypt M:

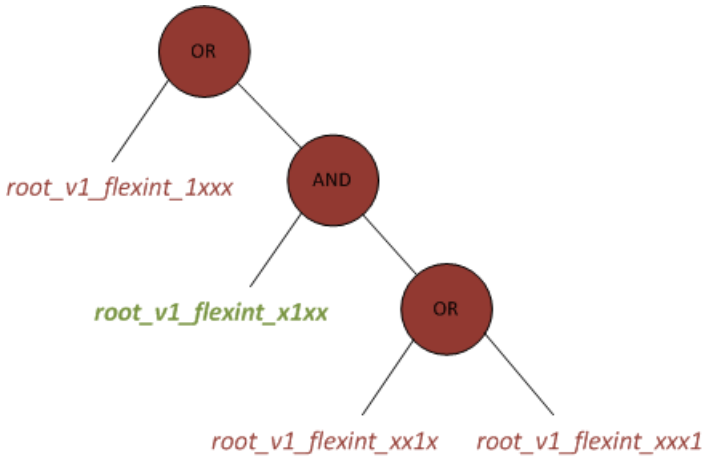


Figure 4.9: Failure of USK_{Eve} to satisfy the policy tree τ.

4.4 Implementation & Evaluation

4.4.1 Implementation Details

To test and fully evaluate our DMACPSABE encryption scheme, a C++ based implementation was created by modifying J. Bethencourt, et al.'s (2006) CP-ABE implementation, to add our extended functions, features and distributed authority setup. As our implementation is based on the CP-ABE implementation it uses the same PBC library (http://crypto.stanford.edu/pbc/) for the algebraic operations and only supports Unix and Linux based systems.

Our Setup (Equation 4.15), AuthAttSet (Equation 4.16) and UserKeyGen (Equation 4.17) functions were added to the CP-ABE implementation. The constant

attribute added for each variable attribute containing the decimal value of the variable was removed (see section 4.3.2.4) and the implementation was split into three components (one for the master authority, one for attribute authorities and one for the users of the system). A hash table was added to store all components of an authority key in memory (mapping an attribute name to the values of D_j and $D`_j$ ($g^r \cdot H(j)^{r_j}$ and g^{r_j} respectively)) for the attribute authority component. This allows for the authority key to be read into memory during the initialization of the attribute authority rather than read from the hard drive for each user key request. As the authority key grows linearly in size with the number of attributes (Figure 4.10) this becomes a required optimization for systems that must fulfill a large number of user key generation requests.

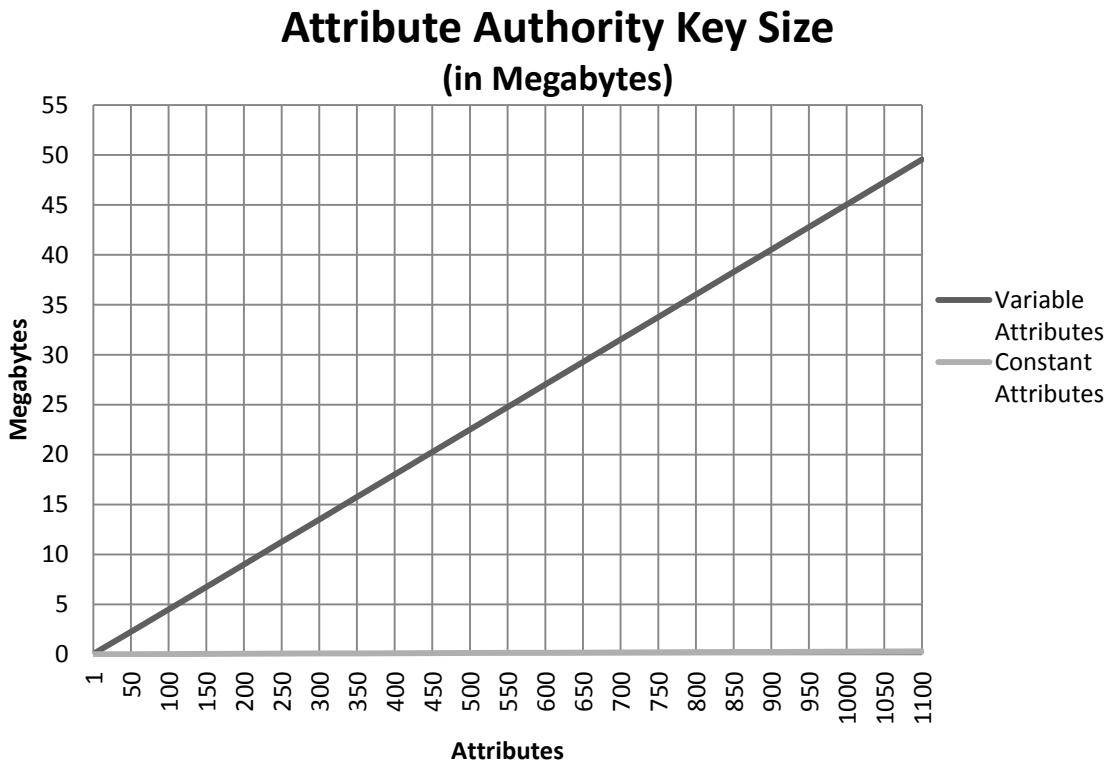


Figure 4.10: Attribute authority key size vs number of variable and constant attributes.

Finally, a Linux daemon was created for the attribute authority component which listens for connections on a local socket and responds to user key generation requests. A

Java based client API was also created to communicate with attribute authority daemon as well as a Java API which uses the user component for encrypting and decrypting strings (both APIs are an important part of using DMACPSABE with HCX and RBACaaS in section 4.5).

4.4.2 Performance Evaluation

To evaluate the performance of DMACPSABE we examined our implementation in terms of number of constant attributes required to represent the same variable attribute, the time required to generate an authority key, the time required to generate a user key, and the size of the resulting user and authority keys. An unmodified version of Bethencourt, et al.'s (2006) CP-ABE implementation is used as a control and comparison for our results when possible.

Tests for the results in the following sections were performed on a Ubuntu Linux based system with the following specifications:

- **CPU:** Intel Core2 Quad CPU Q6700 @ 2.66GHz
- **RAM:** 4GB
- **Hard Drive:** 30GB
- **Network:** 10/100/1000Mbps

4.4.2.1 Attributes Required and Key Size

Unlike the keys used in CP-ABE, attribute authority keys require the attributes to create any possible value for a variable attribute (Table 4.1 and end of section 4.3.2.2). This leads too many of the performance inequities between DMACPSABE and CP-ABE when the size of the authority keys, or the time required to generate the authority keys, is compared. As shown in Figure 4.11, $b - 1$ more attributes are required for each variable attribute in an authority key than in an equivalent CP-ABE key (where b is the number of

bits in a variable's value). However, the number of attributes required for a user key in DMACPSABE is one less than in CP-ABE.

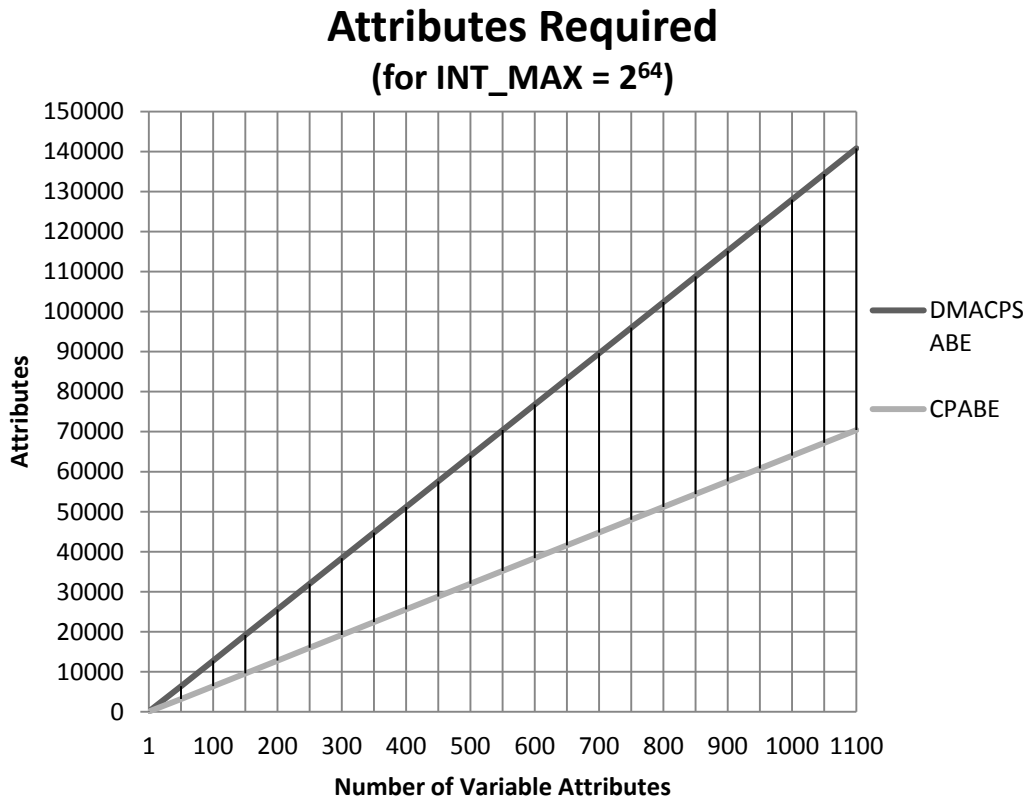


Figure 4.11: Constant attributes required to represent a given number of variable attributes in a DMACPSABE authority key and a CP-ABE user key.

The number of attributes is also directly proportional to the size of the authority and user keys as shown in Figure 4.12. As with the number of attributes, despite the large size of the authority key, the size of a user key in DMACPSABE is slightly smaller than the equivalent in CP-ABE.

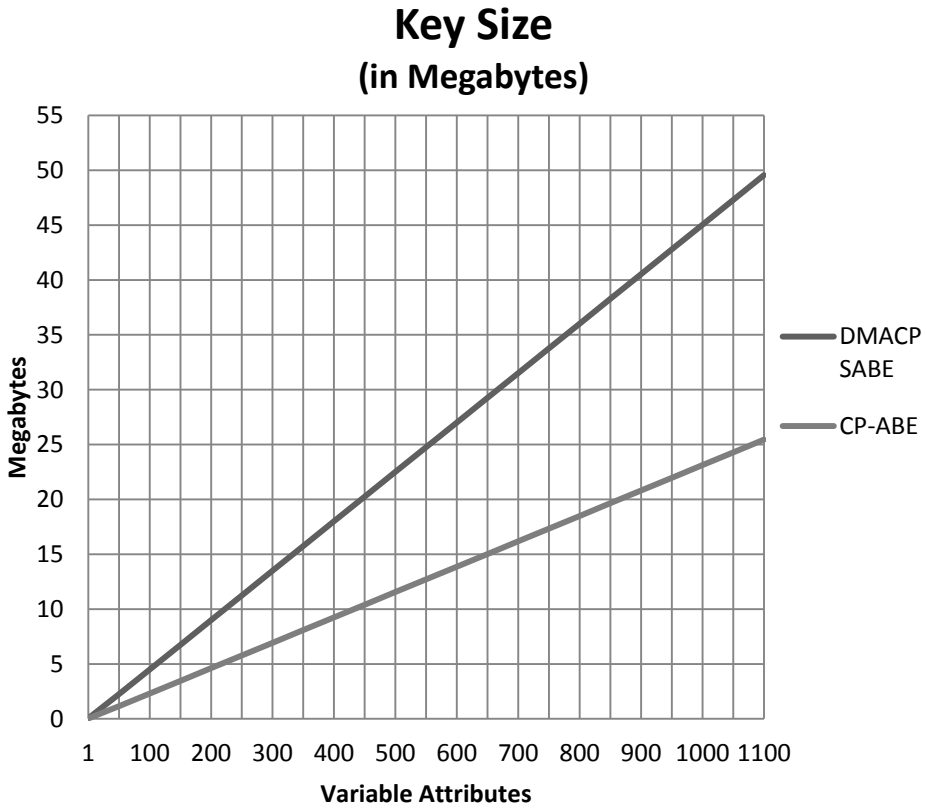


Figure 4.12: Size of a DMACPSABE authority key vs. the size of a CP-ABE user key in megabytes for a INT_MAX of 2^{64}.

4.4.2.2 Time Required to Generate an Attribute Authority Key

The time in seconds to generate an authority key is shown in Figure 4.13. Authority key generation is linear with the number of attributes though still significantly longer than CP-ABE user key generation shown in section 4.4.2.3. However, the times are not easily compared as authority key generation is normally only performed once during the initialization of the master authority, while user key generation may be required frequently. As expected, the time required to create authority keys containing only constant attributes is significantly smaller than a key containing the same number of variable attributes as a variable attribute may be seen as *b * 2* constant attributes.

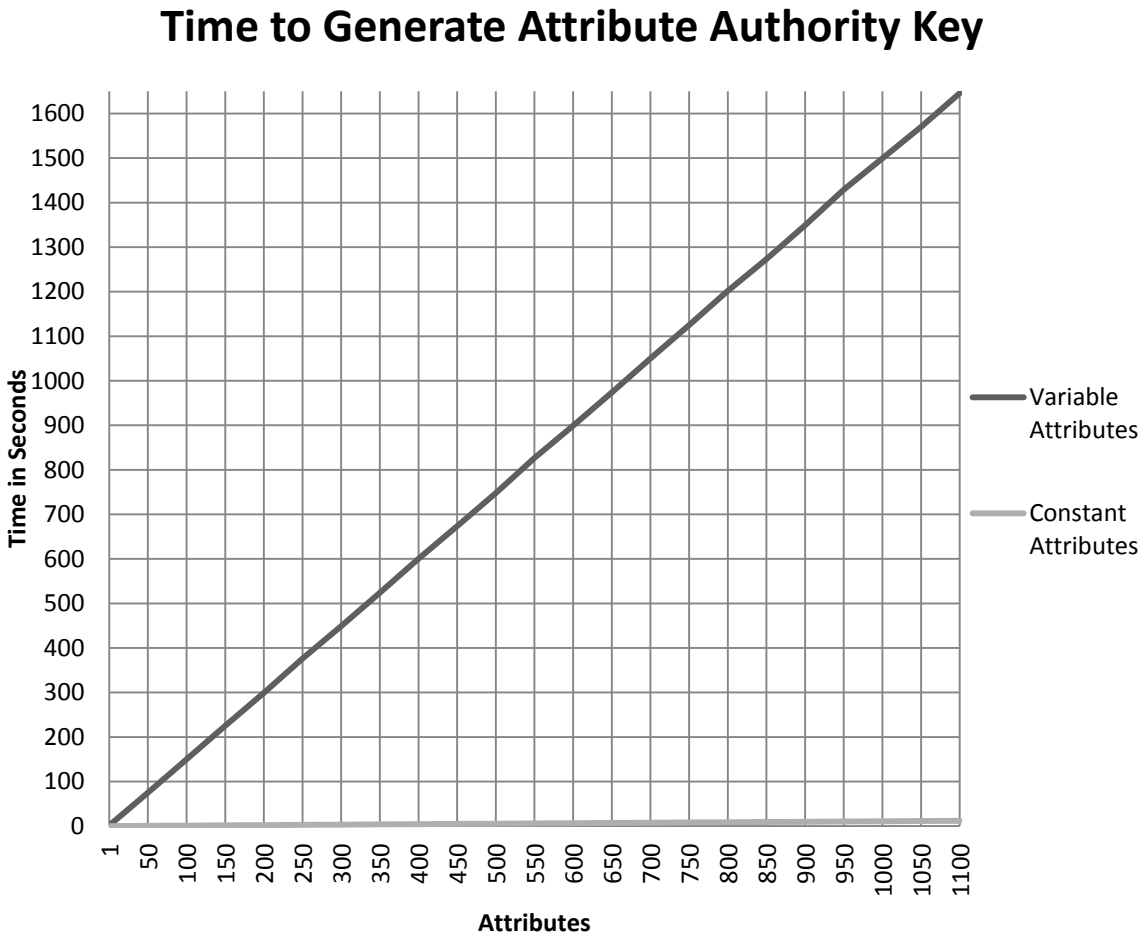


Figure 4.13: Time to generate an attribute authority key in seconds vs. number of variable and constant attribute.

4.4.2.3 Time Required to Generate an User Key

Figure 4.14 shows that the time to generate a CP-ABE user key is almost identical to the time required to generate a user key by delegation from an authority key via the DMACPSABE UserKeyGen function. Additionally, Figure 4.15 shows that this will remain true despite the size of the authority key (assuming the number of attributes in the user key remains the same). Again the relationship between attributes and generation time remains linear and scalable.

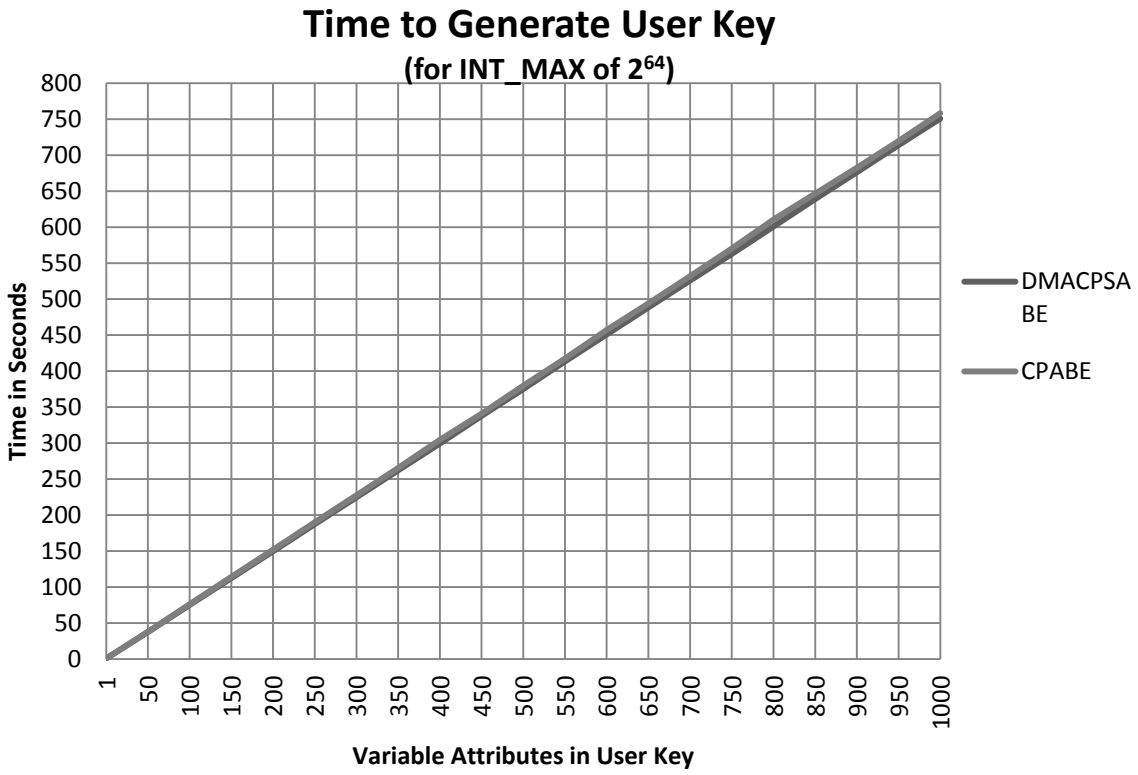


Figure 4.14: Time to generate user key in CP-ABE and DMACPSABE in seconds vs number of variable attributes.

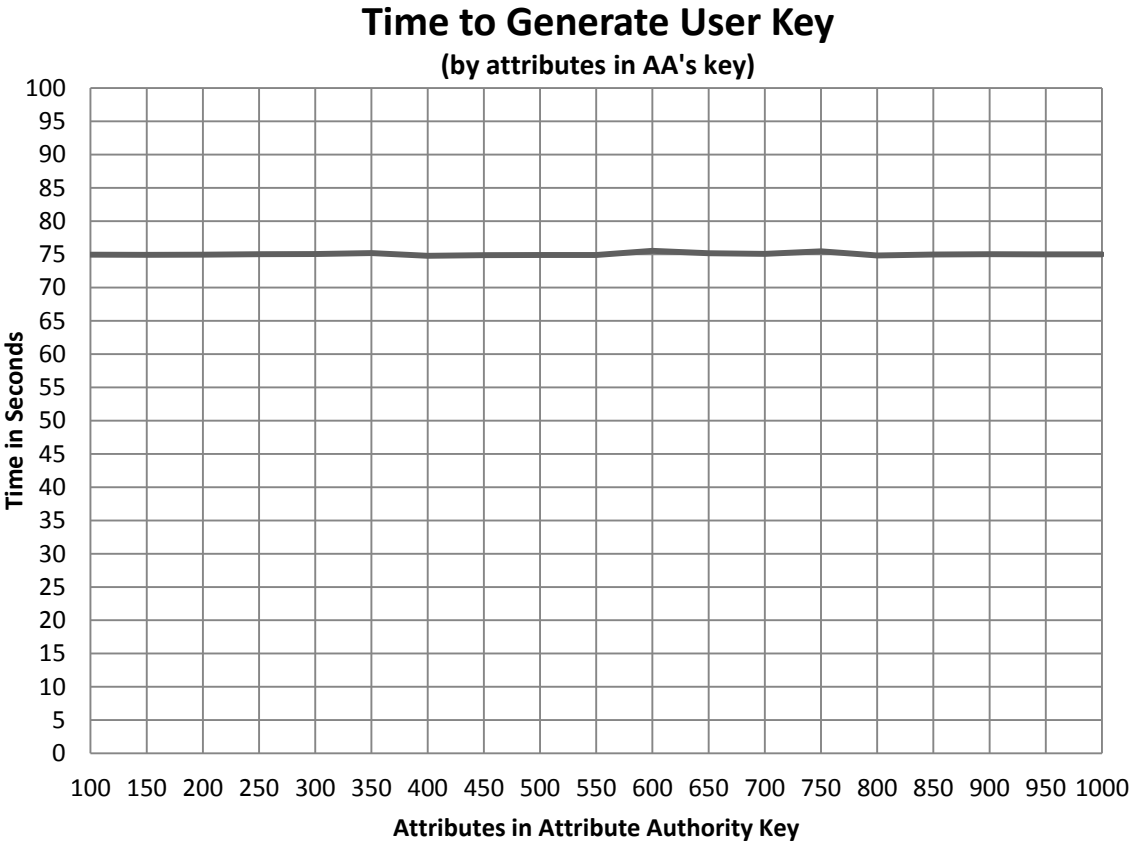


Figure 4.15: Time to generate DMACPSABE user key in seconds vs number of attributes in the authority key for a constant number of attributes in the user key.

4.4.3 Possible Performance Improvements

The UserKeyGen (Equation 4.17) and KEYGEN (Equation 4.11, used by Setup Equation 4.15) functions lend themselves well to parallel processing as there are many independent calculations required in computing the values of D_i and $D`_i$. The values of $D_i$ and $D`_i$ for each i in $\forall i \in US$ (UserKeyGen) or $\forall i \in S$ (KEYGEN) may be calculated independently and in parallel after the random value of r has been determined, so long as the proper order of the set is maintained. This allows for the generation of a particularly large attribute authority key to be set up as a massively parallel solution, reducing the generation time from hours to seconds. For user key delegation this allows for the use of multi core systems (which are becoming common place in both server and home hardware environments) to reduce DMACPSABLE user key generation times to lower than the generation times in standard CP-ABE implementation.

We present the following modifications (Equation 4.18 and Equation 4.20) to our UserKeyGen function and the CP-ABE KEYGEN function to allow for parallel processing. For multi core, or multi CPU systems sharing the same memory, it is assumed that the area in memory is large enough to fit the resulting key that is created (e.g. an array of structures which will hold the value of D_i and $D`_i$) and the results are placed correctly within the block of memory as computed. For distributed systems it is assumed that a central node will create a similar block of memory and store the resulting values correctly as computed. In both cases this should be a constant time, O(1), operation (as it is the same as inserting a value into an array).

$SK = KEYGEN\_PARALLEL(MK, S, PK)$:
$randomize(r)$
$D = g^{(\alpha+r)/\beta}$
$B = Array\ Same\ Size\ as\ S$
$FOR\ \forall i \in S$:
$Start\ Thread\ For\ keygen\_compute(B, r, g, i)$
$WaitForAllThreadsToFinish()$
$SK = (D, B)$

Equation 4.18: Parallelized version of the KEYGEN function.

keygen_$compute(B, r, g, i)$:
$randomize(k)$
$D''_i = g^r \cdot H(i)^k$
$D'_i = g^k$
$B_i = D''_i, D'_i$

Equation 4.19: keygen_compute function to be run in parallel.

$USK = UserKeyGen\_Parallel(ASK, US, PK, f)$:
$randomize(\tilde{r})$
$\widetilde{D} = Df^{\tilde{r}}$
$\tilde{B} = Array\ Same\ Size\ as\ US$
$FOR\ \forall i \in US$:
$Start\ Thread\ For\ userkeygen\_compute(\tilde{B}, \tilde{r}, g, i, D_i)$
$WaitForAllThreadsToFinish()$
$USK = (D, \tilde{B})$

Equation 4.20: Parallelized version of the UserKeyGen function.

userkeygen_$compute\left(\tilde{B}, \tilde{r}, g, i, D_i\right)$:
$randomize(k)$
$\widetilde{D''}_i = D_i \cdot g^{\tilde{r}} \cdot H(i)^k$
$\widetilde{D}'_i = D'_i \cdot g^k$
$\tilde{B}_i = \widetilde{D''}_i, \widetilde{D}'_i$

Equation 4.21: userkeygen_compute function to be run in parallel.

Using the same methodology and system as in section 4.4.2, we tested and compared the performance of the parallelized generation functions with both the standard DMACPSABE and CP-ABE key generation functions. Four simultaneous threads (each

running on a separate CPU core) were used for the parallelized functions on the same Linux based system as used in section 4.4.2. The C++ POSIX threads API was used to provide threading functionality to our implementation. As shown in Figure 4.16 and Figure 4.17, the parallelization of the key generation functions provides a signification improvement in the time required to generate both authority and user keys. This improvement allows DMACPSABE key generation to be further scaled by adding additional CPU cores while maintaining a linear relationship with the number of attributes. It is likely that more modern systems with 6 or 8 CPU cores would show additional improvements in key generation time.

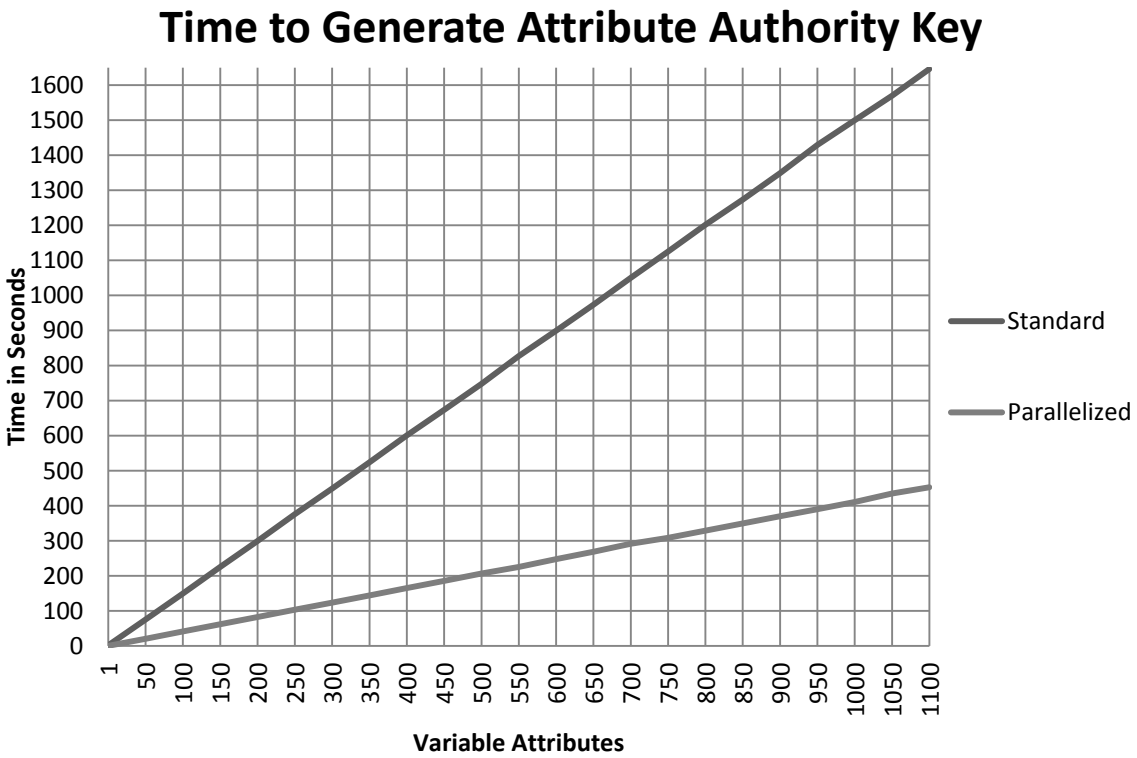


Figure 4.16: Time to generate DMACPSABE authority key with standard and parallelized functions.

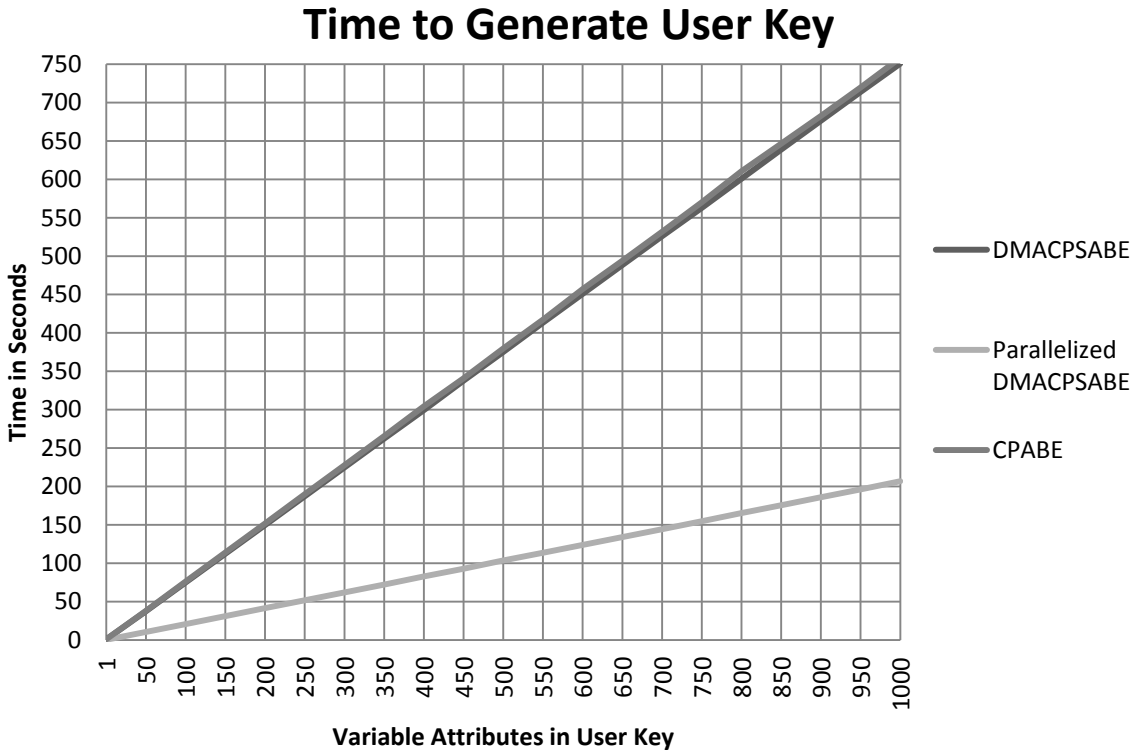


Figure 4.17: Time to generate a DMACPSABE or CP-ABE user key with standard and parallelized functions.

4.4.4 Security

As the encryption and decryption algorithms used in DMACPSABE remain the same as presented in Bethencourt, et al. (2007), the security of DMACPSABE may also be proven secure under the generic bilinear group model (Boneh, Boyen, & Goh, 2005) (as is shown in appendix A of Bethencourt, et al. (2007) for the decryption and encryption functions). As with Bethencourt, et al. (2007) and with Boneh and Franklin (2007)'s schemes, DMACPSABE can be extended to be secure against a chosen ciphertext attack by applying the techniques from Fujisaki and Okamoto (1999).

DMACPSABE also provides a level of privacy in addition to that of CP-ABE by obscuring the names of the attributes in the system. In the CP-ABE scheme, the policy under which a given plain text is encrypted is attached, in plain text, to the ciphertext. This policy (containing multiple plain text attribute names) may inadvertently leak

additional information about the contents of the ciphertext. For example, if a health record is encrypted with a policy such as “is_doctor OR is_ chemotherapy_technician”, it is leaked that the record may have something to do with chemotherapy as the attribute “is_ chemotherapy_technician” is involved.

4.6 Conclusions

This chapter introduces the DMACPSABE scheme for providing CP-ABE in a disturbed form where multiple authorities are granted a set of constant and variable attributes which they may further delegate to their users. Some subset of these attributes may be shared with other authorities such that access policies may be created that allow foreign users to decrypt documents. Additionally, a “not equals” operation is added to CP-ABE as well as a means for creating policies based on the user’s origin (i.e. which attribute authority delegated their key). Details on how revocation and expiration are enforced are discussed as well as how human readable attributes may be provided and how attribute authorities may be added or removed.

The performance of a prototype implementation based on CP-ABE was evaluated and found to scale linearly with the number of attributes. An additional improvement to the key generation and delegation algorithms to support distributed processing (e.g. on multiple CPU cores) was presented which further improved the performance of DMACPSABE to the point of matching the original CP-ABE implementation. The proceeding chapter gives details on how DMACPSABE may be used with the RBACaaS model to enforce role based access policies and discusses some future areas of work for DMACPSABE.

Chapter 5

5 Conclusions

5.1 Putting it all Together

When combined, the HCX, RBACaaS, RBSSO and DMACPSABE components create a system for securely sharing EHRs on an untrusted public cloud. However, to fully integrate these components there are several considerations and issues that must be addressed. This section gives additional details on how theses sub-systems may be combined and an overview of the overall system they create.

5.1.1 RBACaaS Integration with DMACPSABE

To integrate the role based access control policies offered by RBACaaS with the DMACPSABE scheme (such that role based policies may be used to encrypt documents rather than Boolean statements involving attributes) it is first necessary to map both the permissions and user parameters to attribute names (as shown in the modified RBACaaS model in Figure 5.2). Each permission used to protect encryptable objects is mapped to a unique constant attribute devoted solely to that permission, while every user parameter that is involved in conditions which effect the protection of encryptable objects is mapped to a variable attribute (also devoted solely to that parameter). This mapping is performed at creation of the parameter or permission and the attribute is assigned to the same domain as the parameter or permission.

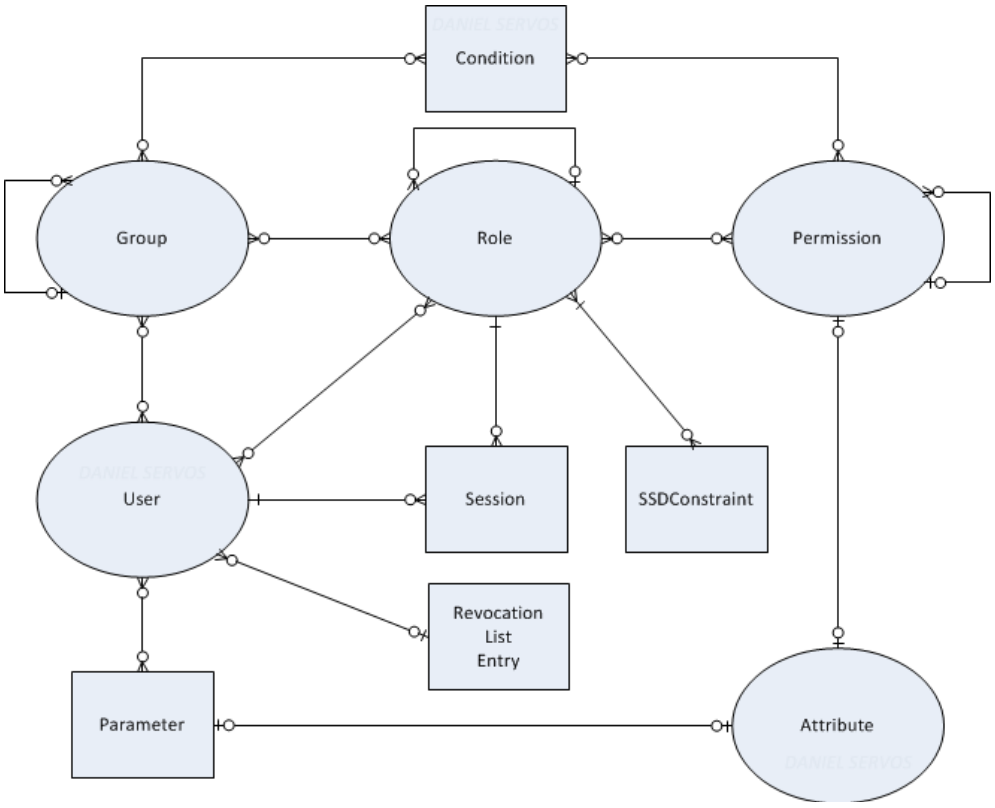


Figure 5.2: RBACaaS model with support for DMACPSABE added.

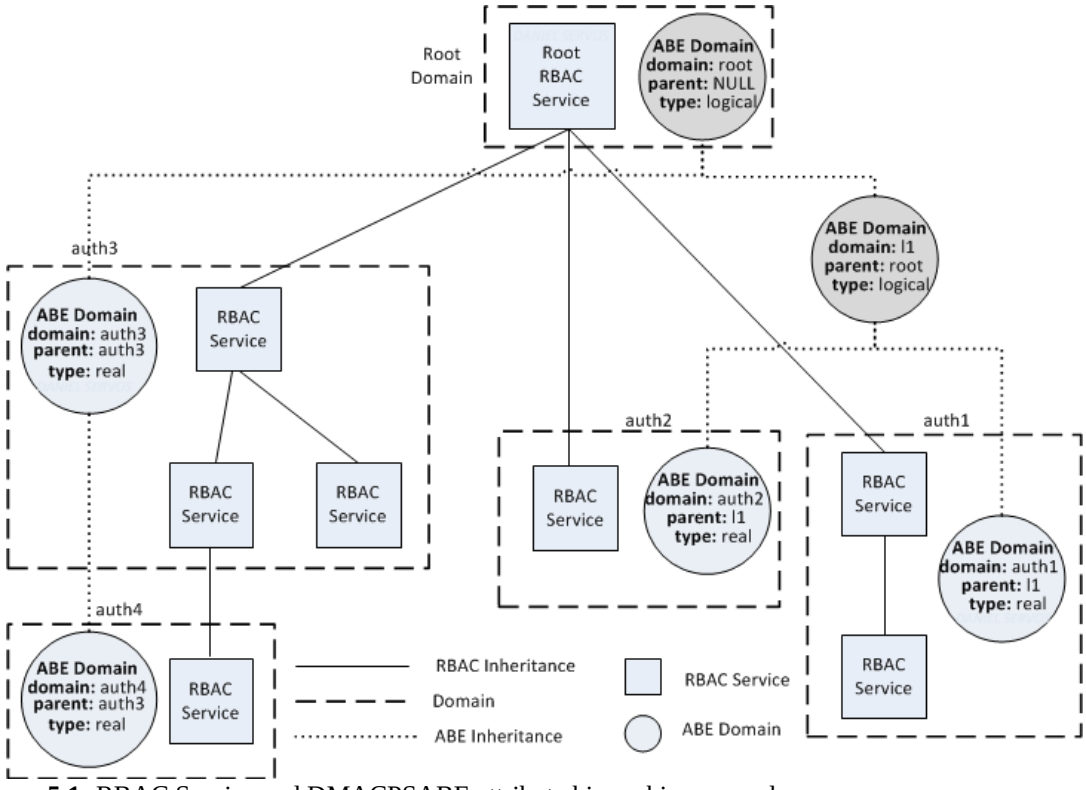


Figure 5.1: RBAC Service and DMACPSABE attribute hierarchies merged.

As with the hierarchy of RBAC services from RBACaaS, which enable decedents of a service access to its elements, the logical DMACPSABE hierarchy only allows sharing of attributes with decedents of nodes which allows them to be combined as in Figure 5.1. Note that in Figure 5.1 domains auth1 and auth2 share an extra set of attributes from the logical domain l1 that domains auth3 and auth4 lack, enabling domains auth1 and auth2 to share documents encrypted with the attributes from l1 but also have private attributes to encrypted documents such that they may not be shared between domains. This is in contrast to the sharing between domains auth3 and auth4, where auth4 has all attributes of auth3 while auth3 only has a subset of those of auth4 such that auth4 can issue attributes to read any document encrypted by auth3. This merged hierarchy keeps the attributes assigned to a given domain consistent with the RBAC elements accessible by that domain.

The root DMACPSABE attribute domain is always assigned and shares the following variable attributes, which correspond to the RBACaaS system parameters from Table 3.1, with all domains:

Attribute Name	Type	Description
SYSTEM:TIME_STAMP	Integer	The date and time on the auth server when the session was started as a Unix time stamp.
SYSTEM:TIME_DAY	Integer	A number [1, 31] representing the day when the session was started in the current month. Based on gregorian calendar and UTC.
SYSTEM:TIME_HOUR	Integer	A number [0, 23] representing the hour when the session was started in UTC.
SYSTEM:TIME_MINUTE	Integer	A number [0, 59] representing the minute the session was started in UTC.
SYSTEM:TIME_SECOND	Integer	A number [0, 59] representing the second the session was started in UTC.
SYSTEM:TIME_WEEK_DAY	Integer	The week day when the session was started represented by a number starting at 0 for Sunday and ending at 6 for Saturday. Based on UTC.
SYSTEM:TIME_MONTH	Integer	A number [1, 12] representing the UTC gregorian calendar month when the session was started.
SYSTEM:TIME_YEAR	Integer	A number representing the gregorian calendar year

		when the session was started in UTC.
SYSTEM:USER_IP	Integer	An integer representation of the user's version 4 IP at the time they authenticated with the server.
SYSTEM:USER_IP_1	Integer	An integer representation of the first byte of a user's version 4 IP at the time they authenticated with the server.
SYSTEM:USER_IP_2	Integer	An integer representation of the second byte of a user's version 4 IP at the time they authenticated with the server.
SYSTEM:USER_IP_3	Integer	An integer representation of the third byte of a user's version 4 IP at the time they authenticated with the server.
SYSTEM:USER_IP_4	Integer	An integer representation of the fourth byte of a user's version 4 IP at the time they authenticated with the server.
SYSTEM:USER_DOMAIN_ID AKA: auth_key	Integer	The ID assigned to the auth server's domain.
SYSTEM:USER_GID	Integer	The user's GID.
SYSTEM:USER_START_DATE	Integer	A unix time stamp containing the date the user's account was activated.
SYSTEM:USER_END_DATE	Integer	A unix time stamp containing the date the user's account will be or was deactivated or "0" if no such date is set.
SYSTEM:SESSION_START	Integer	A unix time stamp containing the date and time the user's session was started.
SYSTEM:SESSION_EXPIRE	Integer	A unix time stamp containing the date and time the user's session will expire.
SYSTEM:CLIENT_VERSION	Integer	An integer representation of the version number of the client software the user used to authenticate with the server.
SYSTEM:SERVER_VERSION	Integer	An integer representation of the version number of the server software being used.
SYSTEM:AUTH_METHOD	Integer	An integer representing the authentication method used to authorize the user.

Table 5.1: Table of default attributes for the root domain.

Users are delegated a new DMACPSABE key by their domain's authentication service through the RBSSO protocol (as described in section 3.2) each time they start a new session based on the role they are activating, the parameters and values they are assigned, the set of permissions the role grants and the current system parameters. Attributes are assigned as follows:

1. The current value of all values in Table 5.1 are determined and assigned as variable attributes to the user's key.
2. For all permissions in the set of permission mapped to the active role which are assigned an attribute, that constant attribute is added to the user's key.
3. For all parameters and their values mapped to a user, a variable attribute is assigned with the corresponding value from the map to the user's key.

For cases were this set of attributes is quite large, limited caching may be possible by storing the random number $\tilde{r}$, the value of $\widetilde{D}$ and the values of $\widetilde{D''}_k$ and $\widetilde{D'}_k$ for each uncommonly changing attribute *k* in the set of attributes *US* in Equation 4.17 for each user. Then only commonly changing attributes such as those related to system parameters would need to be computed at the start of each session (made possible by keeping the value of $\tilde{r}$ constant for each user until the cache is cleared).

RBACaaS policies are translated into DMACPSABE Boolean statements through the following process. First, the rules listed below are added to all statements (such that they are "ANDed" together):

Rule	Explanation
({CURRENT_DATE} < SYSTEM:SESSION_EXPIRE)	"{CURRENT_DATE}" is replaced with the time of encryption. This prevents expired keys from decrypting documents created after the key's expiration date.
(SYSTEM:USER_END_DATE = 0 OR {CURRENT_DATE} < SYSTEM:USER_END_DATE)	"{CURRENT_DATE}" is replaced with the time of encryption. This prevents expired user accounts from decrypting documents created after the accounts expiration date.
({MIN_CLIENT} ≤ SYSTEM:CLIENT_VERSION)	Optional rule for limiting client versions.

	"{MIN_CLIENT}" is replaced with the minimum allowed client version to access a file. Allows banning of out of date clients for newly encrypted files.
({MIN_SERVER} ≤ SYSTEM:SERVER_VERSION)	Optional rule for limiting authentication server versions. "{MIN_SERVER}" is replaced with the minimum allowed server version to access a file. Allows banning of out of date servers for newly encrypted files.
(SYSTEM:USER_DOMAIN_ID ≠ 0)	Ensures that an attribute for a domain is set to anything but 0. (Note that not equals ensures that the user has some value for the attribute so long as it is not the given constant).
(SYSTEM:USER_GID ≠ 0)	Ensures that an attribute for a user's global ID is set to anything but 0. (Note that not equals ensures that the user has some value for the attribute so long as it is not the given constant).
(SYSTEM:USER_GID NOT IN ({USER_BLACK_LIST_SET}))	Optional rule for blocking a set of users from accessing newly encrypted files. "{USER_BLACK_LIST_SET}" is replaced with the set of black listed user's GIDs, blocking them from accessing newly encrypted files.
(SYSTEM:USER_DOMAIN_ID NOT IN ({DOMAIN_BLACK_LIST_SET}))	Optional rule for blocking a set of domains from access newly encrypted files. "{DOMAIN_BLACK_LIST_SET}" is replaced with the set of black listed domains. Domains may be blocked from reading newly encrypted files in the case they are compromised.
(SYSTEM:AUTH_METHOD NOT IN ({AUTH_METHOD_BLACK_LIST_SET}))	Optional rule for blocking weak or compromised authentication methods. "{AUTH_METHOD_BLACK_LIST_SET}" is replaced with the set of black listed authentication methods.
(SYSTEM:USER_IP NOT IN ({IP_BLACK_LIST}))	Optional rule for blocking users by IP rather than GID. "{IP_BLACK_LIST}" is replaced by the set of IPs to be blocked from decrypting newly encrypted files. Blocked IPs are based on the IP used to authenticate with the authentication service.

Table 5.2: List of rules to be added to DMACPSABE decryption policies.

Next, for a given Boolean statement passed to the *encryptWithPermissions* function to encrypt a file (see sub section 3.1.2.2.6), first replace all permissions which lack conditions with the attribute name they map to in the modified RBACaaS model (Figure

5.2). Conditional permissions are then converted by replacing permission names with their corresponding attribute names (as with non-conditional permission) and "ANDed" with the set of conditions (with each parameter name replaced with the corresponding attribute name in the same way) such that each statement is "ANDed" together (e.g. for one conditional permission: "(PERM_ATT AND (CON1) AND (CON2) AND (CON3) …)").

Once the Boolean statement from the rule set (Table 5.2) and the converted Boolean statement from the RBACaaS policy are compiled, they are "ANDed" together (i.e. "(RULES_STATMENT) AND (POLICY_STATMENT)") and used with the DMACPSABE encryption function (Equation 4.10) to encrypt the RBACaaS protected object/data. For complex data structures (such as a health record) this encryption may be applied to the whole data structure or to individual elements according to the resulting policy statement (see section 5.1.4 for how we envision its use with CCR documents). Decryption is performed as would be expected by the system's users, that is, using the secret key they received from the authentication service to decrypt a given document using the DMACPSABE decryption function (Equation 4.12) assuming they have the correct attributes.

5.1.2 Searching DMACPSABE Encrypted Files (HCX Integration)

While the HCX architecture presented in Chapter 2 is largely independent of the health record format used, encrypted records may pose a problem while searching for and retrieving records based on a given keyword. This is problematic for two reasons: first, encrypted records may not be read/decrypted by the HCX service offering them limiting retrieval to a single key/record type mapping; and second, storing a map of plain text

keywords to encrypted records (or even sending the keywords to the service) would leak information about the contents of that record. Several solutions to this problem (searching encrypted files on remote systems) already exist and have been explored in detail in recent literature (Chang & Mitzenmacher, 2005) (Li, Wang, Wang, Cao, Ren, & Lou, 2010) (Wang, Cao, Li, Ren, & Lou, 2010) (Ballard, Green, Medeiros, & Monrose, 2005). As many of these solutions are independent of the encryption system used and suitable for (or in many cases made for) searching encrypted files on remote systems (such that the remote system may not determine the keyword or hints at the files contents) we leave this as an implementation detail for practical systems and consider it out of the scope of the presented research. In cases where an additional key or map is required to be distributed to the system's clients, to enable search functionality, the authentication service may be extended to provide this as it is isolated from the cloud and considered secure.

For our prototype, a trivial, but efficient solution of simply hashing each keyword with a salt was used to provide some level of obscurity to keywords. In this method every encrypted element of a record was mapped to a set of hashes paired with an integer representing the hash's relevance to that cipher text. When a user encrypted an element of a record, they would be responsible for generating the hashes and relevance integer based on some metric such as word count, and including the map in the appropriate plain text section of the record. When requesting a list of records based on a given keyword (or set of keywords), the user would compute the hash of the keyword + salt and send it in the request to the HCX service. The HCX service would respond with a list of the top records containing the hash ordered by total relevance. While this method provides a simple means of performing the search, it is not correlation-resistant and fails to stop a malicious cloud provider or system administrator from finding identifying common keyword hashes

either by analyzing their use or guessing words that might appear in a health record and generating the corresponding hash (assuming they have the correct salt). As such this method is not recommended for a practical implementation on an untrusted cloud.

5.1.3 HCX Integration with RBACaaS and RBSSO

The main task in integrating HCX with the RBACaaS system is simply creating permissions for each task a user may perform and using the service client API provided by RBACaaS to check if a requesting user has permission to perform the request. Per file permissions may be embedded in a given document (as described in section 5.1.4) by listing the Boolean permission statements for different levels of access within that document and only allowing authorized users to update that section of the file (i.e. rejecting requests which change the line without the user having the correct permission in their authtoken). When a record is requested, its permission statement may be checked against the user's active role's permission set and the request may be accepted or rejected accordingly.

Integration with the RBSSO protocol may be accomplished by having each request to an HCX service accept a Request Token (as detailed in section 3.2.2.4) and having a simple HCX service for authenticating users as explained in section 3.2.2.4 (i.e. via an authtoken from the domain's authentication service). The HCX service may then examine the user's authtoken to determine the permission set their active role grants and the conditions on those permissions (resulting from group conditions). Additionally, the machine instance running HCX may occasionally query a central trusted third party (e.g. the service controller or authentication services) for revocation lists of users, domains,

authentication methods, client versions, or server versions to block their access from the system.

5.1.4 Extensions to CCR and other XML formats

To allow for RBACaaS access policies to be embedded in EHRs and support the encryption of different EHR elements (rather than only full file encryption) some changes to the CCR and CCD EHR formats are required. Presented in this section is an XML based format for encapsulating DMACPSABE encrypted data elements and linking them to a BASCaaS policy which dictates a user's rights to view, edit or change the access rights on that element. The following is an outline of the extension:

```
<?xml version="1.0"?>
<DMACPSABE>
	<DMACPSABE:header>
		<DMACPSABE:meta>
			<DMACPSABE:versions>
				<DMACPSABE:encryption>{ENCRYT_VER}</DMACPSABE:encryption>
				<DMACPSABE:rbac>{RBAC_VER}</DMACPSABE:rbac>
				<DMACPSABE:format>{FORMAT_VER></DMACPSABE:format>
			</DMACPSABE:versions>
			<DMACPSABE:id>{RECORD_ID}</DMACPSABE:id>
			… Other meta data needed by an implementation. …
		</DMACPSABE:meta>
		<DMACPSABE:permissions>
			<DMACPSABE:view>{PERM_VIEW}</DMACPSABE:view>
			<DMACPSABE:edit>{PERM_EDIT}</DMACPSABE:edit>
			<DMACPSABE:perm>{PERM_PERM}</DMACPSABE:perm>
		</DMACPSABE:permissions>
		<DMACPSABE:keys>
			<DMACPSABE:public>
				{PUB_KEY}
			</DMACPSABE:public>
			<DMACPSABE:private>
				ENCRYPTED WITH {PERM_EDIT} POLICY:
				_____
				<DMACPSABE:id>{RECORD_ID}</DMACPSABE:id>
				<DMACPSABE:sigkey>{PRVI_KEY}</DMACPSABE:sigkey>
				<DMACPSABE:nonce>{NONCE}</DMACPSABE:nonce>
				_____
			</DMACPSABE:private>
		</DMACPSABE:keys>
	</DMACPSABE:header>
	<DMACPSABE:body>
		… Any unecrypted XML data …
		<DMACPSABE:element>
			<DMACPSABE:permissions>
				<DMACPSABE:view>{PERM_VIEW}</DMACPSABE:view>
				<DMACPSABE:edit>{PERM_EDIT}</DMACPSABE:edit>
```

```
                        <DMACPSABE:perm>{PERM_PERM}</DMACPSABE:perm>
                    </DMACPSABE:permissions>
                    <DMACPSABE:ciphertext>
                        ENCRYPTED WITH {PERM_VIEW} POLICY:
                        _____________________________________
                        … Any XML data with elements sorted alphabetically …
                        <DMACPSABE:cttail>
                            <DMACPSABE:id>{RECORD_ID}</DMACPSABE:id>
                            <DMACPSABE:nonce>{NONCE}</DMACPSABE:nonce>
                        <DMACPSABE:cttail>
                        _____________________________________
                    </DMACPSABE:ciphertext>
                    <DMACPSABE:signature>
                        {CIPHERTEXT_SIG}
                    </DMACPSABE:signature>
                    <DMACPSABE:searchindex>
                        … Optional implementation dependent search index …
                    </DMACPSABE:searchindex>
                </DMACPSABE:element>

                … Any unecrypted XML data …
            </DMACPSABE:body>
        </DMACPSABE>
```

Figure 5.3: DMACPSABE XML Format Extension

The DMACPSBE element encapsulates the contents of the XML based document being encrypted. A header is added (in the DMACPSBE:header) element which includes meta data (the versions of the software and XML extension being used, the record's ID and any other needed meta data for the system), the default/global permissions (permissions are stored as Boolean statements as described in Figure 3.13), and a pair of keys. The public/private key pair (PUB_KEY and PRVI_KEY) is used for signing and verifying the encrypted elements of the document. While the public key is in plain text in the header, the private key required for creating the signature is encrypted with the global edit policy, limiting signing to only those with the correct attributes. This signing ability will allow users to verify that no single encrypted data element has been replaced with another by an unauthorized user.

The body section of the DMACPSBE element (DMACPSABE:body) contains the original XML document (minus the XML header, e.g. "<?xml version="1.0"?>") but with any elements containing sensitive information replaced with

DMACPSABE:element. DMACPSABE:element contains an optional permissions element (DMACPSABE:element) which overrides the documents default permissions, a DMACPSABE:ciphertext element that contains the encrypted XML element, a DMACPSABE:signature element containing a signature of the XML element using the PRIV_KEY from the header, and an optional DMACPSABE:searchindex element which contains a protected index of keywords relating to the encrypted text (as discussed in 5.1.2). Before encryption of the protected XML element, the DMACPSABE:cttail element is appended to the plain text such that the authenticity of the text may be verified (i.e. that the nonce matches the encrypted nonce in the header and the record ID matches the ID used to retrieve the record).

For the case of a HCX service, the default view access policy in the header determines if a user may request the file. The edit policy of a given section determines if a user may update that section. The perm policy of a given section determines if a user may change the permissions of that section or the policy under which the data is encrypted. These policies are enforced by the HCX service (using the RBACaaS service client API), however, the ability to view a protected part of a file (i.e. decrypt it) is enforced by the DMACPSABE encryption scheme (such that a user must have a key granted by an attribute authority that meets the access policy used during encryption) using the view policy for a given DMACPSABE:element. The creation of the original policies embedded in the document is the responsibility of the document's original creator (as is the generation of the private/public signing key pair and nonce). However, it would be trivial to create an HCX service such that a minimal access policy is enforced (e.g. by rejecting weak policies based on some set criteria or policies that do not enforce rules detailed in section 5.1.1). In a real world implementation, the appropriate default policies would likely be encoded into the client application, or document creation would

be performed by a policy engine capable of converting existing health records and/or automatically determining the correct policy (as described in the work by Akinyele, et al. (2010)).

While this format protects a given record from a malicious cloud provider changing a single protected element (or any number of elements so long as not all encrypted elements including the private key in the header), it does not protect against the provider completely changing the whole document (and generating their own private key and nonce). However, such an attack would not likely succeed because the provider would have no knowledge of the contents of the document or to whom it may pertain, making such changes immediately noticeable. For example, if an EHR was requested with an ID corresponding to John Doe, but the received EHR contained a fake record for the patient Joe Bloggs (note that it would not be possible to switch the EHR with another real EHR in the system as the record ID is included in the ciphertext) it would be immediately evident that the EHR had been compromised. Extending the DMACPSABE scheme to also support signing of documents would provide a potential fix for this problem (and is listed among the future areas of work in section 5.2), as would having the authentication authority distributing signing keys to users such that they may be used to authenticate documents.

5.1.5 System Overview

The diagram presented in Figure 5.4 displays an overview of the complete system with all components functioning together. For any given domain, the RBAC service, attribute authority and authentication service would likely be combined in one server software package in an implementation of the system that connects to an existing

database with user credentials for the organization (e.g. LDAP{_footer_}). The trusted third party (which may be a domain trusted by the other domains to perform the role or an completely independent entity) would only primarily be responsible for running the service controller which dynamically creates and destroys the machine instances running the HCX services according to current levels of demand. Additionally, the trusted third party is responsible for the initial creation of the DMACPSABE authority keys, initial creation of the root roles and permissions and for publishing the public keys and revocation lists.

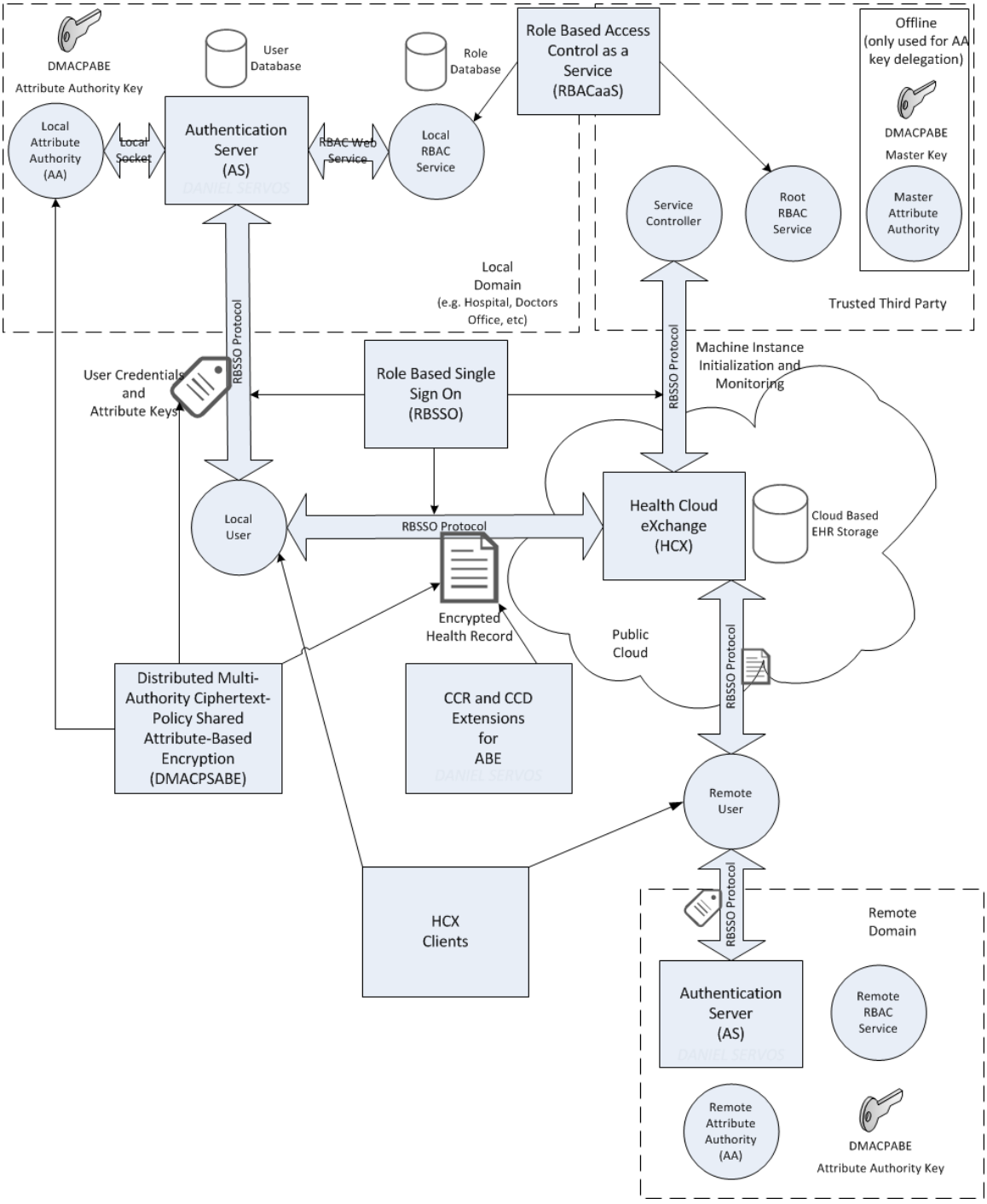


Figure 5.4: System Overview

Clients of the system follow the RBSSO protocol to authenticate with their domain and gain an authtoken and decryption which allows them to access the HCX services on the cloud and decrypt records respectively. Once authenticated, clients may publish new records on to the cloud by encrypting them with the appropriate access

policy and uploading them to a HCX service. Reversely, clients may obtain records by requesting the encrypted file from a HCX service and decrypting the elements of the record for which they have access. Updates to records are performed by requesting the record, decrypting the relevant section, making the desired changes, generating a new keyword map (if applicable for the search method being used), and encrypting the section with the same access policy (a different access policy may only be used if the user has the correct permissions active), and finally reuploading the record to the HCX service. If the HCX service determines that the client has the appropriate permissions active for the given changes, the record is updated.

5.2 Future Work

While the presented research is a step towards cloud privacy and security for EHRs, there are still many areas for improvement, future research, and open problems to be solved. This section identifies several of these areas and suggests potential directions for future research.

5.2.1 Automated Policy Discovery/Creation

While RBACaaS, RBSSO and DMACPSABE provide the tools for creating and enforcing role based access policies, it is still left to the policy administrator to ensure the proper policies are created for a given origination’s needs and that they are correctly applied. Automating the process of policy discovery based on an overall set of criteria for an organization would indirectly improve the security of the system (if implemented correctly) by simplifying administration and ensuring that access policies correctly correspond to the requirements of the organization. Some limited research in this

direction currently exists for other systems (Akinyele, Lehmann, Green, Pagano, Peterson, & Rubin, 2010), however, creating such an automated system for RBACaaS would likely introduce additional challenges to support its distributed nature and potentially complex policies.

5.2.2 Automated Role and Permission Discovery

As with automated policy discovery and creation, a system for automatically identifying roles and permissions within an organization would lead to simplified administrator and indirectly a potentially securer system. Such discovery would likely be a prerequisite for accurate automated policy discovery and would require some initial information about the organization's users, protected objects/services and access policy requirements. Recent research into role mining, discovery and migration (Vaidya, Atluri, & Guo, 2007) (Kuhlmann, Shohat, & Schimpf, 2003) (Guo, Vaidya, & Atluri, 2008) presents a promising start for the basis of implementing such a system for RBACaaS, however, the automation of the discovery of RBACaaS based permissions may prove more challenging due to their potentially conditional nature.

5.2.3 Automatic Role Activation

In the current RBSSO protocol a user is able to activate a single role for which they have been granted access at the time of authentication. However, there are many cases where a user using the system may wish to escalate their role to one with a greater or different set of permissions. Similarly, once a user has completed a task that required some elevated privilege they may wish to reduce their access in accordance with the principle of least privilege. Currently, this would require starting a new session with the

authentication service, which while functional may not be ideal in all cases. A system by which a user may seamlessly switch between roles as needed may be desired. Techniques, such as the "smartaccess" system proposed by R. Adaikkalavan, et al. (2006), may prove to increase usability of the system and reduce the occurrence of users running the most privileged role to avoid having to deal with multiple role activations.

5.2.4 Explore Alternative Hierarchy Structures

For simplicity reasons and to help facilitate the distributed nature of the RBACaaS model (by making it easy to transverse the complete set of roles and calculate their permission sets), a tree based data structure was used for role, group and permission hierarchies. However, it is likely that a superior graph-based hierarchy that would offer more flexibility could be adapted to the RBACaaS model. Current graph-based RBAC models (Nyanchama & Osborn, 1999) (Wang & Osborn, 2006) (Wang & Osborn, 2011) may provide an appropriate starting point for such improvements to the RBACaaS hierarchy model.

5.2.5 Explore Alternative Access Control Models

Traditionally access control has largely been limited to discretionary, mandatory and role based models. However, in recent years several new promising models have emerged in access control literature, one of the most notable being usage control (Park & Sandhu, 2004) (Zhang, Park, Parisi-Presicce, & Sandhu, 2004). Usage control (UCON) enables more flexible access policies based on a user's attributes and usage of resources. For example, a policy could be created with a user's right to access an object is "consumed" once used, limiting them to viewing its contents only a set number of times.

Such dynamic access policies would be fitting for a health care setting, were it may be desired to give some (such as a lab tech) only temporary access to an EHR that is consumed after the access right is used.

Either extending or replacing the current RBACaaS and RBSSO system components with usage based access controls could provide more flexibility to the system. As the current RBACaaS model already incorporates many UCON like aspects (conditions, user attributes, etc.) the UCON model would be a reasonable extension in the same direction as the presented research. Another possibly interesting application of UCON for the presented research would be incorporating its use with attribute based encryption and the DMACPSABE scheme presented in Chapter 4. As most UCON models are heavily attribute based (applying attributes to both objects and subjects), ABE could coincide nicely with UCON policies.

5.2.6 Removal of the Master Attribute Authority

Currently the DMACPSABE scheme relies on a cauterized authority to generate the initial master key and maintain each attribute authorities' attribute set. While the master authority is not needed for the normal function of the system (after initialization) it is needed when a new attribute authority is created or updates are needed to the set of attributes an authority may delegate. Ideally, attribute authorities should be able to create their own attributes and share them with other authorities without relying on a master. Such an improvement would be a large step to creating a more fully distributed system.

5.2.7 Human Readable Attribute Names

As the master attribute authority must assign sets of attributes to each attribute authority before the purpose or meaning may be fully realized, the attributes in the DMACPSABE scheme are represented by an alpha numeric string consisting of the assigned authority's name, a letter representing their type (variable or constant) and a number. This string then needs to be mapped to a more meaningful name/purpose by the attribute authority. A system by which each individual attribute authority could directly name their attributes without such a map may increase the usability of the system and allow searching encrypted files by attribute names and required values. However, it may also decrease the privacy of a system by potentially leaking information about the encrypted document in the access policy (normally embedded in plain text with the ciphertext).

5.2.8 Searchable DMACPSABE

As brought up in section 5.1.2, a secure means for searching DMACPSABE encrypted documents on a remote system for a given keyword (or Boolean statement involving multiple keywords) may be needed for practical applications of the system. Recent research literature (Chang & Mitzenmacher, 2005) (Li, Wang, Wang, Cao, Ren, & Lou, 2010) (Wang, Cao, Li, Ren, & Lou, 2010) (Ballard, Green, Medeiros, & Monrose, 2005) has presented several methods to accomplish this kind of search on a remote system that is independent of the encryption cipher used, however, it is likely additional extensions to the HCX services described or DMACPSABE scheme would be needed to properly support them. Which method may be most suitable for DMACPSABE and HCX or EHRs in general is left for future work on the system.

5.2.9 DMACPSABE Based Signing

While the DMACPSABE scheme provides a means for documents to be encrypted based on given Boolean access policy involving constant and variable attributes, a system for signing documents based on the same set of attributes the user is granted in their key is not available. Such a signing system would allow for proof to be attached to DMACPSABE encrypted EHRs that the user who last modified a given section was authorized to edit that section (by attaching a signature of the plain text using the set of attributes meeting the edit policy). Additionally if a variable attribute containing a user ID was assigned to each user, such a signing system would allow a user to attach proof of their identity to documents they sign. Several attribute based signature schemes currently exist (Shaniqng & Yingpei, 2008) (Li, Au, Susilo, Xie, & Ren, 2010), however, incorporating a similar scheme into DMACPSABE such that it may be used for both encryption and signing may prove challenging.

5.2.10 Fully Secure XML Extensions

The current XML extensions for applying DMACPSABE encryption to XML based records presented in section 5.1.4 provides data confidentiality and assurance that a subset of protected elements have not been replaced or switched with another record. However, it does not protect from a malicious cloud provider or administrator from completely replacing the contents of the whole record. Potential solutions to this issue range from distributing signature keys to all users of the system, to creating a new DMACPSABE based signing mechanism to prove that data was created by an authorized user. As the issue is relatively minor (randomly replacing a whole health record would be

almost immediately noticeable, as the provider has no knowledge as to whom the record pertains) determining which method is most appropriate and adjusting the XML extensions (and possibly authentication service) to match is left to future work on the system.

5.2.11 Mobile Support

While many of the DMACPSABE based operations (namely encryption, decryption, delegation and key generation) scale linearly with the size of the attribute set and document being encrypted/decrypted, the computations may still be too resource intensive for mobile applications. Creating a DMACPSABE prototype for mobile handsets may provide valuable for determining if the scheme is feasible for mobile applications. Additionally, the encryption/decryption overhead in the RBSSO protocol may prove challenging for limited mobile devices.

5.2.12 Real World Implementation and Use

While prototypes of the system components presented in this research (HCX, RBACaaS, RBSSO, and DMACPSABE) have been created and evaluated individually, there is still a need for a large scale prototype to be created to evaluate the overall systems use for real world EHR applications. A limited trial of such a prototype in real life situations would provide valuable information about usability and user acceptance of the role activation paradigm in a health care setting. Additionally, such a trial may provide valuable data about the costs associated with a cloud based EHR solution v.s. a traditional centralized data center approach.

5.3 Conclusions

In the introduction of this thesis we presented a set of design objectives (section 1.5) that any cloud based EHR system would have to fulfill to ensure security, preserve privacy and be feasible in a large scale distributed environment. We believe that the presented system accomplishes these objectives through a variety of techniques used in each system component. The HCX architecture provides a DOSGi based framework for sharing health records that enables dynamic discovery and communication between EHR services such that they may be properly scaled in a distributed environment. The RBACaaS model and system enable conditional role based access policies on records and services based on user parameterization and role assignment. The RBSSO protocol allows for distributed access control and the confidentiality of user credentials while connecting the other components and the DMACPSABE encryption scheme presents a means of embedding RBACaaS access policies in documents to accomplish legal compliance, confidentiality of encrypted records, and a comprehensive enforcement of access policies both on and off the cloud.

The performance of these components was evaluated and determined to meet or even surpass the performance of existing systems and scale linearly. For the RBSSO protocol, testing of the prototype implementation (see section 3.2.4) showed performance over a wide area network which surpassed that of Kerberos and SSL based methods, while testing on a faster and lower latency local area network still showed performance gains over the SSL based method and only a minor disadvantage compared to Kerberos. Testing of the DMACPSABE scheme (see section 4.4) showed that key generation and delegation times scaled linearly with the number of attributes with only a minor drop in performance when compared to CP-ABE. However, this drop in performance was

overcome when performance enhancements were added, including utilizing the threaded DMACPSABE algorithm, which made key generation time closely match that of CP-ABE.

The research presented in this thesis is an important step towards secure and confidentiality preserving usage of cloud infrastructure under an assumption where the cloud provider may not be trusted. Unlike most recent research into the issues which utilizes hardware based crypto coprocessors that are currently unavailable in almost all current cloud offering, the presented solution is solely software based and implementable on any cloud infrastructure or platform which supports DOSGi (i.e. most offerings that support running java applications). Once minor usability, EHR formatting and searching issues are resolved, we believe that this system will make storing, sharing and processing health records on the cloud as safe and as efficient as traditional local data center solutions but without the large initial investment of time and resources, making EHRs more accessible to smaller medical offices and healthcare facilities.

APPENDICES

A. HCX Interfaces

The following subsections detail the web service/DOSGi based interfaces for the various HCX services described in section 2.2:

A.1 EHRProvider

Operation	Description
`list_records([Filter]): list`	Lists record ids in this domain matching the optional filter rule given. If no filter rule is given, a full list is returned (or rather a full listing of records the user has permission to view).
`get_record(id): data`	Retrieves the record identified by *id*.
`list_attachments(id, [Filter]): list`	Lists the attachment_ids of all attachments linked to the record (or a filtered listing if a filter rule is given).
`get_attachment(record_id, attachment_id): data`	Retrieves the attachment identified by *attachment_id* on the record identified by *record_id*.
`search(keyword_set, [Filter]): list`	Optional function (depending on encryption method employed) which returns a list of records matching a given set of keywords. A filter rule may also be applied.
`get_domain(): domain`	Returns the domain this service is operating in/for.
`get_service_mode(): mode`	Returns the current mode this service is operating in. e.g. “Middleware” or “CloudEHR”.
`get_remote_serivce_name(): name`	Returns the name of the remote EHR service being connected to if run in “Middleware” mode. Otherwise returns null.
`get_service_id(): id`	Returns a unique id for this service (as there may be multiple EHRProvider services in the same domain).

A.2 EHRManager

Operation	Description
`update_record(id, data): void`	Updates a record identified by *id* with the partially encrypted data from *data*.
`add_record(id, data): void`	Adds a new record to be identified by *id* with

	the partially encrypted data from *data*.
`remove_record(id): void`	Removes the record identified by *id.*
`add_attachment(id, attachment_data): attachment_id`	Adds an attachment, consisting of the data in *attachment_data* to the record identified by *id*. Returns the attachments *id*.
`remove_attachment(record_id, attachment_id): void`	Removes the attachment identified by *attachment_id* from the record identified by *record_id*.
`move_record(id, new_domain): void`	Moves a record identified by *id* to a new domain identified by *new_domain*. This triggers a call to *receive_record* in an HCX EHRManger service in the new domain.
`receive_record(id, data): void`	Receives a record identified by *id* from a domain to be placed in the current domain. May only be called by other EHRManger services.
Also includes EHRProvider functions.	

A.3 EHRPortal

Note: The EHRPortal provides a web based interface for patients, the following interface is solely for administration of that portal. Users still need to authenticate with their authentication service, share the authtoken with the portal and have the correct permissions to view their own records.

Operation	Description
`start(): void`	Starts publicly offering the EHR portal at the configured URL and port.
`stop(): void`	Stops offering the EHR portal.
`restart(): void`	Restarts the portal.
`blacklist(ip_host_set): void`	Black lists the given set of IPs, IP ranges or hostnames from accessing the portal. This function adds to the blacklist.
`whitelist(ip_set): void`	Limits access to the patient portal to only the IPs, IP ranges and hostnames in the given set. This function adds the given set to the whitelist.
`deblacklist(ip_host_set): void`	Removes a set of IPs and hosts from the blacklist.
`dewhitelist(ip_host_set): void`	Removes a set of IPs and hosts from the whitelist.
`get_whitelist(): set`	Returns the set of IPs, hosts and ranges in the current white list or null if there is no active whitelist.
`get_blacklist(): set`	Returns the set of IPs, hosts and ranges in the current black list or null if there is no active black list.
`accept_domain(domain): void`	Adds the given domain to the set of domains for which the portal accepts users from.
`reject_domain(domain): void`	Removes the given domain from the set of domains for which the portal accepts users from.
`get_domains(): set`	Returns the set of domains for which the EHR

	accepts users.

A.4 AuditLog

Note: The auditlog is only called from other HCX services (to add log entries) and by HCX administrators to view log entries. There is intently no way to edit or remove log entries, however a configuration option may be set to remove entries older then a set amount.

Operation	Description
`list([Filter]): list`	Returns a list of log entries, optionally filtered by a given filter rule.
`get(entry_id): LogEntry`	Returns an individual log entry object by a given id. The LogEntry object contains all details added by the HCX service adding the entry.
`put(AuthToken, RequestToken, RequestSummary, service_id): void`	Called by an HCX service to add a new log entry. The user's auth and request tokens are sent to be part of the log, as well as a summary of the request and the services identification information. The auditlog service may reject a log request if the authtoken and/or requesttoken are not valid.

B. RBACaaS Web Interface

B.1 RBAC Service

The following operations are publicly provided to service clients and others via the RBAC service's web service:

Operation	Description
`get_domain(): domain`	Returns the domain the RBAC service is in/operating for.
`get_conditions(perm_id): set`	Returns the set of conditions for a given permission id.
`get_permissions(role_id): set`	Returns the set of permissions for a given role id.
`get_revoked_sessions(): list`	Returns the list of revoked sessions.
`check_session(session_id): boolean`	Returns true if a given session id is still valid, otherwise false.
`get_attribute(perm_id): attribtue`	Returns the ABE attribute name for a given permission id. Use of this function may be restricted in some case (e.g. if attribute names are not public).
`get_attribute(param_id): attribtue`	Returns the ABE attribute name for a given parameter id. Use of this function may be

	restricted in some case (e.g. if attribute names are not public).

Note: in most cases services implementing RBACaaS access controls will not call these operations and will use the client API show in appendix C.

The following operations are provided only to other RBAC services that have been authorized as a child or parent of the current domain:

Operation	Description
`get_ element(id): RBACElement`	Returns a signal RBACElement object by its id. The object includes its relations to other objects (e.g. a user object would include the set of groups, roles and parameter/value pairs it is mapped to).
`get_ children(): list`	Lists the current authorized children for this domain.
`get_parent(): domain`	Returns the name of the parent domain.
List operations from B.2.2	Selective access to the list same operations as provided by the administrative interface in appendix B.2.2 are provided to authorized child domains.

B.2 Administrative Service

B.2.1 Administrative Permissions

The administrative service is protected by the RBACaaS system itself, with the following permissions giving access to each function:

Permission	Function
`RBACAdmin.*`	Grants access rights to all administrative functions.
`RBACAdmin.user.*`	Grants access rights to all user related functions (add user, mapping user to roles/groups, removing user, etc.).
`RBACAdmin.user.add`	Grants right to add a user.
`RBACAdmin.user.remove`	Grants right to remove a user
`RBACAdmin.user.maprole.*`	Grants right to map or unmap any role to a user.

RBACAdmin.user.mapgroup.*	Grants right to map or unmap any group from a user.
RBACAdmin.user.maprole.{role_name}	Grants the right to map or unmap the role {role_name} to a user.
RBACAdmin.user.mapgroup.{group_name}	Grants the right to map or unmap the group {group_name} to a user.
RBACAdmin.user.addparam.*	Grants the right to add any parameter/value pair to a user.
RBACAdmin.user.removeparam.*	Grants the right to remove any parameter/value pair from a user.
RBACAdmin.user.addparam.{param_name}	Grants the right to add the parameter/value pair for {param_name} to a user.
RBACAdmin.user.removeparam.{param_name}	Grants the right to remove the parameter/value pair for {param_name} from a user.
RBACAdmin.group.*	Grants all access rights on group functions.
RBACAdmin.group.add	Grants the right to add a user group.
RBACAdmin.group.remove	Grants the right to remove a user group.
RBACAdmin.group.parent	Grants the right to set a groups parent.
RBACAdmin.group.mapcon.*	Grants the right to add or remove a condition to a group.
RBACAdmin.group.mapcon.{group_name}	Grants the right to add or remove a condition to the group {group_name}.
RBACAdmin.group.maprole.*	Grants the right to add or remove a role to a group.
RBACAdmin.group.maprole.{role_name}.*	Grants the right to add or remove the role {role_name} to any group.
RBACAdmin.role.*	Grants all access rights on role functions.
RBACAdmin.role.add	Grants the right to add a role.
RBACAdmin.role.remove	Grants the right to remove a role.
RBACAdmin.role.parent	Grants the right to set a roles parent.
RBACAdmin.role.mapperm.*	Grants the right to map or unmap permission to a role.
RBACAdmin.role.mapperm.{perm_name}	Grants the right to map or unmap the permission {perm_name} to a role.
RBACAdmin.perm.*	Grants all rights to permission functions.
RBACAdmin.perm.add	Right to register a permission.
RBACAdmin.perm.remove	Right to unregister a permission.
RBACAdmin.perm.mapcon.*	Grants right to add or remove a condition to a permission.
RBACAdmin.perm.mapcon.{perm_name}	Grants right to add a condition to the permission {perm_name}.
RBACAdmin.ssd.*	Grants all right to SSD constraint functions.
RBACAdmin.ssd.add	Grants right to add an SSD constraint
RBACAdmin.ssd.remove	Grants right to remove an SSD constraint
RBACAdmin.revoke	Grants right to revoke a session.
RBACAdmin.view.*	Grants right to view all RBAC elements.
RBACAdmin.view.user.*	Grants right to view all user records.

RBACAdmin.view.user.{user_name}	Grants right to view record for given {user_name}.
RBACAdmin.view.role.*	Grants right to view all role records.
RBACAdmin.view.role.{role_name}	Grants right to view record for given {role_name}.
RBACAdmin.view.group.*	Grants right to view all group records.
RBACAdmin.view.group.{group_name}	Grants right to view record for given {group_name}.
RBACAdmin.view.con.*	Grants right to view all condition records.
RBACAdmin.view.con.{con_name}	Grants right to view record for given {con_name}.
RBACAdmin.view.perm.*	Grants right to view all permission records.
RBACAdmin.view.perm.{perm_name}	Grants right to view record for given {perm_name}.
RBACAdmin.view.ssd	Grants right to view all ssd records.
RBACAdmin.view.rl	Grants right to view all revocation list records.
RBACAdmin.view.param.*	Grants right to view all parameter records.
RBACAdmin.view.param.{param_name}	Grants right to view record for given {param_name}.
RBACAdmin.view.sessions	Grants right to view all active sessions.
RBACAdmin.view.log	Grants right to view the auditlog.
RBACAdmin.system.*	Grants all system commands.
RBACAdmin.system.shutdown	Grants right to shut down the RBAC service.
RBACAdmin.system.restart	Grants right to reboot the RBAC service.
RBACAdmin.system.setdomain	Grants right to set RBAC domain name.
RBACAdmin.system.addchilddomain	Grants right to add a child domain.
RBACAdmin.system.setparentdomain	Grants right to set the domain's parent.

B.2.2 Administrative Interface

The administrative interface provides a web service based interface to the RBACaaS administrative functions listed in appendix D.5. RBAC elements (e.g. users, roles, etc.) are represented by an object which contains their ID, required details, and maps relating them to other objects. In addition to these functions the following system, view and search functions are provided:

Operation	Description
search(Filter): list	Return a list of RBACElements based on filter rules in the given Filter object.
list_users([Filter]): list	Return a list of user objects based on the

	given filter rules.
`list_groups([Filter]): list`	Return a list of group objects based on the given filter rules.
`list_roles([Filter]): list`	Return a list of role objects based on the given filter rules.
`list_perms([Filter]): list`	Return a list of permission objects based on the given filter rules.
`list_params([Filter]): list`	Return a list of parameter objects based on the given filter rules.
`list_cons([Filter]): list`	Return a list of condition objects based on the given filter rules.
`list_ssd([Filter]): list`	Return a list of constraint objects based on the given filter rules.
`list_rl([Filter]): list`	Return a list of revocation list objects based on the given filter rules.
`list_sessions([Filter]): list`	Return a list of user session objects based on the given filter rules.
`list_log_entries([Filter]): list`	Returns a list of audit log entries based on the given filter rules.
`get_ element(id): RBACElement`	Returns a signal RBACElement object by its id.
`shutdown(): void`	Shuts the RBAC web service down.
`restart(): void`	Restarts the RBAC web service.
`set_domin(domain): void`	Sets the RBAC services RABC domain name.
`set_parent(domain): void`	Sets the domain's parent domain.
`add_child(domain): void`	Adds a new child to this domain.
`list_ children([Filter]): list`	Lists the current authorized children for this domain.
`get_parent(): domain`	Returns the name of the parent domain.
`get_domain(): domain`	Returns the name of the current domain.

Note: The Filter object is an object passed to the web service operation which contains rules for filtering out RBAC elements from a list.

C. RBACaaS Client API

The following are the critical functions provided by the RBACaaS client side API which cloud services may use to enforce RBACaaS access controls based on a given Boolean permission statement (see Figure 5.5):

Function	Description
`validate(authtoken): boolean`	Validates a given authtoken (see section 3.2

	for details on authtokens). This involves checking the signature, expiration dates, and check that the session id is not listed in the last revocation list. The client may occasional contact the RBAC service for an updated revocation list.
`get_permssions(authtoken): set`	Extracts the set of permission/condition pairs from an authtoken.
`get_paramters(authtoken): set`	Extracts the set of paramter name/value pairs from an authtoken.
`paramters_value(authtoken, param_name): value`	Returns the value corresponding to the given parameter name or a null value if the authtoken does not contain such a pairing.
`has_permssion(authtoken, perm_id): boolean`	Returns true if the authtoken contains a given permission id.
`has_parameter(authtoken, param_name): boolean`	Returns ture if the authtoken contains a given parameter pairing with the given paramter name.
`get_domain(authtoken): domain`	Returns the name of the domain who issues the authtoken.
`get_gid(authtoken): gid`	Returns the user's GID.
`get_ expiration(authtoken): date`	Returns the expiration date of the authtoken session.
`get_session(authtoken): session_id`	Returns the authtoken session id.
`hasPermission(authtoken, perm_statment): boolean`	Returns true if the authtoken passes the Boolean permission statement. Normally if this check passes, the user is granted access to the service. It is up to the implementing service to create the correct permission statement to limit access.
`encryptWithPermissions(perm_statment, data): encrypted_data`	Uses DMACPSABE to encrypt the given data with the given permission statement. It may be necessary to call on the RBAC service for a mapping of permission or parameter names to attribute names.
`encryptFileWithPermissions(perm_statment, file): void`	Uses DMACPSABE to encrypt the given file with the given permission statement. It may be necessary to call on the RBAC service for a mapping of permission or parameter names to attribute names.
`permStatmentToABEPolicy(perm_statment): ABE_Policy`	Translates a permissions statement into a DMACPSABE policy statement useable to encrypt data.

D. RBACaaS Formal Description

D.1 RBAC Elements

Each “element” in the RBACaaS model (Figure 3.6) is referred to by a unique URI (as described in Figure 3.10) and is defined as follows:

- **USERS:** The users of the system.
- **GROUPS:** A subset of users: *group* ⊆ USERS
- **PARAMTERS:** A mapping of parameter names to a values for each user: *parameter_map*(*name*, *user* ⊆ USERS) → *value*
- **CONDITIONS:** Boolean statements involving one or more parameter names, system properties or constants following the grammar in Figure 3.11.
- **ROLES:** The systems roles.
- **PERMISSIONS:** The systems permissions strings.
- **SSDCONSTRAINTS:** Parings of a subset of roles and a number limiting the number of roles in the set a user may be assigned: (*num* $\geq$ 0, *roles* ⊆ ROLES)
- **SESSIONS:** Active user sessions, the set of a user, role, and expiry date: (*user* ∈ USERS, *role* ∈ ROLES, *date* $\geq$ 0)
- **REVOCATIONLIST:** Set of sessions that have been forcibly expired: *list* ⊆ SESSIONS

D.2 RBAC Relations

The following are the formal definitions of the relations between RBAC elements in the RBACaaS model:

- **USER_ASSINGMENT (UA):** The many-to-many mapping of user-to-role assignment relation: UA ⊆ USERS ×ROLES
- **GROUP_ASSINGMENT (GA):** The many-to-many mapping of group-to-role assignment relation: GA ⊆ GROUPS ×ROLES
- **PERM_ASSINGMENT (PM):** The many-to-many mapping of permission/conditions pair-to-role assignment relation: PM ⊆ {(role, (perm, cons)) | perm ∈ PERMSSIONS, cons ⊆ CONDTIONS, role ∈ ROLES}
- **ROLE_HIERARCHY (RH):** RH ⊆ ROLE × ROLE were a role, *r1*, is considered to be a descendent of role *r2* if *r1* contains all permissions of *r2* (and it's ancestors) with negative permissions removed and does not inherit permissions from any other role. Formally: $parent(r1) = r2$ iff $(pset(r2) \setminus negative\_perms(r1)) \subseteq pset(r1)$ and $r2 \notin decedents(r1)$
- **GROUP_HIERARCHY (GH):** GH ⊆ GROUP × GROUP were a group, *g1*, is considered to be a descendent of group *g2* if *g1* contains all roles of *g2* (and it's ancestors) with negative roles removed and does not inherit roles from any other group. Formally: $parent(g1) = g2$ iff $(rset(g2) \setminus negative\_roles(g1)) \subseteq rset(g1)$ and $g2 \notin decedents(g1)$
- **USER_GROUP_ASSINGMENT (UGA):** The many-to-many mapping of user-to-group assignment relation: UGA ⊆ GROUPS × USERS
- **USER_PARAMETER_ASSINGMENT (UPA):** The many-to-many mapping of user-to-name/value pair assignment relation: UPA ⊆ $2^{(PARAMETER\_NAMES,\ PARAMETER\_VALUES)}$ × USERS

- **CONDITION_GROUP_MAP (CGM):** The mapping of a group onto a set of conditions: CGM(*group*) → *cons* ⊆ CONDTIONS
- **CONDTION_PERM_MAP (CPM):** The mapping of a permission onto a set of conditions: CPM(*perm*) → *cons* ⊆ CONDTIONS

D.3 Core Functions

The following are the core functions supporting the operation of the RBACaaS system and model:

- ***pset***: The set of all permissions/conditions pairs granted by a role: *pset* ⊆ PERMISSIONS × $2^{\text{CONDITIONS}}$
- ***rset***: The set of all role/conditions pairs granted by a group: *rset* ⊆ ROLES × $2^{\text{CONDITIONS}}$
- ***type:*** The type of role or permission such that a negative role or permission returns *negative* and a positive element returns *positive*.
- ***negative_perms***: The set of all negative permissions a role is assigned: {*perm* ∈ PERMISSIONS | *type*(*perm*) = *negative*}
- ***negative_roles:*** The set of all negative roles a group is assigned: {*role* ∈ ROLES | *type*(*role*) = *negative*}
- ***positive_perms***: The set of all positive permissions a role is assigned: {*perm* ∈ PERMISSIONS | *type*(*perm*) = *positive*}
- ***positive_roles***: The set of all positive roles a group is assigned: {*role* ∈ ROLES | *type*(*role*) = *positive*}
- ***parent***: The parent of a role or group in their respective hierarchy tree.

- ***children***: The set of children of a role or group in their respective hierarchy tree: {*child* ∈ ROLES | *parent*(*child*) = *role*} or {*child* ∈ GROUPS| *parent*(*child*) = *group*}
- ***descendants:*** The set of all descendants of a group or role group in their respective hierarchy tree.
- ***ascendants:*** The set contacting the parent of a group or role and all parent's parent and children up to the root node in the given hierarchy tree.
- ***perms:*** The set of permission/conditions pairs a role is assigned (not including inherited perms): {(*perm* ∈ PERMISSIONS, *cons* ⊆ CONDTIONS) | (*role*, (*perm*, *cons*)) ∈ PM}
- ***roles****:* The set of roles a group is assigned (not including inherited roles): {*role* ∈ ROLES | (*role*, *group*) ∈ GM}
- ***create_session:*** Creates a new session for a given user and role if valid:

$$
\begin{aligned}
&session = create\_session(user, role):\\
&\quad IF\ role \in user\_rlist(user):\\
&\quad\quad session = \{session\_id, user, role, expiry\_date\}\\
&\quad ELSE:\\
&\quad\quad session = \emptyset
\end{aligned}
$$

- ***user_roles****:* The set of roles available to a given user:

$$
\begin{aligned}
&roleset = user\_roles(user):\\
&\quad roleset = \{role \in ROLES \mid (user, role) \in UA\}\\
&\quad groups = \{group \in GROUPS \mid (user, group) \in UGA\}\\
&\\
&\quad FOR\ \forall group \in groups:\\
&\quad\quad FOR\ \forall (role, cons) \in rset(group):\\
&\quad\quad\quad IF\ \forall condition \in cons: evaluate(condition, user) == TRUE:\\
&\quad\quad\quad\quad roleset = roleset \cup \{role\}
\end{aligned}
$$

- ***evaluate***: Evaluates a given condition against a user's parameters and the current system's parameters. Returns TRUE if the condition's Boolean statement is true with the given parameters, otherwise returns FALSE.

- ***session_perms***: The set of permission/conditions pairs granted by a given session: {pair ∈ PERMISSIONS × $2^{\text{CONDITIONS}}$ | *pset*(*role* ∈ *session*)}
- ***user_params***: The set of parameter name/parameter value pairs for a given user: {(*name* ∈ PARMATER_NAMES, *value* ∈ PARAMTER_VALUES) | (*user*, (*name*, *value*)) ∈ UPA}
- ***descendant_of***: Takes two permissions, *p1* and *p2*, and returns true if *p1* is a descendant of *p2* such that *p2* is closer to the root permission than *p1*. For example "some.permission.descendant.*" is a descendant of "some.permission.*" and both are descendants of "some.*" and "*".

D.4 Cache Computation Functions

- ***comp_role_pset***: Computes the set of permission/conditions pairs for each role and that role's children in the role hierarchy. Ran on a role when its permissions are updated or parent is changed.

$comp\_role\_pset(R)$:
    $IF\ parent(R) \neq \perp$:
        $pset(R) = pset(parent(R))$
    $ELSE$:
        $pset(R) = \emptyset$

    $FOR\ \forall(perm, cons) \in perms(R)$:
        $IF\ type(perm) = positive$:
            $pset(R) = pset(R) \cup \{(perm, cons)\}$
        $ELSE$:
            $pset(R) = pset(R) \setminus \{(perm \in PERMISSIONS, x \subseteq CONDTIONS) | (perm, x) \in pset(R)\}$

    $minimize(pset(R))$

    $FOR\ \forall r \in children(R)$:
        $comp\_role\_pset(r)$

- ***minimize**:* Takes a set of permission/condition pairs and removes any redundant pairings were the permission would be negated by a higher permission. For example ("some.permssion.*", ∅) would negate ("some.permssion.lower.*", ∅).

$minimize(pset)$:
    $FOR\ \forall(perm, cons)\ \in pset$:
        $If\ \exists(p, c) \in pset$: $(descendant\_of(p, perm)\ OR\ p\ = perm) AND\ (cons = c\ OR\ cons = \emptyset)$:
            $pset = pset\ \setminus \{(p, c)\}$

- ***comp_group_rset***: Computes the set of role/conditions pairs for each group and that group's children in the group hierarchy. Ran on a group when its roles are update or parent is changed.

$comp\_group\_rset(G)$:
    $IF\ parent(G) \neq \perp$:
        $rset(G) = rset(parent(G))$
    $ELSE$:
        $rset(G) = \emptyset$

    $cons = CGM(group)$

    $FOR\ \forall role\ \epsilon\ roles(G)$:
        $IF\ type(role) = positive$:
            $rset(G) = rset(G) \cup \{(role, cons)\}$
        $ELSE$:
            $rset(G) = rset(G)\ \setminus \{(role\ \in ROLES, x\ \subseteq CONDTIONS) | (role, x) \in rset(G)\}$

    $minimize(pset(G))$

    $FOR\ \forall g\ \in children(G)$:
        $comp\_group\_rset(g)$

D.5 Administrative functions

- ***add_user(user):*** Adds the given user to the set of all users such that *user* ∈ *USERS*.

- ***remove_user(user):*** Removes the given user from the set of all users, removes all parameters/value pairs associated with that user, removes all active sessions for that user, and removes all relations involving the user.
- ***add_role(role, role_parent):*** Adds a new role and places it in the hierarchy such that *parent*(*role*) = *role_parent* and *pset*(*role*) = *pset*(*role_parent*).
- ***remove_role(role):*** Removes the role only if *children*(*role*) = ∅. If removed, all relations involving the role are also removed and *comp_group_rset* is called on all groups mapped to the role.
- ***add_perm(perm):*** Adds a new permission to the permission set such that *perm* ∈ *PERMISSIONS.* Note that the permission hierarchy is maintained in the name space and does not need to be updated.
- ***remove_perm(perm):*** Removes the permission from the permission set and all relations between roles and permissions. Note that the permission hierarchy is maintained in the name space and does not need to be updated.
- ***add_con(con):*** Adds a new condition to the condition set such that *con* ∈ *CONDTIONS.*
- ***remove_con(con):*** Removes the condition from the condition set and all relations involving that condition. *comp_role_pset*(*R*) will need to be called, were *R* is the set of roles mapped to a permission with the condition *con*.
- ***add_param(param, value, user):*** Adds the (param, value) pair to the UPA mapping for the given user.
- ***remove_param(param, user):*** Removes the parameter name/value pair from the UPA mapping for the given user for the given parameter name.

- ***add_constraint(roles, num):*** Creates a new SSD constraint for the set of roles such that a user may not be assigned more than *num* roles in the set *roles*. Note: does not affect existing mappings of roles to users or users to groups.
- ***remove_constraint(roles)***: Removes the SSD constraint on the given set of roles.
- ***add_group(group, group_parent):*** Adds the given group to the set of groups such that $group \in GROUPS$, $parent(group) = group\_parent$ and $rset(group) = rset(group\_parent)$.
- ***remove_group(group):*** Removes the given group only if $children(group) = \emptyset$. If removed, all relations involving the group are also removed.
- ***map_user_role(user, role):*** Adds the given (user, role) pair to UA only if it does not violate an SSD constraint such that: $(user, role) \in UA$ iff $pass\_constraints(user\_roles(user) \cup \{role\}) == TRUE$. Assuming all conditions are true.
- ***unmap_user_role(user, role):*** Removes the (user,role) pair from the UA set.
- ***map_group_role(group,role):*** Adds the given (group, role) pair to GA only if it does not violate an SSD constraint for any user in that group. *comp_group_rset*(*group*) is called.
- ***unmap_group_role(group,role):*** Removes the (group,role) pair from the GA set. *comp_group_rset*(*group*) is called.
- ***map_user_group(user,group):*** Adds the given (user, group) pair to UGA (user group assignment) so long as it does not violate an SSD constraint for that user.
- ***unmap_user_group(user,group):*** Removes the (user,group) pair from the UGA set.

- ***map_group_con(group,con):*** Adds the (group, condition) pair to the CGM map such that *con* ∈ *CGM*(*group*). *comp_group_rset*(*group*) is called.
- ***unmap_group_con(group,con):*** The given (group, con) pair is removed from the CGM map. *comp_group_rset*(*group*) is called.
- ***map_role_perm(role,perm):*** The given (role, perm) pair is added to the PM set and *comp_group_pset*(*role*) is called.
- ***unmap_role_perm(role,perm):*** The given (role, perm) pair is removed from the PM set and *comp_group_pset*(*role*) is called.
- ***map_perm_con(perm, con):*** The given (perm,con) pair is added to the CPM map such that *con* ∈ *CPM*(*perm). comp_group_pset* is called on all roles that map to the permission.
- ***unmap_perm_con(perm, con):*** The given (perm, con) pair is removed from the CPM map. *comp_group_pset* is called on all roles that map to the permission.

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