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Departamento de Eletrónica, Telecomunicações e Informática
MAP-I - Doctoral program in Computer Science

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Sistemas Interativos e Distribuídos para Telemedicina

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tese apresentada às Universidades de Aveiro, Minho e Porto para cumprimento dos requisitos necessários à obtenção do grau de Doutor em ciências da computação (MAP-I), realizada sob a orientação científica do Doutor Carlos Manuel de Azevedo Costa, Professor Auxiliar do Departamento de Eletrónica e Telecomunicações e Informática da Universidade de Aveiro e do Doutor José Luís Guimarães Oliveira, Professor Associado do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro.

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resumo

Durante as últimas décadas, as organizações de saúde têm vindo a adotar continuadamente as tecnologias de informação para melhorar o funcionamento dos seus serviços. Recentemente, em parte devido à crise financeira, algumas reformas no sector de saúde incentivaram o aparecimento de novas soluções de telemedicina para otimizar a utilização de recursos humanos e de equipamentos. Algumas tecnologias como a computação em nuvem, a computação móvel e os sistemas Web, têm sido importantes para o sucesso destas novas aplicações de telemedicina. As funcionalidades emergentes de computação distribuída facilitam a ligação de comunidades médicas, promovem serviços de telemedicina e a colaboração em tempo real. Também são evidentes algumas vantagens que os dispositivos móveis podem introduzir, tais como facilitar o trabalho remoto a qualquer hora e em qualquer lugar. Por outro lado, muitas funcionalidades que se tornaram comuns nas redes sociais, tais como a partilha de dados, a troca de mensagens, os fóruns de discussão e a videoconferência, têm o potencial para promover a colaboração no sector da saúde.

Esta tese teve como objetivo principal investigar soluções computacionais mais ágeis que permitam promover a partilha de dados clínicos e facilitar a criação de fluxos de trabalho colaborativos em radiologia. Através da exploração das atuais tecnologias Web e de computação móvel, concebemos uma solução ubíqua para a visualização de imagens médicas e desenvolvemos um sistema colaborativo para a área de radiologia, baseado na tecnologia da computação em nuvem. Neste percurso, foram investigadas metodologias de mineração de texto, de representação semântica e de recuperação de informação baseada no conteúdo da imagem. Para garantir a privacidade dos pacientes e agilizar o processo de partilha de dados em ambientes colaborativos, propomos ainda uma metodologia que usa aprendizagem automática para anonimizar as imagens médicas.

palavras-chave

PACS, Imagem médica, DICOM, Trabalho colaborativo, Radiologia, Anonimização, Computação em nuvem

abstract

During the last decades, healthcare organizations have been increasingly relying on information technologies to improve their services. At the same time, the optimization of resources, both professionals and equipment, have promoted the emergence of telemedicine solutions. Some technologies including cloud computing, mobile computing, web systems and distributed computing can be used to facilitate the creation of medical communities, and the promotion of telemedicine services and real-time collaboration. On the other hand, many features that have become commonplace in social networks, such as data sharing, message exchange, discussion forums, and a videoconference, have also the potential to foster collaboration in the health sector.

The main objective of this research work was to investigate computational solutions that allow us to promote the sharing of clinical data and to facilitate the creation of collaborative workflows in radiology. By exploring computing and mobile computing technologies, we have designed a solution for medical imaging visualization, and developed a collaborative system for radiology, based on cloud computing technology. To extract more information from data, we investigated several methodologies such as text mining, semantic representation, content-based information retrieval. Finally, to ensure patient privacy and to streamline the data sharing in collaborative environments, we propose a machine learning methodology to anonymize medical images.

keywords

PACS, medical imaging, DICOM, Computer supported collaborative work, Radiology, De-identification, Cloud computing

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Acronyms

3D	Three-Dimensional
ACL	Access Control List
API	Application Programming Interface
BOSH	Bidirectional-Streams Over Synchronous HTTP
CBIR	Content-Based Image Retrieval
CNN	Convolutional Neural Network
CSCW	Computer Supported Collaborative Work
CSS	Cascading Style Sheets
CT	Computed tomography
CUI	Concept Unique Identifier
DB	Database
DBMS	Database Management Systems
DICOM	Digital Image and Communication in Medicine
DIMSE	DICOM Message Service Elements
ECG	Electrocardiogram
EHR	Electronic Health Records
FAT	File Allocation Table
FN	False Negative
FP	False Positive
GPU	Graphics Processing Unit
HIPAA	Health Insurance Portability and Accountability Act
HIS	Hospital Information System
HL7	Health Level seven
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
IaaS	Infrastructure-as-a-Service
ICT	Information and Communications Technology
IOD	Information Object Definition
IoT	Internet of Things
IP	Internet Protocol
IQ	Info/Query
IT	Information Technology
ITK	Insight Segmentation and Registration Toolkit
JSON	JavaScript Object Notation
JVM	Java Virtual Machine
MG	Mammography
MLP	Multilayer Perceptron
MMIS	Medical Management Information System
MR	Magnetic Resonance

MRI	Magnetic Resonance Imaging
MVC	Model-View-Controller
NEMA	The National Electrical Manufacturers Association
NIH	National Institute of Health
OCR	Optical Character Recognition
PaaS	Platform-as-a-Service
PACS	Picture Archiving and Communication System
PC	Personal Computer
PDF	Portable Document Format
PHI	Protected Health Information
PHR	Personal Heath Record
PIN	Personal Identification Number
PRA	Personal Remote Archive
QIDO-RS	Query based on ID for DICOM Objects by RESTful Services
R&D	Research and Development
RAM	Random-Access Memory
RBAC	Role-Based Access Control
RBM	Bernoulli Restricted Boltzmann Machine
RDF	Resource Description Framework
REST	Representational State Transfer
RF	Random Forest
RIS	Radiology Information System
RS	Recommender System
RTC	Real-Time Communications
RWL	Revision Work List
SaaS	Software-as-a-Service
SCP	Service Class Provider
SCU	Service Class User
SN	Social Network
SNOMED CT	Systematized Nomenclature of Medicine - Clinical Terms
SOP	Service Object Pair
SSL	Secure Sockets Layer
STOW-RS	Store Over the Web by RESTful Services
TCP	Transmission Control Protocol
TF-IDF	Term Frequency-Inverse Document Frequency
TLS	Transport Layer Security
TLV	Tag-Length-Value
TN	True Negative
TP	True Positive
UDP	User Datagram Protocol
UI	User Interface

UID	Unique Identifier
UMLS	Unified Medical Language System
UMLS	Unified Medical Language System
URI	Uniform Resource Identifier
URL	Uniform Resource Locator
US	Ultrasound
VPN	Virtual Private Network
VR	Value Representation
VTK	Visualization Toolkit
WADO-RS	Web Access to DICOM Objects by RESTful Services
XA	X-Ray Angiography
XDMCP	eXtensible DICOM Communication Protocol
XML	Extensible Markup Language
XMPP	eXtensible Messaging and Presence Protocol

1 Introduction

"The present is theirs; the future, for which I really worked, is mine."
Nikola Tesla

The evolution of information and communication technologies (ICT) and its progressive adoption by the healthcare providers has improved the knowledge about diseases and treatments, the communication between professionals, the workflow and processes efficiency, and generally enabled the delivery of high quality services [1] [2]. Since its early adoption, it has changed the way physicians describe and manage health information, providing more interactive ways to store and to search in large amount of clinical data.

This fast evolution of health informatics has also brought some new challenges. For instance, the large amount of data that is daily generated is now a burden for healthcare institutions which need to spend a significant budget in infrastructures for storing and managing these data [3]. Several researchers have worked on solutions for reducing costs in healthcare, regarding infrastructure management and large data storage [4]–[8]. At the same time, several solutions have been developed to improve the way healthcare practitioners access this information [9]–[12].

Following this trend, some healthcare organizations have also adopted telemedicine solutions to provide remote assistance to institutions with less specialized human resources. Despite its social and economic benefits, telemedicine has yet a reduced record of execution and a very irregular adoption, with a slow and fragmented acceptance in routine operations of healthcare. Nevertheless, the increasing demand for more efficient economic models in the health sector is reopening the path for telemedicine approaches, as ways for optimizing human resources and diagnostic equipment usage. In this context, today's emerging technologies, like cloud computing and mobile devices, maybe the key for the success of the next-generation telemedicine solutions [13], [14]. The continuous evolution on technologies will help the development of richer telemedicine services, and the distinction between medicine and telemedicine will gradually vanish. Telemedicine will become a true standard of medical care by its pervasiveness. This progress will be strongly impacted by wireless and broadband innovations, promoting portability and the seamless integration of technology into daily life. Telemedicine applications will go beyond Internet-based solutions, becoming wireless, portable, and eventually wearable [15].

Ubiquitous services can easily be provided to healthcare centres with limited resources via telemedicine, without the need for large investments in the core information technology infrastructure. Recently, cloud-based solutions have simplified the dissemination of distributed medical communities, promoting telemedicine services and real-time collaboration [16]–[19]. The use of social media features, such as sharing of multimedia, messaging, forum, video-conferencing and virtual shared spaces, fit well in telemedicine solutions. The increasing awareness of this kind of tools will help to reduce the barriers for telemedicine general adoption. At the same time, mobile devices are getting successively more powerful, and telemedicine solutions are taking advantage of this shift to stimulate and to facilitate remote work, based on the anytime and anyplace access paradigm [20]–[23].

Focusing on radiology, medical imaging is one of the health areas which owe much of its success to the IT sector. Informatics systems were developed to increase the efficiency of how medical images data are acquired, stored and transmitted inside and across health care institutions. The Picture Archiving and Communication System (PACS) was created to deal with the huge amount of data and with the lack of standardization [24]. The IT infrastructure supporting these systems, namely the storage units and communication layers, needs to be prepared to deal with a large amount of data that can reach terabytes generated per year in a central hospital [25]. Moreover, the creation of computer supported collaborative work (CSCW) in teleradiology (for second opinion on a medical examination or to interact with experts in each area) is a requirement that is not yet fully satisfied. Combining these collaborative work tools with clinical decision systems could also yield even more positive results to healthcare services. Using collaborative decision support systems, physicians would build better-informed opinions during clinical decision processes. Furthermore, besides enabling remote support to low resources settings, collaborative systems may contribute to richer educational scenarios.

1.1 Research Objectives

The main objective of this research work was to investigate computational solutions that allow us to promote the sharing of clinical data and to facilitate the creation of collaborative workflows in radiology.

We centred our research in the medical imaging area, considering novel aspects of data sharing, communication and visualization, and validating our hypothesis with experimental results. Several, more detailed, research objectives that have guided this work:

- Propose new methods to streamline the telework and remote diagnostic in radiology centres, allowing the radiologists to access and visualize medical studies remotely in a seamless way, using their personal computers or even using mobile devices.

- Investigate novel collaborative scenarios in radiology by connecting physicians via social network alike services.
- Enrich the information currently available at the point of care, by integrating clinical information with recommendation systems, helping the physicians in diagnostics, prescriptions and treatments.
- Research solutions to preserve patient's privacy in agile collaborative radiology environments where data sharing is the basis of the workflow.

1.2 Research Contributions

During this work, we investigated several computer-based solutions to address our main research question, studying and proposing a computational architecture for teleradiology and creating new models to streamline collaboration in this area.

In the first contribution, we have focused on the trends shaping the future of medical imaging in radiology. As an outcome of this research, we propose an architecture for medical image visualization, enabling radiologists to connect to a standard radiology network (PACS) and remotely perform medical image diagnosis using any HTML5 browser. In the proposed architecture, features like reporting, printing, data sharing and image visualization may be accessible in the same way from inside the institution or from remote locations. Since the entire workflow can be performed within this architecture, by enabling digital data sharing we can reduce paper and traditional film prints that are normally used to exchange imaging studies between institutions and persons.

The second contribution is a software-as-a-service solution to support professional collaborative work in radiology, allowing the easy creation of communities and workgroups. On this matter, we show the applicability of cloud-based solutions to promote the collaboration in radiology. Moreover, by investigating the benefits of social network for professional radiology network, we created a platform that offers several tools for communication, data transmission, case discussion, and video-conferencing.

In the next contribution, using our collaborative platform, we have explored the integration of a recommender system in the clinical workflow. The amount of data stored into databases supporting radiology tends to grow fast. This information can represent relevant knowledge for non-expert radiologists, and even for experts when dealing with rare clinical cases. In this regard, we propose a method that integrates data from clinical reports and medical imaging to generate relevant recommendations for physicians. We have developed a software architecture for streamlining the access to these recommendations when physicians are analysing a study.

As the fourth contribution, we expanded the procedure of clinical text processing in the recommender system, annotating the reports with semantic information. Thus, we propose a pipeline to generate a semantic knowledge from radiology clinical reports. This pipeline processes any biomedical clinical text through a biomedical text annotator and a biomedical semantic layer. We offer a solution capable of transforming biomedical textual data into semantic triples and store them into a semantic knowledge base (i.e. in the RDF format).

In the last contribution, we analyse the performance of machine-learning methodologies applied to medical image anonymization. This work was conducted due to the need of ensuring patients' privacy in the collaborative platform. In this system, medical images are shared between practitioners, and in some imaging modalities (e.g. ultrasound) there are patient information burnt into images' pixel data. We propose a method based on machine-learning algorithms which automates images de-identification. The implemented process consists of a novel pipeline to find and remove sensitive information from the pixel data.

1.3 Thesis Organization

The remaining chapters of this dissertation is organized as the following structure:

- **Chapter 2** will present the state-of-the-art related to our research question. We provide an overview of radiology information systems, medical imaging solutions, cloud technology, computer supported collaborative work, recommender systems, discussing how these concepts are improving radiology services, their main advantages and limitations.
- **Chapter 3** will be focused on the barriers that standard radiology systems face regarding telework, remote data access and data sharing. This chapter will specially discuss the difficulties that radiologists have when remotely accessing data from traditional radiology infrastructures to perform diagnosis. We propose several computational solutions to overcome these barriers, which the outcome is a web viewer for medical imaging.
- **Chapter 4** will discuss how the computer supported collaborative work can be applied in radiology environments. Other important concepts like social network services, recommender system, and cloud computing will be explored, demonstrating their value for creating radiology collaborative workflows.
- **Chapter 5** will focus on patients' privacy in collaborative radiology environments, where data sharing is the key feature in the workflow. We propose a machine-

learning approach that allows the de-identification of patients' data in our collaborative PACS viewer.

- **Chapter 6** will present the overall conclusions and the final remarks about this research, and will discuss some future work.

2 Information Technology in Medical Imaging

"The science of today is the
technology of tomorrow."
Edward Teller

Healthcare centres have early recognized the benefits of using IT-based solutions for the management of medical information. Daily, hospitals assist many patients, generating an enormous amount of data (e.g. patient records, medical images, diagnostic information). During their lives, citizens go through many distinct health institutions, and perform many medical examinations, creating the need for keeping all this history. The storage of patient history information was the motivation behind the appearance of several Electronic Health Record (EHR) systems. EHRs have improved the management of healthcare information by keeping track of information, such as patient demographic, past medical history, admission notes, symptoms and medications.

On the other hand, health informatics have been applied to healthcare institutions for improving workflows and institution's management. Hospital information systems (HIS) support hospitals management providing features like registration of daily financial transactions, management of all clinical workflows from patient admission to discharge procedure, and cost operation analysis.

Different healthcare institutions have different operation requirements, and sometimes they need to develop specific systems to meet these needs. Medical imaging is one of such examples. Consequently, Radiology Information Systems (RIS) have emerged as a solution to provide medical imaging centres with features not found in standard HIS. However, the integration between different systems became an issue. Usually, HIS are capable to integrate multiple information systems via standard interfaces, such as the HL7 (Health Level 7) [26]. This standard was defined to support the healthcare workflows providing automatic actions, thus, avoiding ad-hoc solutions to communication data between systems. However, the compatibility between distinct RIS could not be assured through HL7, and other solutions were developed, namely Picture Archiving and Communication System (PACS) and Digital Imaging and Communications in Medicine (DICOM) [24].

2.1 Radiology Information System

2.1.1 Picture Archiving and Communication System

The emergence of the first Picture Archiving and Communication System (PACS) [24] occurred three decades ago, and has revolutionized radiology services, and somehow the medicine practice. The large amount of data generated in radiology centres demanded the creation of an infrastructure and of workflows to clearly define how medical images are stored and accessed in hospital networks [24]. PACS uses the Digital Imaging and Communications in Medicine (DICOM) standard [27] to store and transmit medical images, ensuring in this way interoperability between equipment from different manufacturers.

As an overview, it can be said that PACS encompasses technologies used for acquisition, archive, distribution and visualization of a set of digital images using a computer network for diagnosis and revision in dedicated workstations. Typically, a PACS is composed of four components: a) gateway for medical imaging acquisition, b) archive server to store the images, c) workstations for data visualization and d) application servers.

Acquisition of medical imaging is one of the main functionality in a PACS. The information produced by modalities can be sent directly to an archive server or through gateway units. Gateways are placed between equipment and the rest of the network, and they are responsible to obtain medical images from modalities. They interact directly with image acquisition equipment and they are important elements to format medical images from radiological equipment to the DICOM standard format.

The archive server is the engine of any PACS. It is composed of a database where information about patients is indexed, and a DICOM objects repository where files are stored. The PACS archive server is responsible for receiving the images from medical imaging equipment and updating the management system database. In addition, the server can include functions like, file compression, integrity check and information extraction from DICOM images.

Revision workstations are connected to the PACS network and usually we can find high resolutions monitors for visualization of images and specialized image processing software in these workstations. Some workstations may also be equipped with a local database to cache examinations, depending on the performance needs. Workstations with local database are usually equipped with many features for medical image processing, and need only to communicate with the PACS server sporadically as they can keep information locally. On the other hand, workstations not equipped with a local database need only some basic processing functions and are constantly requesting data from the PACS server.

Radiologists use workstations to do diagnosis interacting with a PACS archive server via features, such as search and retrieve of medical images. Other features like measurement tools can aid physicians in image interpretation and diagnosis. Also, it is possible the accumulation of all relevant information and images of patients' examinations.

Several application servers may be connected to the PACS to fully explore data stored in the system. For instance, application servers can be used to filter data retrieved from a PACS server or to make data processing. Moreover, one can find many types of application servers, such as web services to support visualization of medical images, gateways to allow the integration with EHR, gateways to support data access through mobile devices, and CAD (Computer Aided Diagnosis) system.

2.1.2 Digital Imaging and Communications in Medicine

Much equipment with capacity to acquire, to transfer and to store medical images have brought the need to standardize communication processes on PACS networks. DICOM is the international standard which defines data formats, storage organization and communication protocols of digital medical imaging. Its first version was approved by American College of Radiology and National Electrical Manufactures Association in October 1993. Currently, the DICOM standard is divided into 20 parts that include 168 supplements on specific aspects of one or several parts of the standard. DICOM defines the entire set of methods for storage and transmission of digital medical images, enabling the communication between digital equipment, such as imaging modalities, workstations, printers and servers.

The DICOM commands and most of the DICOM data attributes are always bonded with the four-level information model represented by Patient-Study-Series-Image hierarchy (Figure 2.1). This DICOM hierarchy reflects what happens in the real world. For example, a patient goes to a hospital and can make several studies (i.e. MR, CT, and ultrasound exams) and these studies may have multiple image series (coronal, axial, with or without contrast, with varying imaging protocols, and so on). And each series will have one or more images associated with it. This hierarchy uses a UID (Unique Identifier) to identify the patient, study, series, and images. The patient level is identified using a unique "Patient ID", and the same applies to the other three levels of the Patient-Study-Series-Image hierarchy: at Study level, each study has its unique "Study Instance UID"; at Series level, each Series has its unique "Series Instance UID"; and at Image level, each Image has a "SOP Instance UID".

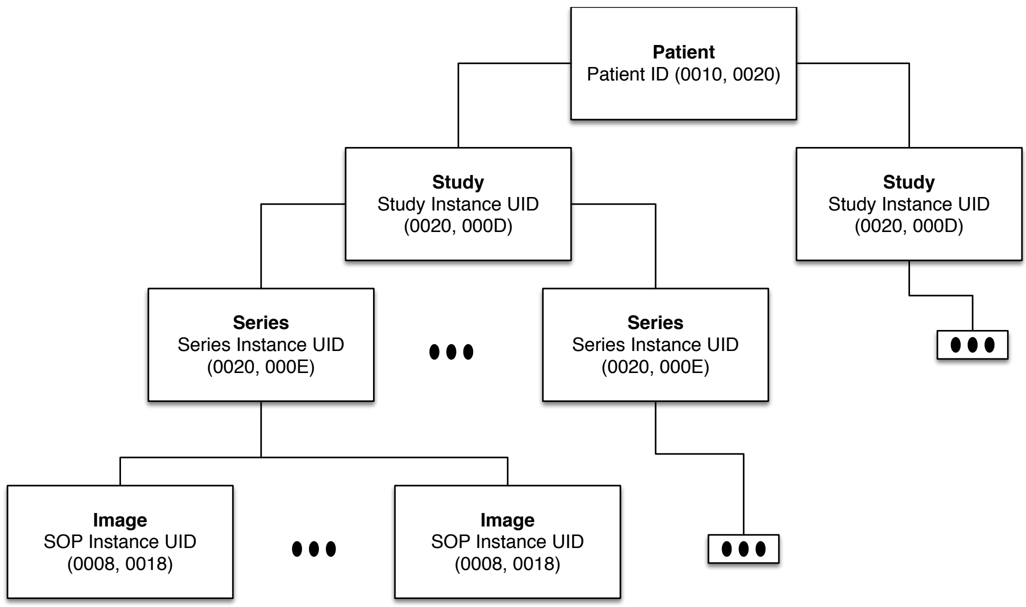

Figure 2.1 DICOM information hierarchy.

DICOM Object Data

DICOM supports multiple types of medical information elements, such as different medical imaging modalities, waveforms and clinical structured reports. Every DICOM has a header (Figure 2.2) that contains metadata used to store the DICOM Information Model (i.e. information about patient, clinic staff, institution, equipment and conditions of the examination).

DICOM objects are composed of many attributes. One special attribute is the pixel data element which can contain a single image or multiple frames (to store cine loops or other multi-frame images). Moreover, it can be compressed using different standard compression algorithms, such as JPEG, JPEG Lossless, JPEG 2000 and MPEG.

A DICOM data element is structured as follows: GROUP (2 bytes), ELEMENT (2 bytes), VR (2 bytes), Length in byte (2 bytes) and Data (variable length). Data elements packing follows the TLV format (Tag, Length, Value) as shown in Figure 2.3. The tag has four bytes, where the first two bytes are for the group and the last two bytes for the element; thus, representing the "(group, element)" tag used to identify a given Data Element. For example, Patient Name tag has the group value 0x0010 and element value 0x0010, thus it is represented as (0010,0010) tag.

According to DICOM objects transfer syntax, the value representation (VR) field can by explicit or implicit. With explicit syntax, the data element contains the VR field that defines the element's value representation (that can be DA for date, TM or time, PN for patient name, etc.). In implicit syntax, this VR field is not present and it is necessary to consult the standard DICOM dictionary. Considering the tag value, the dictionary defines the data element type. The Length field is used to define the length in bytes of element's value field.

This value depends on the tag value. At last, the element has the value field, which contains the data that is stored in the element (e.g. image pixel data, patient birthday, patient name, patient ID, etc.).

As said, DICOM files are composed of well-defined standard data elements. However, we can define private tags to represent extra information not defined in the standard.

DICOM Services

DICOM defines services that are used to transmit data between entities connected to a PACS network, creating a standard communication protocol, over TCP/IP, to establish a reliable connection between endpoints. As others protocols, like SMTP, HTTP and FTP, the DICOM standard only adds its own networking language (at application layer) over TPC/IP. This language consists of high-level services known as DICOM Message Service Elements (DIMSE).

The communication defined in the DICOM standard follows the client/server model, using the Service Class Provider (SCP) and Service Client User (SCU). An entity can play either a SCP (i.e. server) or SCU (i.e. client) role to communicate with each other. For instance, if a modality or a workstation needs to interact with PACS archive, the modality or the workstation is the SCU and the PACS archive server is the SCP.

The DICOM network has also an addressing mechanism which assigns to each device an Application Entity Title (AETitle), used to identify different peers.

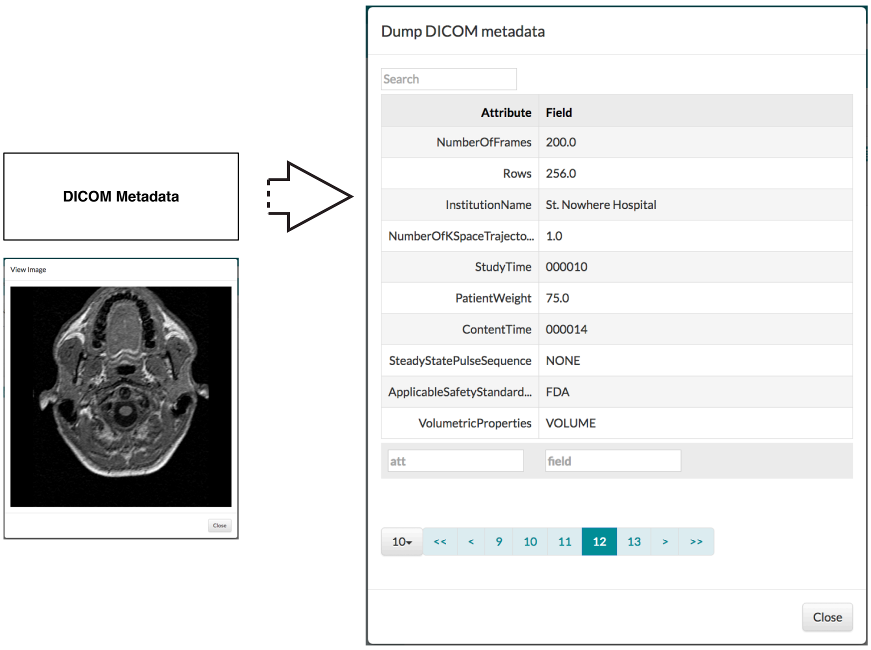

Figure 2.2 DICOM Object structure.

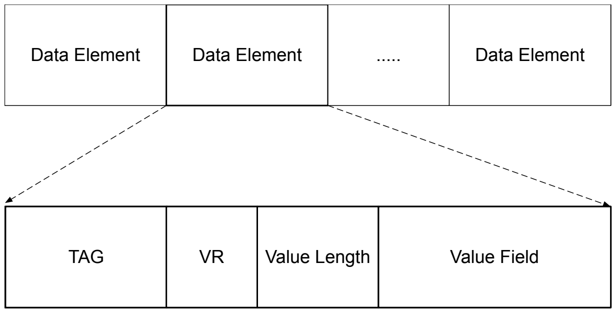

Figure 2.3 DICOM elements structure in TLV format.

Firstly, a DICOM association must be created to establish a channel for information exchange when accessing a DICOM service or communicating with a DICOM device. This association implies the negotiation of several parameters, such as encoding (ex. little-endian, big-endian), image compression formats, what kind of information will be transferred, and the duration of the association. After the negotiation, the service commands are executed between SCU and SCP to perform the service goal.

There are several services defined in the DICOM standard. For instance, the DICOM Store service is used when a SCU pretends to send DICOM objects to a PACS archive server or to a workstation. This service uses the C-Store (Storage SOP) command to move DICOM objects between the entities over a DICOM network. The Query/Retrieve service is another important service defined in the DICOM standard which enables finding and retrieving studies, series or images from a PACS archive server. This service consists of a retrieval process using the C-Get command. This command wraps C-Find and C-Store commands into a single service class. The C-Find is used to query the archive database, and the C-Store to retrieve the images from the server to an application peer on the network. While the C-Get is used to return images to the same SCU that makes the request, it is possible to use the C-Move command to move images to third party applications. Thus, the C-Move command needs to know where to return the images. However, this question is never raised in C-Get since the SCP always returns the images to the requesting entity (SCU). Besides the services previously presented, there are many others, like the *Storage Commitment*, the *Modality Worklist*, the *Modality Performed Procedure Step* and *Printing*.

DICOM Web Services

Recent versions of the DICOM standard introduced 3 Web services to access and present DICOM objects. These Web services are simple interfaces for accessing DICOM object through HTTP/HTTPS protocol, identifying the objects by DICOM UIDs. With these services, the DICOM standard became Web-ready, allowing us to extend DICOM-based solutions to work in the Web. Therefore, data stored in DICOM repositories can be retrieved either in the raw DICOM format or in a presentation-ready format, such as PNG or GIF, which is desired in Web-based communications.

The services proposed in the DICOM standard allow storing, querying, retrieving DICOM objects from a repository, using RESTful services. They are known as DICOM STOW-RS (STore Over the Web by RESTful Services), DICOM QIDO-RS (Query based on ID for DICOM Objects by RESTful Services) and DICOM WADO-RS (Web Access to DICOM Objects by RESTful Services).

The DICOM STOW-RS allows a store action which creates a new instance for a given SOP instances. A DICOM STOW-RS request can be converted to a DICOM C-Store request. Using this service, one or more instances of one or more studies can be stored in a repository through a HTTP POST request.

The DICOM QIDO-RS is used to search studies, series and instances in a DICOM repository. This RESTful service acts like DICOM C-Find. It can be accessed using HTTP GET method, where the query level is defined by the URL end-point (i.e. {*}/studies[?query], {*}/series[?query] or {*}/instances[?query]). The query is specified using key-value pairs, defined by DICOM attributes ID and its value. Also, we can define which DICOM attribute IDs should be returned, an offset used to define the number of entries to skip and the maximum number of entries to be returned in the response.

The DICOM standard defines a RESTful service to retrieve DICOM objects, which is similar to DICOM C-Move action. This service is known as DICOM WADO-RS, and it is accessed using the HTTP GET method. In the DICOM standard, it is defined 6 actions that should be supported by the DICOM-RS, which includes retrieve studies, series, instances, frames, bulk data and metadata. All response must be a HTTP multipart message, and binary data must be encoded using the corresponding media type, which is defined in the mapping table for DICOM transfer syntax to media type and parameters.

2.1.3 Telemedicine and Teleradiology

Telemedicine consists of providing remotely clinical healthcare services, using informatics and communications technologies. For this, doctors may use specialized software to examine, monitor and treat patients that are in remote locations and unable to travel to the healthcare centre. Telemedicine is an area of medicine that has lately captivated the interest of several researchers. This healthcare service emerges as a vital resource which can save lives in countries where the population is highly dispersed, and with low population density in certain regions. It can also be a way to deliver qualified health services in anyplace. Furthermore, countries where the demands on hospitals are increasing, telemedicine can make easier for hospitals to provide therapies and teleconsultations for patients. Therefore, these solutions may contribute to the reduction of patient’s travels and physical space occupation in hospitals, and such means can also be used to assist doctors in remote diagnosis processes, based on examinations data or teleconsulting sessions.

In view of rapid developments in IT, telemedicine is no longer a forthcoming idea and the concept is becoming more mature and very important for patients and institutions that provide healthcare services. It can leverage quality and availability of services provided by health institutions, reducing the distances between patients and hospitals, speeding up the access to high quality services and supporting healthcare professional collaboration.

Many healthcare specialties are being delivered as telemedicine services, and are contributing to telemedicine adoption in healthcare centres. Telecardiology, telepsychiatry, telepathology, teleophthalmology, teleradiology are some of these services. In our research, we have focused on teleradiology since it is the branch of telemedicine which encompasses medical imaging. First steps towards teleradiology dates to the 1920s when first medical image was transmitted through a telegram to a distant location [28]. Kumar [29] reported that the most frequent users of teleradiology are typically radiologists on call, rural primary-care physicians, hospital physicians in inter-departmental collaborative processes, and subspecialist physicians in remote consultations. He also presented some potential applications of teleradiology in scenarios like, training of new radiologists, assisting radiologists in developing countries, and providing medical assistance to isolated regions.

In telemedicine services, like teleradiology, data are transmitted to remote location via a network connection, such as telephone lines POTS (Plain old telephone service), LAN (Local Area Network), WAN (Wide Area Networks). In the case of teleradiology, the transmitter station is often responsible for converting medical images to digital format, and responsible for compressing digital data image considering the desired resolution and bit rate. Compression reduces the density or number of bits per pixel, and, if a loss algorithm is used, there is degradation in image quality. Many times, the image resolution is also reduced. Ideally, image compression would not be necessary if high-speed communication channels are available. However, when is not possible fast transmission of high resolution image we should deal with a situation where the optimization of a parameter implies the degradation of others, i.e. increasing the speed of transmission often involves an increase in the level of compression and the reduction of the images quality.

Regarding receiving stations, they should also be connected to high-speed networks. Besides network speed, the quality of the monitors used to display medical images is also important in diagnosis. Receiving stations are usually equipped with large monitors with high pixel resolution. The ability to support monitor splitting is another important requirement in medical imaging analysis. This features enables performing complex visualization workflows where more than one image can be visualized and compared at a time. The monitor brightness is also very important because the monitors with greater vividness enable a better identification of regions of interest within the images.

Additionally, radiologists use specialized software to review medical studies. Most of these applications provide basic features to manipulate image, such as medical image “window/level” settings, visualization window (brightness and contrast) and zoom. More specific software offers specialized functions, e.g. enhance edges, display histogram equalization, add notes to the relevant parts of the image, map a grayscale image, apply filters, and 3D reconstruction. These advanced image processing techniques usually depend on the users’ needs and on the type of image being analysed.

2.2 Healthcare Informatics Applications

Ubiquitous computing consists of designing software that is accessible from everywhere and anywhere, in a seamless manner using underlying technologies, such as the Internet, mobile computing and sensors [30]. PACS and all applications that support radiological workflows are frequently located in same local area networks and remote access is typically supported through VPN connections. However, this local access constraint seems very restrictive when ubiquitous access to data is becoming increasingly important in health informatics [31], [32].

Dataflow and data availability are very important in telemedicine to build a solid and useful system. Yang et al. [33] implemented a cloud-based system for medical images called Medical Image File Accessing System (MIFAS). Cloud-based solutions have been used to solve the problem of medical information exchange and compute power sharing between hospitals [19]. Also, Silva analysed advantages of using cloud computing to improve healthcare systems [34]. They implemented a PACS archive in the cloud, taking advantage of the cloud’s elasticity and scalability.

We can point out other important features in evolving healthcare informatics, such as allowing physicians to have ubiquitous access to patient records, medical data storage, database queries and medical data retrieval. For instance, there are solutions which allow physicians to manage the patient health records and medical images using mobile computing [35]. Viana et al. [36] analysed limitations of current mobile phones and tablets in terms of reduced computational power, limited storage and memory, and proposed a three-tier architecture with a relay on the cloud.

Focusing now in the visualization technology, several researchers implemented DICOM Web viewers based on Java applets in order to be platform-independent [37], [38]. In the same line, Arguiñarena et al. [39] proposed the use of Adobe Flash technology to implement a DICOM Web viewer. However, these cannot be considered pure Web applications due to their dependency on external components. Mahmoudi et al. [40] explored the implementation of 3D volume rendering in a DICOM Web viewer. They used Virtual Reality Modelling Language (VRML) [41] to provide 3D features over the Web.

Meanwhile, VRML became obsolete, and 3D representation is now possible using the WebGL Application Programming Interface (API) introduced in the HTML5 specifications. In summary, the web technology panorama is changing very quickly and nowadays the market encourages the use of HTML5, Canvas and JavaScript. HTML5 features are being explored when building Web viewers for medical imaging, allowing the visualization of DICOM studies in any HTML5 compliant Web browser without the need for extra components [42].

Focusing on healthcare collaboration, Porumb et al. [43] created a system for synchronous collaboration mechanisms among medical staff, improving telemedicine services and real time collaboration. They provided synchronous and asynchronous collaborative capabilities, but the system was limited to a single institution.

Recently, several web-based platforms, such as Radiopaedia, GoldMine, myPACS, and AuntMinnie, have appeared to provide rich collaborative repositories of radiology cases with descriptive information like patient demographics, image modalities, related articles, and clinical findings. Although these systems are good forums for teaching and knowledge dissemination, they are not targeted for synchronous online collaborative work.

2.3 Cloud Computing

Cloud computing is a concept which despite being recently spread around the world, is not entirely new. In the 60's, John McCarthy, an American computer scientist, foretold that "computation may someday be organized as a public utility" and that would happen to the computer the same that happened with electricity and other commodities [44]–[48]. Therefore, instead of having generators in our homes, we pay for electricity used. This is the concept that is currently used in cloud computing, where people pay-as-they-go. Hence, cloud computing consists on delivering computing as a service rather than a product [49].

Describing cloud computing in terms of its characteristics and how it works along with other information technologies, can be said that it is a computer model that basis its functionalities over virtualized systems, where an aggregation of distributed resources is available and shared by virtual servers, enabling a massively scalability and the creation of a dynamic infrastructure [50].

2.3.1 Cloud Computing Features

The cloud computing paradigm brought many features adjusted to enterprise companies' needs, driving web-based services providers to use cloud computing to support their business. Cloud services provide a combination of capabilities, such as universal access, fine-grained usage controls and pricing, standardized platforms and management support services.

A massive scalable infrastructure is another key characteristic of cloud computing, distinguishing it from other architectures such as Grid computing. From the perspective of end users, this scalability allows them to manage and control the amount of computation and storage, as they need, simplifying the IT management.

Enterprises and web-based service providers that run their own servers usually need to expand their infrastructure to improve computation power and storage capacity. Often problems related with buying of additional hardware and fitting computation onto existing servers come with infrastructure management. Additionally, IT managers also run into issues related with operating system licenses and conflicts in scheduling workloads. These problems are avoided when cloud computing is used taking advantage of its technology principles: rapid allocation of virtual servers, standardized hardware and persistent cloud storage.

Rapid allocation of virtual servers is very important to enable computing elasticity. This is one of the major features that characterize this computing model. It allows allocating specific number and type of virtual machines as needed to perform tasks.

In a cloud, all physical servers become shared resources. The distribution of jobs and virtual servers running on a set of physical servers can change quickly among those physical servers. Elastic computing enables allocating and releasing virtual machines instances on demand. So, the computation power allocation and release is completely transparent.

Some cloud providers allow the users applications to scale horizontally if they need more virtual machine instances to run a task. There are services where the providers enable instant scalability. They monitor the virtual machines CPU utilization, so that a new instance is automatically created if a given limit of utilization is reached. But the truth is that not all applications are capable to take advantage of this scalability. The application must be designed considering cloud elasticity. Indeed, infrastructure scalability may not automatically reflect in application scalability.

Another important feature is that it provides persistent storage on the cloud. Any instance allocates computing resources and storage on physical servers, but once the virtual machines are released, all data locally stored can be lost. Therefore, is necessary to have persistent data storage over the cloud. Cloud storage services can be accessible thought access control restrictions, authentication and accounting. Usually, persistent storage is decoupled from computing servers on the cloud. This enables a fine-grained control over the resources allocated and different accounting for computation and storage. In fact, massive scalability is possible due to combination of rapid provisioning of standard hardware and the use of persistent storage.

Cloud computing also provides universal access to services, from anywhere on the Internet. The access can be through standard application programming interfaces, web browsers, light-weight desktop applications or mobile applications, while business model and data are stored on servers on the cloud. Needless to say that universal access is not the same as open access, especially when we are referring to private cloud. Authorization and authentication mechanism are used to restrict access to cloud resources. Even in public cloud, identity mechanism is required for accounting and to support the management and billing.

Cloud is becoming a popular computing model especially because services consumers can rent what they need instead of building and running the entire infrastructure, bearing in mind fine-grained usage control and controlled expenses. Deploy enterprise IT infrastructure has a huge cost to set up and run. For instance, besides costs related with hardware and software licensing when implementing a data centre, there are some other concerns like air conditioning, electricity, physical security, security systems anti-disasters (e.g. fire, floods, earthquakes), and so on.

The economic benefits of cloud computing paradigm are key to its broad adoption, mainly in enterprise environments. Measuring the computation needs is a common issue when is necessary to buy new server to an infrastructure. There is the risk of undersize the needs and do not meet the service-level agreements (SLA) or to oversize the capabilities required spending an unnecessary amount of money. But with cloud computing, these risks are unlikely to cause problems because users can allocate the compute power and storage, as they need.

2.3.2 Deployment Models

Three distinct implementation models are available for cloud computing infrastructure: public, private and hybrid.

The public cloud model consists on outsourcing the computation and storage to third parties, i.e. those resources are in data centres which operate outside consumers' enterprise. In this model, a cloud provider handles all resources, computing and data. Therefore, it can face some privacy and security issues. Usually, public cloud services are provided through a pay-per-use model. Users can see resources on the cloud as infinite, allocating only what they need and paying just for what they use. Commonly, cloud providers offer web services and applications to access and manage allocated infrastructure, over the Internet. Companies like Amazon, Hewlett-Packard, IBM, Google, Microsoft, Rackspace, Salesforce, offer public cloud services.

On the other hand, a company may consume services provided internally in its own private cloud. This deployment model use the same technology as the public model and is often used when infrastructure compliance, security, and other requirements are not met in public Clouds. Private cloud also enables a company to maximize the use of its computing resources. Moreover, it allows users to better manage policies and access control, and to define their own virtual machines. In-house private cloud usage can be more efficient to a company compared with traditional IT operating model regarding the computing characteristics previously presented. However, compared with the public model, a private cloud may require, at the head, a higher amount of capital expenditure with hardware and software licensing. It usage is seen with some criticism, and one may affirm that this computing model has maintenance requirements like traditional infrastructure where an IT professionals staff must be available to support it. Moreover, private cloud does not get rid of some issues which affect traditional servers' infrastructure, such as capacity planning and infrastructure expansion (requiring capital and time expenditure).

Finally, there are hybrid Clouds which are composition of private Clouds and public Clouds. A company that has a private cloud can use resources from public Clouds to extend its resources. Hybrid Clouds are commonly used when customers need to have more control over infrastructure dealing with issues such as security, privacy, and access control. There are a few ways to implement hybrid Clouds. For example, using two clouds as separately managed service platforms, where policies are defined to designate what kind of task can be executed on the public or on the private cloud. Consumers can choose which service to use for each task, considering variables such as cost, performance, or security requests. Having a unique service management platform over both private and public components is another way to implement the hybrid model. In this approach, the private and the public component are still two independent services, but managed using a single point. In some hybrid cloud, a Virtual Private Network (VPN) can be implemented in the public area, to treat that portion of the public cloud as an extension of the private cloud. There are some vendors offering solutions that can be used to enable hybrid cloud deployment model. For example, one can use Amazon Virtual Private Cloud, Skytap Virtual Lab, and CohesiveFT VPN-Cubed to implement a hybrid cloud. These solutions use IPSec VPN tunnelling to connect the public cloud infrastructure to the on-premise cloud resources.

2.3.3 Service Layers

We can divide cloud computing services into three layers each one implementing a different service model: Software-as-a-Service (SaaS), Platform-as-a-Service (PaaS), Infrastructure-as-a-Service (IaaS). These layers are organized in a manner where each one can be composed of underneath layer services.

Software-as-a-Service (SaaS) is the top layer offering a high level of abstraction and providing ready-to-run services deployed and configured for end-users. In this layer, users have no control over the underlying infrastructure. Therefore, it represents just an access point to reach a given service like, portals or visualization tools. Unlike traditional software, SaaS does not need a client-side software installation, and all data and business logic are held on cloud infrastructures. Universal access via the Internet and high availability are some important feature of SaaS. Applications provided as SaaS usually have a Web interface that is accessed through web services [51], [52] or graphical user interfaces [53], [54]. SaaS is massively used nowadays. For instance, email services are quite common and always available and accessed through web browsers or thin clients. Besides email services, there are other software like Dropbox, Google Apps and social network applications (e.g. Facebook and Twitter) provided as services.

The next cloud service layer is Platform-as-a-Service (PaaS) which allows consumers to have an abstraction of hardware limits. Thus, developers can focus on application development not worrying about operating systems, infrastructure scaling, load balancing and system administration task. PaaS enables users to implement applications and to deploy them on a cloud provider infrastructure using specific programming languages and APIs defined by the cloud provider. PaaS provides users limited control over the underlying cloud infrastructures, therefore, they can deploy and configure applications using programming environment offered by cloud vendors. The process of implementing and deploying a cloud application becomes more manageable while allowing programmer to focus on important issues. A well-known PaaS is Google App Engine which enables the deployment of applications using Python and Java API. Windows Azure is Microsoft's PaaS platform and offers different types of runtime environments and storage services for applications.

The last service layer one can find in cloud computing is Infrastructure-as-a-Service (IaaS), where low-level virtualized resources like computation, storage and network are offered on demand and used in a self-service manner. IaaS enables instantiating virtual servers with distinct operation systems and software stack. Cloud providers allow users to choose which operating system to use from a variety of pre-configured VM images. IaaS also provides instant scalability and elasticity making possible to dynamically expand applications computing power through instantiation of virtual machines. We can find numerous cloud providers offering IaaS, such as Amazon EC2, Rackspace or GoGrid.

As a final consideration, there are many ways cloud computing can be delivered, and the choice of which model to use depends highly on specific requirements, and a good balance between optimization of earnings and reduction of costs, i.e. capital expenses and operating expenses.

2.4 Collaborative Healthcare Systems and Social Media

Computer Supported Collaborative Work (CSCW) has been implemented in many areas where joint group activities have an important role. These systems have been used to share tasks, knowledge and experiences, mainly via videoconference applications and electronic meeting rooms. The most recent systems are being implemented using Web-based technologies, a paradigm shift that was fundamental in the dissemination of this kind of applications.

2.4.1 Computer Supported Collaborative Work Models

Baecker defined, in 1995, four kinds of CSCW system, taking into account if the actors are geographically in the same place, or not, and if they interact synchronously or asynchronously in the group activities [55]:

- **Same time/same place:** These systems aim to provide applications to manage and coordinate interaction between actors in the same place and at same time. Usually these systems use supported by shared tables, digital whiteboards and roomware.
- **Same time/different place:** Consist of CSCW designed for collaboration between users geographically distributed and users cooperating in a synchronous way. These systems provide remote interaction by the means of messaging, real-time groupware and videoconferencing.
- **Different time/same place:** These systems has as an objective to enable coordinated task in groups where actors access the system at the same place but at different time. Usually, they create a team room where actors are aware of what their colleagues do over time and where actors can report their process to the group.
- **Different time/different place:** These systems are helpful to support collaboration in groups where actors are geographically apart and interaction is made asynchronously. In fact, enabling groupware coordination between users physically apart. Usually, this kind of system provides collaborative workflow management using version control, wikis or blogs.

2.4.2 Collaborative Application in Healthcare

CSCW has been also applied in healthcare. Tang et al. [56] developed a system to support nurses while they take notes at point of care. The system aimed to explore digital technologies to replace the traditional information flow based on paper and pen. Also, Aarhus R. et al. [57] proposed a computer supported system to integrate healthcare provision, between home and hospital, for pregnant women with diabetes. The system allowed the interaction between physicians and pregnant women to minimize risk of complications during pregnancy period. The follow up is especially important in pregnant women with diabetes which need to frequently visit the clinic for controlling glucose values. The proposed system provides several services, like the register of glucose values and tele-consultations, serving as a collaboration tool between doctors and patients.

Another example of CSCW application in healthcare was presented by Jirotka M. et al. [58] where they investigated how technologies can support collaboration in healthcare in a breast cancer screening scenario. The study presented results of using a Grid-enabled system to support breast cancer screening in a distributed environment. Their objective was to make better use of scarce physicians specialized in medical images analysis. The system enabled information sharing between multiple healthcare institutions, considering also privacy aspects and providing trust in handling sensitive data.

CSCW has shown useful to improve workflow in healthcare environment. For instance, Ellingsen et al. [59] suggested a laboratory requisition system with improved way of submitting requisitions electronically to hospital laboratories. The project allowed the coordination and the maintenance of interactions between general physicians (GP) and hospital laboratories. GPs could operate day-to-day activities within the proposed system. The authors focused in integration of three different laboratories with distinct workflows: medical biochemistry, microbiology and pathology. The authors conducted a well-founded interpretative research to gather and in-depth understanding of the overall environment that support laboratory activities.

2.4.3 Social Media

Social networks (SN) are formed by a set of entities interconnected through some kind of relation. These networks are composed by nodes (e.g. Web pages, Web of things, articles and authors), and is possible to establish meaningful relations between these entities. The analyses of these relations may lead to the discovery of patterns between nodes. The social networks analysis is a challenging research topic, where the main issues are in identification of members, of the relations between members, and of clusters or motifs.

Some techniques have been proposed to identify members in social networks [60]:

- **Event-based:** this approach identifies social network nodes based on its activity in some events. For example, a node is part of a social network if it participated in a key event during a period.
- **Positions-based:** this method only chooses members holding a position inside the network. For example, in a healthcare-based social network, only physicians working in a specific institution are selected to be part of the network.

- **Relation-based:** this common method uses information about inter-nodes relation. In the beginning, the social network is composed by a set of members that share a relation. Next, the initial set of node is expanded by adding new nodes sharing a relation with nodes already present in the selected population.

The relation between nodes may define the network organics. Entities inter-connection may define friendship, collaboration, web links or citations. Borgatti et al. [61] have used social relation, similarity, interactions and flows to describe possible relations between nodes:

- **Social relation:** Family relationship (e.g. friend, co-author, etc.) is usually used to define node relations. However, it can also be based on affinity between entities (e.g. like, follow, etc.).

- **Similarities:** Common attributes like statistical aspects, geo-location, attitudes, organization association and so forth, can be analysed to find nodes that share similar characteristics and infer a relation between them. However, social network analysts usually only consider the organizational association as an important feature to define the similarity between different nodes.

- **Interactions**: Network nodes execute behaviour-based activities along with other nodes. The analysts see these activities (e.g. talk, assist, contact) as strong ties between nodes in a social network.

There are many mathematical properties associated to social networks. Over years, researchers have used statistical and probability theory, algebraic models and graph theory as the most important mathematical foundations applied to social networks [62] [63]–[66]. The application of graph theory and random graph distribution are useful to define models for a suitable understanding and representation of social networks. Other researchers have analysed social networks using statistical theory. They have used key properties like transitivity, balance, mutuality and reciprocity. The algebraic models are important to support the analysis of multi-relational networks and to interpret combination of relations. Inter-nodes relations like, "is a friend of", "is co-author" or "is a co-worker", are frequently identified onto position-based and relation-based defined social networks using algebraic models.

2.5 Recommender Systems

The purpose of recommender systems (RS) is to provide to the users some suggestions considering previously identified needs. Usually, a RS makes recommendations based on user's experience, i.e. past actions. For example, the system can be fed with information regarding what the users listen to, what they buy, or what they usually do in each situation.

The data collected enable creating ground knowledge necessary to make useful suggestions [67]–[69].

The targets of recommender systems are non-expert users that may have some difficulties to find relevant information in the system. RS focus their action on items that the users may be interested in. For example, Amazon uses previous acquisitions information to predict what kind of product a costumer may be interested. The RS output is presented as recommended items in the web page when the user is browsing. This type of RSs has been successfully implemented in many ecommerce platforms for improving the profit [70]–[72].

The first RS were based on very simple observations of users basic daily activities [68], [73]. For example, if a costumer frequently buys books about a given area, it exists a high probability of acquiring another book related to that area. Meanwhile, those basic approaches have been improved to leverage the quality of those systems. A common method, denominated as collaborative-filtering, considers a group of users from which the system tries to infer what item it can suggest to an active user. The group knowledge is used to implement decision-making process that can determine what can be suggested to a user taking into consideration what other users, with similar interests, like. The systems can filter the content display to only display items that may be of user interest. This aspect is important to improve the user experience. In fact, due to the rapid increase of information, it is fundamental to filter content to avoid bothering users with non-useful data.

Usually the knowledge built into the RSs is interactively improved. Feeding the system with feedback about whereas the users are interested in the recommended item is what does that improvement. The feedback may be obtained from an explicit or an implicit way. The interactive process that built the RS decision-making knowledge usually uses the feedback from actual user to build recommendations for next users.

RS have shown great importance for service providers because it enables them to improve the number of items sold by suggesting similar or complementary products, increasing the user satisfaction, having a better understanding of what the user wants, etc. Moreover, RS can enable selling items that might be hard to sell because they are difficult to find without an explicit recommendation.

Beside ecommerce business, RS can be also effective for other kind of services. For instance, a service provider that offers content distribution, which aim is to increase the number of page views, may also use a RS to increase the amount of contents consumed by the users.

All RS are focused on the satisfaction of user needs, allowing a quickly identification of interesting items. However, to improve the user experience, an RS must be efficient and precise while suggesting items for the user. A major feature that can be found in RS is the capability to allow the service providers to become more aware of client habits. These systems enable obtaining a picture about the users. From that picture, service providers can improve the quality of the service being offered, and fulfil other goals.

Recently, RSs have been also applied to health environment. Some researchers argue that RSs have great potential to improve healthcare informatics, and they have been using this concept in applications like nursing care plan to provide clinical decision support, nursing education, or to complement existent practice guidelines [74]. Furthermore, some RSs algorithms have already been adapted to healthcare in order to make recommendations and suggestions for preventive intervention in healthcare [75].

Social Network (SN) together with RSs, has potential to be an added value to healthcare information systems. In 2012, Song et al. [76] proposed a system that demonstrated how useful the combination of social SN and RS concepts could be to support patients with chronic diseases. These kind of solutions have shown useful to create social link between patients with similar assessment report, and also to assist physicians in their assessment [77], [78].

It is important for any RS to find some good item to recommend. These recommended items are usually ranked per what the RS thinks is the most relevant for the user. According to Herlocker et al. [79] there is a set of features fundamental for any recommendation systems: find some good Items, find all good items, highlight in context, recommend a sequence, recommend a bundle, just browsing, credible recommender, advanced profile, express an opinion, help others, influence others.

For some systems where the RS is critical (e.g. medical applications) or the number of items is small, it seems better to recommend all the important items, ordered by their relevance, instead of a few that the RS thinks to be relevant. The order is frequently useful when the user needs help to identify which items are more important.

Another important feature in a RS is the suggestion of a sequence of items that are somehow related. Sometimes the items are more likely to be bundled together as one item, so a well-implemented RS must be able to identify those cases and create suggestions based on those assumptions. A good example for demonstrating how useful this feature can be, is to apply it on musical tracks recommendation [80], [81]. Moreover, the composition of many items as a bundle is common in travel systems, where items like attraction and destinations services are more important to the user as a whole rather than individual items [82].

The users can provide some important information about what they like or dislike to improve the RS. This information is important to create an advanced profile that describes the user. Using this profile, the RS can improve the system performance when recommending items to the user. RSs usually ask users to leave a rating after acquiring an item. The pair *user – item*, with the corresponding rating, is stored into a utility matrix, which defines how much a user likes an item. Usually, this matrix is very sparse and most entries are unknown. Predicting the values for the unknown rating in the utility matrix, based on information about the known ratings, is a complex task that a RS must solve.

The utility matrix contains key information for the implementation of any RS. It becomes very unlikely to efficiently recommend relevant items to the users without this matrix. However, populating the matrix with enough information is considered as a difficult task to achieve. There are two approaches that one can follow to gather information for populating the utility matrix. One method consists of directly asking the user for rating items. For example, e-commerce Web sites may ask for user rating after an item purchase and, Web sites providing content may ask for user rating after viewing the content. Another approach to obtain data for filling the utility matrix consists of analysing users behaviour to infer if a user is interested in an item. For example, an approach using implicit rating may add 1's (meaning that the user liked the content) to videos that the user has viewed until the end, or to articles that he has read. And, we can find 0's for filling blanks or for items that the user has not shown interest to view or read. The 0's and 1's does not represent ratings in this kind of utility matrix, rather they are used to infer interest from behaviour.

Several techniques may be used to filter and predict the items that could be relevant for the users. These techniques are based on diverse factors: the knowledge gathered and used, the domain and, most important, the recommendation algorithm. Burke has identified some approaches that can be used to implement a recommender systems [67].

2.5.1 Content-based Filtering

A content-based recommender system suggests items that are similar to those that the user liked in the past. It uses item features and the item rating given to generate new recommendations. The rating is used to identify what kind of items the user likes, and this information is important to a profile learner that defines the users' profile. RS applies similarity functions based on items features and user's profile to filter the items that may be of interest to the user. A profile learner can automatically learn the user' profile from user's activity or can be explicitly specified by the user. In Figure 2.4 we depict a high-level architecture of a content-based recommender.

Discovering items features is a challenging task because it is not immediately obvious what are the features that better describe and distinguish the items. However, researches have been conducted to propose computational algorithms that automatically extract descriptive features.

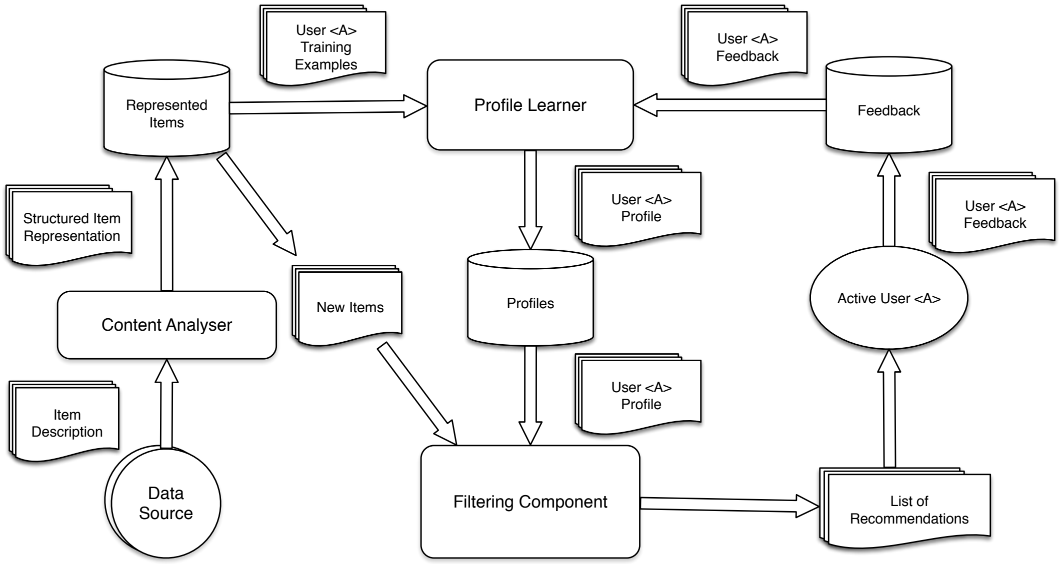

Figure 2.4 High level architecture of a content-based recommender (image adapted from [83])

To recommend documents such as news articles, web pages and books, it is important to identify the document topic. But, the topic is not readily available, and it becomes important to use methods that tries to identify words that characterizes each topic of a document. Text mining methods are used in this task. The term frequency-inverse document frequency (TF-IDF) score is used to find the *n* most relevant words, which are the words that characterize the document topic. In the end, each document is represented by a set of words which expresses the main ideas present in the document. We can find the coefficient of similarity between documents using distance measurements, such as Jaccard distance and cosine distance. The distance between documents is used to find similar documents considering that they share many common keywords.

In complex scenarios, such as of image collections, it is very difficult to automatically extract descriptive features from the data. We can extract features like the amount of red in the picture, key points, and so on, but these features may not be meaningful for a recommender system. Consequently, users are usually asked to introduce some tags to describe the images. These tags can be more important to a recommender system than the features extracted using image analysis tools. Tags can be used as features to describe any kind of data. However, this approach only works if users are willing to tag the items.

Learning user profile using Bayesian models

Profile learner is important to a content-based recommender system because it allows inferring what should be suggested to the user. This task can be defined as a binary classification task where we have a set of training entries labelled as interesting or not (with labels $\mathrm{C} = \{c^{+}, c^{-}\}$) regarding the user preferences. Mainly, the RS has to solve a classification problem where the classifier has to consider what users like (c^+) and dislikes (c^-) based on the items features [84]–[86].

Probabilistic methods are simple approaches that can be used to find the user profile. The Bayesian classifiers, like the Naïve Bayes classifier, define a probabilistic model using previously observed data, and estimates then a *posteriori* probability, P($c|d$), of document d belonging to class c. The probability is calculated based on a *priori* probability, P(c), which is the probability of observing an item with the label c, the probability of item d given class c, P($d|c$), and the probability of observing item d, P(d). With this, we can use the Bayes theorem to calculate P($c|d$) as:

$$\mathrm{P}(\, c|d\,) = \frac{\mathrm{P}(c)\mathrm{P}(\, d|c\,)}{\mathrm{P}(d)}$$

Then to predict the label for a new item d, we use the class with the highest probability using the function:

$$c = argmax_{c_j} \frac{\mathrm{P}(c_j)\mathrm{P}(\, d|\, c_j\,)}{\mathrm{P}(d)}$$

Naïve Bayes classifier performs well in text classification problems as it simplifies the model using the independence assumption, taking into consideration that all words in a document are conditionally independent of each other given the document class [87]. The multivariate Bernoulli event model and the multinomial event model [88] are the most common Naïve Bayes classifier used in text classification problems. These models use a vector space model to represent the corpus vocabulary, V, where each entry represents if a work is present or not in the document regardless the position in the document. The multinomial event model considers the number of occurrences of a word appeared in the document d instead of just using information of whether a word appeared or not in the document, to estimate the probability of belonging to class c. The multinomial event model usually performs better than the multivariate Bernoulli model [88]. Using the multinomial event model, we calculate P($c_j|d_i$) as follows:

$$\mathrm{P}(\, c_j|d_i\,) = \mathrm{P}(c_j) \prod_{w \in V_{d_i}} \mathrm{P}(t_k|\, c_j)^{N(d_i,t_k)}$$

Where, $N(d_i, t_k)$ is the number of occurrences of term t_k in document d_i. Note that, to estimate the probability, the model only considers the words that appear in document d_i, given by $w \in V_{d_i}$, therefore, the product is limited to a subset of the vocabulary.

A key aspect in this kind of model is to infer the value for the probability of a work given a class, $\mathrm{P}(t_k|\, c_j)$. This value is derived from the training data, and it is done via statistical inference using likelihood functions. For example, the maximum likelihood estimates for Naïve Bayes models, with Laplace smoothing to eliminate zeros, is defined as:

$$P(t_k|c_j) = \frac{1 + \sum_{i=0}^{|D|} N(d_i, t_k)\, P(c_j|d_i)}{|V| + \sum_{s=1}^{|V|} \sum_{i=0}^{|D|} N(d_i, t_s) P(c_j|d_i)}$$

Researches have used the Naïve Bayes classifier in content-based recommendation systems with success. The following are some examples of RS using the Naïve Bayes classifier: Syskill & Webert [89], Daily Learner [90], LIBRA [91] and ITR [92].

Using Relevance Feedback and Rocchio's Algorithm to improve user profile learning

Sometimes it is important to immediately update the recommender model to have an improved user profile which leads to better knowledge of what kind of information the user is looking for. To achieve this goal, systems allow refining the RS suggestions using user feedback from to previous recommended items. Rocchio's algorithm [93] is one of the most used relevance feedback algorithm in content-based recommender systems, which works with the vector space model to represent profiles features. The algorithm uses user feedback to refine user profile, and this refinement increase the importance of relevant documents and reduces the significance of non-relevant ones. The Rocchio's method is used to compute the vector $\overrightarrow{c_i} = < \omega_{1i}, \omega_{2i}, \dots, \omega_{|V|i} >$, which depends on user explicit feedback or pseudo-feedback [93]. ω_{ki} is defined as:

$$\omega_{ki} = \beta \cdot \sum_{\{d_j \in POS_i\}} \frac{\omega_{kj}}{|POS_i|} - \gamma \cdot \sum_{\{d_j \in NEG_i\}} \frac{\omega_{kj}}{|NEG_i|}$$

Where, ω_{kj} is the TF-IDF weight of term t_k in document d_j; POS_i is the set of relevant documents in the training set for the class c_i; NEG_i is the set of documents with negative feedback for the class c_i; and β, γ are weights that control the influence of documents with positive feedback and the documents with negative positive feedback, respectively. To estimate if a document d_j belongs to the class c, we compute the similarity between $\overrightarrow{c_i}$ and $\overrightarrow{d_j}$ (for example, using cosine similarity), and assign to document d_j the class c_i with highest similarity score.

Relevance feedback algorithms have been used in content-based recommender systems allowing them to refine suggestion based on user feedback on past activities [94], [95]. These algorithms have evolved following the trends in artificial intelligence and machine learning, and they have been adapted to use deep learning methods [96]–[99].

Other methods to learn user profile

Beside using Bayesian classifiers and Rocchio's algorithm, researches have applied many other machine learning methods to solve the problem of learning user profile in content-based recommender systems.

Nearest Neighbor algorithm [100] is another machine learning algorithm that has been used in content-based recommender systems. The algorithm uses information from training data, labelled with respective class, to classify a new entry which the label is unknown. The new item is compared to all known items using a similarity function. Usually, nearest neighbour algorithm use distance metrics like the Euclidean distance, the Manhattan distance and the cosine similarity, to measure similarity between entries [100]. The distance between a new entry and the known entries is used to determine the nearest neighbour or the *k* nearest neighbours. Label assignment for an unseen item depends on the vote (i.e. label) of the nearest neighbour or the label with the most votes of the *k* nearest neighbours.

There are recommender systems, such as Daily Learner [90] and Quickstep [101], which use the nearest neighbour algorithm to model the user profile and for automatically assigning semantic annotations to documents using an ontology, therefore, building an ontological user profile.

Decision tree learning is another machine learning method which has also been used to model user profile in content-based recommender systems [84]. Attributes that describe users can be used to define the decision tree. The splits are computed based on the user's past ratings and the items features. For example, this algorithm was tested in the Syskill & Webert [84] recommender system.

Decision tree learning performs a recursively partitioning of the training data, learning simple decision rules inferred from the features [102]. A partition is based on the test value of some feature. There are different metrics (e.g. Information Gain, Gini Impurity and Variance Reduction) for choosing the most informative feature which best splits the data at each iteration [103]. Many decision tree algorithms recursively split the data creating a hierarchical tree where the leafs define the item class. This decision trees feature may force a significant number of searches, when compiling a recommendation list for a user. To solve this problem and to allow scaling of a content-based recommendation system, Gershman et. al. proposed an alternative tree where each leaf consists of a set of recommended items [104].

2.5.2 Collaborative Filtering

This kind of systems are centred on what other users like. In its basis, collaborative filtering RS uses information about what similar users liked in the past to decide what would be relevant to recommend for the active user [105]. This technique, known as "people-to-people correlation" [106], is the most used to implement modern RS.

Users rating history is very important to build the user profile. This profile is important to determine which users are similar within the system. For determining similar users, the system has to deal with a problem generally associated with the nearest neighbourhood estimation [69], [107], [108].

2.5.3 Demographic Filtering

The main objective of a demographic-based RS is to provide recommendations based on user demographic information. The demographic information is useful to create different targets with specifics characteristics (e.g. age, country, etc.). The identification of different niches based on users' demographic profile is important to enable the service provider to make different kinds of recommendations for each niche. Also, many researchers have explored this kind of RS, clustering the users in niches wherein they combine the rating to create recommendations [109], [110].

2.5.4 Knowledge-based Filtering

A knowledge-based filtering RS uses explicit knowledge about items classification, user preferences and recommendation conditions to generate suggestions. Usually, this type of system is designed to specific use cases, with a well-defined domain [111], [112]. They are used in scenarios where collaborative filtering and content-based filtering do not perform well. In this system, the relevance of an item is inferred based on explicit knowledge about what to recommend for a given context using decision criteria [113].

2.5.5 Community-based Filtering

Some systems use information about users' inter-connections to leverage the RS. Useful information like, for instance, user friendship and co-workers can be important to determine the user interests [114]. The system tries to take advantage from the fact that the user is more prone to follow recommendations from his friends rather than suggestions from an unknown user [115]. Currently, social networks have become very important and widely explored. In this sense, RS are implemented using community-based filtering fed with information gathered from social relations. This kind of systems is also known as social recommender systems [116].

Some researchers have shown that social network data can be used to successfully improve the recommendations in a RS [117], and that a social recommender system can in some cases outperform traditional RS, which uses profile similarity information [118].

2.5.6 Hybrid Recommender System

Hybrid RS proposes the combination of several RS techniques, aiming to fill gaps present in the isolated techniques. So, the hybrid model explores techniques complementarity to enables the creation of a more complete RS [67]. There are several possible combinations of diverse RS techniques. For example, content-based filtering and collaborative-based filtering can be combined to overcome the issue related with collaborative RS, which has some problems to deal with new items added to the system. Due to new items have less ratings compared with the old ones, they will be less probable to appear as a recommendation. Thus, the content-based filtering technique can be used to improve the decision-making process, by considering the item features in the process.

2.6 Web Technology in Medical Systems

This section will describe the contributions of Web technology in shaping the future of Health informatics. Mainly, it is important to highlight the potentials that Web technology offers to improve e-Health as we know it today, empowering the dissemination of health care worldwide. Moreover, beside promoting health, Web technology are being used to innovate workflows in clinical practices providing agile tools for improving daily activities. The evolution of Web technology has empowered its adoption by health informatics, and nowadays one can observe its application in many areas. For instance, in radiology, this technology has been influential of data sharing solutions and infrastructure interoperability, simplifying the connectivity between different institutions via the Internet.

From the point of view of personal health, one should recognize the worthiness of Web technologies for promoting of health, because the Web is an accessible channel for spreading information. Currently, there are dedicated Web portals disseminating health care information. This kind of initiatives seek to develop self-learning competencies, stimulating the establishment of personal health awareness and an easier adoption of personal health solutions.

2.6.1 Web Technology to Leverage Radiology Informatics

Web technology have been changing the eHealth landscape and has been promoting new software applications such as teleradiology, web-based features for PACS, collaborative diagnostic imaging repositories, cloud-based PACS infrastructures, and mobile applications. Web-based telemedicine solutions have several advantages from which we can point out features like platform-independent, license free solutions (i.e. accessible via free Web browser software), the Internet's access high availability from every-where, any-time and device independent, and capable of developing desktop-like and powerful application using emerging HTML5 capabilities [119].

Teleradiology solutions have been exploiting the Web to create communication channels which allow institutions outsourcing exams revision [120]. The usage of telemedicine solution has been gradually established in many countries including Canada, United Kingdom, USA, and many other European countries. Web-based solutions can solve some of the technical and interoperability problems that have to be handled for supporting cross-border teleradiology solutions [119], [121], [122]. Teleradiology is much about remote medical image visualization, and one can find already some tools designed for the Web [119], [42], [123], [124]. However, there are still main challenges that need to be overpassed such as data access latency, security, and display quality [119]. Remote diagnostic of medical images implies a significant network transmission time, which varies considering images resolution of the medical imaging modalities. To handle access latency in modalities producing high-resolution images, such as digital radiography and mammography, Web-based medical image viewers developers need to carry out more complex decisions such as integration of caching and prefetching mechanisms [125]. The next important issue is data security, which is paramount for any health informatics system. The transmission of sensitive data from local area network, behind health institution firewall, to remote location using the Internet, requires to carry out higher security measures. The implementation of authorization and authentication mechanisms, as also using secure communication channels, for instance through HTTPS protocol, need to be in place [126]. More complex methods using cryptography algorithms can be applied to enhance the security level and to ensure that only who have rightful access to data can decode them [127]. Finally, we have to take into consideration the display quality which is key for medical diagnostic [128]. One concrete example of screen quality impact in the diagnostic performance resides in the detection of masses and micro-calcifications of breast cancer on digital mammography. Researches have stated that 5-megapixels display should be used for this task to obtain optimal performance, and when comparing with 3-megapixels displays there is a degradation in masses and micro-calcifications of breast cancer detection [129], [130].

2.6.2 Promoting Health Through the Web

Each day, the Web is becoming accessible to more and more people, connecting them to an easy way to gather useful information. These changes have also influenced health promotion through solutions which reside on participatory healthcare, patient centric and evidence based [131], [132]. Using the Web to promote health potentially allows a broader intervention coverage [133], [134] because the Web is ubiquitous and it reaches easily more people than traditional clinical centres, including those that are more difficult to reach such as adolescents [135] and ethnic minorities. Moreover, the usage of the Web for health promotion also has other advantages including the capability of developing more interactive and personalized approaches [132], [134]. It may also be a way to develop low cost health intervention using social media-based solution for health information dissemination [136].

Online medical consultation has a significant growth potential [137], [138], since care providers can offered this kind of services worldwide. This is a novel healthcare paradigm which brings new characteristics to remote consultations. Using this service, the users can autonomously seek for consultation online as they do when searching for services or products. Moreover, this healthcare service model is designed for direct patient-doctor consultation, increasing accessibility to health services, reducing the travel and waiting time to get a consultation. The number of online medical consultation services available in the Internet has been growing at a rate of 150% per year, which is a great indicator of its good acceptance by healthcare providers and patients [139].

2.6.3 Social Media Networks for e-Health

Social media networks have the power to increase users' connectivity via the Internet. Social researches have studied the impact of social media in health practices, and they have identified many benefits of social media to leverage health promotion [140]–[142]. These networks promote users' participation and intercommunication health related support programs [143]. Consequently, users' participation in health promotion via social media empowers the generation of patient-centric data because they can share their healthcare experiences increasing the amount of user-generated information shared in the network [144].

Public health programs have used social media as communication platform to reach target people. Social media use for public health programs have shown positive outcomes in health promotion including dietary care, quit smoking and diabetes self-control [140]–[142], [145]–[147].

Social networking plays an important role in the rise of Medicine 2.0 applications where connection between people is modelled to create network of relation which enables collaboration between participants. Eysenbach points out the potential of social media to gather people interest about personal health and health information, and above all, retain the interest overtime [131]. Consequently, exploiting social media in healthcare practices may help to overcome the issues pointed out by Eysenbach in the "Law of Attrition" [148], which says that patients tend to decrease their interest and eventually stop using online health applications after a while.

Specialized social media for health have been developed targeting many purposes and interaction models. For example, some of the most relevant platforms for patient experience exchange are DailyStrength, Tudiabetes, CureTogether and PatientsLikeMe. These social media networks are used to share health experiences, where patient with same illness can exchange information about symptoms and treatments [149], [150]. Social media concept is also used to develop healthcare applications for doctor-doctor interaction, allowing them to share and discuss specific clinical cases. For example, Sermo and Ozmosis are social media platforms used for doctor to share insights about medical cases [151]–[153].

3 Moving Toward Ubiquitous Radiology Systems

" Divide each difficulty into as many parts as is feasible and necessary to resolve it."
René Descartes

The first research question of this thesis was focused on identifying and proposing a computational architecture, for the ubiquitous use of radiology systems. In this chapter, we will start by discussing the main technologies supporting radiology informatics and we will propose novel solutions to streamline the wider use of radiology data. We will focus our work in the medical imaging scenario, which consists of complex workflows and has been quickly evolving by the successive adoption of new technologies.

Medical imaging services has an important role in healthcare centres, and they are nowadays an influential factor for quality of medical diagnostic and patient treatments. Healthcare informatics has been crucial to support innovation in this field. Medical imaging workflows are complex and require specialized equipment, from the image acquisition to the visualization. Additionally, storage and networking infrastructure are needed to handle the huge amounts of data produced in the imaging centers. PACS emerged gradually as a solution to standardize data storage, transmission and management inside a radiology department. Undoubtedly, PACS was revolutionary for medical imaging, and it has been widely adopted since the 90s, simplifying interoperability between distinct equipment and institutions.

Nevertheless, there is still some need for improvement to meet the emerging requirements concerning connectivity and complex workflows for which PACS was not intrinsically designed to handle. The evolution of portable devices computing power is paving the way to new workflows addressing mobility. Thus, raising the concept of universal radiology systems that can be accessed from almost everywhere. Currently, the ubiquitous systems paradigm has been changing the way healthcare are designed. A concrete example is the evolution from electronic health systems (eHealth), supported by traditional desktop solutions, to mobile health systems (mHealth), handled by wireless and mobile communications.

The main purpose of this chapter is to study the current bottlenecks hindering the adoption of universal radiology systems, and to propose an architecture for supporting medical imaging workflow, from anywhere and anytime, allowing the integration of tools like medical imaging viewer, reporting and printing in a radiology platform. The proposed platform includes a DICOM Web viewer that permits visualization and analysis in a common Web browser. This solution enables, for instance, the remote access to an institutional PACS archive using a HTTPS communication channel. Additionally, the implemented platform enables the accessibility to multiple PACS archive under a single view, allowing a seamless interoperability between institutions that share their archives. This solution relays on the standards implemented by medical imaging devices and repositories. The implemented architecture offers several features including clinical reporting workflow, cloud printing functionality, and a flexible deployment model.

3.1 Health Informatics and PACS Evolution

The scientific and technical developments in ICT have successively created greater demands of healthcare services leading to the rise of new multidisciplinary fields such as health informatics, medical informatics, and biomedical informatics. Healthcare informatics, a general classification, deals with several challenges such as interoperability, resources availability, security, privacy, data storage, data management and ubiquitous access [154]–[156]. Also, an increasing number of health applications have been developed, oriented to distinct end-users, from clinical personal up to the citizen. Solutions including patient health records, regional/national healthcare networks and pervasive healthcare, have appeared as an evolution of healthcare informatics.

Networking infrastructure and protocols are fundamental assets to handle specific requirements of medical workflows, such as data access reliability, data protection and quality of service. Ensure a reliable and secure communication between computing nodes is very importing when defining health telematics networks.

Many computer networks protocols have evolved along with the Internet's expansion. At a base level, networking is supported by packet-based communication protocols such as IP, TCP and UDP. These protocols are used to transmit data between computer and most of the network applications rely in one of these protocols. Regarding healthcare telematics, and more specifically telemedicine applications, the transmission of multimedia streams is of great importance to handle institution's workflows and to deliver high quality service to end-users. The evolution of computing and networking resources has led to the emergence of more complex applications which make use all resources available to deliver better services.

The least demanding health telematics applications consist of exchanging small amounts of data such as textual data (for example blood sugar level and blood pressure), but many others require demanding data transmission, therefore, need large bandwidth to send and receive data, like audio and video streams in telemedicine solutions. For these solutions, ADSL and fibre-optics connections provide enough bandwidth to handle the requirements but is also possible to find wireless technologies providing sufficient bandwidth to streaming data. Wireless technologies for communication in networks like 4G and Wi-Fi, among others wireless technologies available, provide suitable bandwidth for supporting healthcare telematics. Indeed, healthcare services have increasingly adopted wireless technology, since it acts as a facilitator to connect health professionals and patients at home or hospitals, and to interconnect ambulances in an emergency where wireless connection is the only possible connectivity choice.

3.1.1 Wireless Healthcare Informatics

Embracing of wireless technology, many R&D initiatives have been using different kinds of computational devices to assists the provisioning of healthcare services. For example, wireless devices like personal digital assistant (PDA), tablet PC, smartphones and workstations on wheels can be used in healthcare institutions to support internal workflows.

Although the majority of devices used in healthcare settings are stationary devices, we are assisting to a solid adoption of wearables and mobile devices [157]. Given the increasing adoption of pervasive healthcare solutions, the number of wireless devices used by patients and healthcare practitioners is also rising. In this path, it becomes fundamental to design wireless infrastructures and new applications to cope with the change of paradigm and to ensure a suitable quality of service.

Wireless sensor networks and wearable devices are other technologies which have been influencing the healthcare informatics. This tendency indicates that in the future, all kind of sensors will be even more integrated and used in daily monitoring; health telematics fits perfectly in this kind of application. The most recent trend arising from wireless sensors network is called Internet of Things (IoT), which has evolved from the widespread adoption and merging of wireless technologies, micro-services, micro-electromechanical systems, and the Internet. In the IoT, an IP address can be assigned to “anything” that generates data that are relevant to collect. For example, it can be a person wearing a smartwatch, an animal with a biochip transponder, an automobile with a set of built-in sensors to transmitting data like tire pressure, speed and objects distance. The IoT has brought the necessary tools to allow gathering data from any kind of machine, which are being explored by many industry fields, such as agriculture, healthcare, energy and transports. The potential of the IoT and wireless sensor technologies is being exploited to improve the usage of specialized medical resources [158]. Nevertheless, although the IoT may bring interesting features to healthcare telematics, one should always consider the pros and cons when selecting the most appropriate technology to use in a given scenario, bearing in mind that in some medical applications it may be impractical to use sensor and wearable devices [159].

Wireless sensor networks also have empowered the creation of intelligent and eco-friendly networks, essential for solutions like “smart” homes [160]. Considering that healthcare is not only concentrated on hospitals and clinics, but is increasingly moving to the patient’s home, one can see wireless sensor networks as a mean to allow the remote monitoring of patients [161]. Moreover, users may have continuous follow-up and automatic emergency warning triggers even outside their home.

3.1.2 PACS and Medical Imaging Services

Several studies have shown the role of PACS and DICOM viewers, and their importance for implementing medical image review workflows [124], [162], [163]. Since the beginning of digital medical imaging era, many electronic platforms were developed to provide visualization and processing tools. Several reports clearly demonstrated the importance of DICOM viewers to support rapid and efficient workflows [164][165]. Radiologists’ daily activities are supported by informatics systems, allowing them to search, retrieve and visualize medical images studies from a PACS archive. In fact, this is not a recent reality. In 1999, Zeman et al. published a paper in which they demonstrated that personal computers could be very useful in teleradiology scenarios [164]. They equipped the computer with inexpensive medical image viewers and accessed to a repository to visualize computed tomography scans. In 2000, Eversman et al. [166] integrated a clinical viewing system into an electronic medical record allowing the integration of PACS images with textual reports. Their clinical viewer provided access to all images available in the PACS, including computed radiography, magnetic resonance images, computed tomography and ultrasounds.

Medical image visualization tools have evolved significantly, and advanced features, like interpretation of multidimensional or multimodality images and 3D reconstruction, are already available in many viewers. As example, Rosset et al. developed the OsiriX DICOM viewer [167] which offers advanced medical images analysis features. Developers of the OsiriX viewer took advantage of powerful 3D graphics capabilities of the OpenGL, which is optimized to explore hardware graphics accelerator, by using frameworks like the VTK and the ITK.

Visualization of medical image is fundamental to radiology workflow. Traditionally, radiology workstations are equipped with specialized medical image viewers for medical exams review. These tools are available at almost every operating system but, they are often platform specific, and sometimes demand complex setups. Moreover, radiologists are limited to use these applications in a given environment, and requiring physical access to workstations where the software are installed [25], [168], [169].

Despite recent advances in web applications for radiology, most of actual professional medical viewers cannot be considered pure Web-based solutions because they depend on plugin that needs to be locally installed before starting using it. Zero-Footprint Viewers (ZFV) are clients that use standard browsers to provide access to medical imaging repositories. These thin clients do not need initial application download, an installation process or administrator privileges to run. Moreover, they are also suitable for mobile imaging environments.

Usually, radiology systems follow a tree-tier architecture, where data layer, logic layer and presentation layer are separated. Considering PACS interoperability, a broker unit [170] is often attached to an application Web-server engine, providing functionalities, such as data access and data format transformation. There is also a need to promote bridging between PACS-DICOM and the Web. On the client-side, operation for medical image visualization and manipulation are usually implemented using HTML and JavaScript [42], [171]. Now, these technologies are evolving and becoming more powerful, bringing some important and useful tools to empower development of web applications.

The usage of web applications, i.e. running on browsers, is quite common in various computerized areas, including in healthcare. These applications are multiplatform, and the user experience is the same in every platform. However, medical imaging is a demanding area, requiring development and management of applications with special communication, decoding and visualization concerns [172]–[175]. Previously developed DICOM viewers did not deal adequately with web scenarios, because they were mainly conceived for enterprise environments. In fact, the repository and client viewers were in the same local area network and the remote access is typically supported by VPN connections. Nowadays, the local access constraint seems to be very restrictive when ubiquitous access to data is becoming increasingly important [31], [175]. Moreover, despite PACS can be deployed in a wide area network, its use has been mostly limited to intranet scenarios due to the huge amount of data that is necessary to transfer, between the archive and the visualization stations, and because these workstations are typically desktop-oriented. Visualization solutions are targeted to specific operating systems, hindering the adoption of ubiquitous healthcare service systems.

Considering the limitations of current radiology applications in web environments, we investigate a solution that uses pure web technologies to assure ubiquitous workflows in medical imaging.

3.2 Architecture of a Universal DICOM Viewer

In the following sections, we propose a software architecture to solve some limitations that have been hindering the ubiquitous access to medical image repositories using Web technologies. The proposed model allows interconnecting distributed repositories, and it offers a solution for remote work through the Internet.

The architecture relies on independent modules, enabling DICOM image viewing, DICOM objects archiving, radiology case reporting, DICOM image printing.

3.2.1 Server-side Module Implementation

The server-side module is a Web server, and it is a "ready-to-use" solution to enable the connection to standard PACSs. Therefore, it allows accessing the data stored in a PACS from a web application.

In the Web server, we implement a PACS connector component which implements the application logic for supplying communication interfaces between the data layer (i.e. the PACS) and the presentation layer (i.e. the Web application). It supports standard DICOM services for querying and retrieving medical images. Moreover, we decide to expose all DICOM-related functionalities through Representational State Transfer (REST) Application Programming Interface (API). Hence, the REST API offers an interface between the PACS/DICOM environment and the Web. Through this REST API, we provide a rich set of features, including search, images download and image annotations.

The Web server was developed using Java, therefore, it can run over a Java Virtual Machine (JVM) in any operation system. We used the Play Framework [176] with a Model-View-Controller (MVC) design pattern, allowing us to decouple the logical components (i.e. the model, the view and the controller).

Many health informatics system tends to create different views for users regarding their role, restricting users' actions including what they can access, download and change [177], [178]. Security requirements attached to health systems can lead to complex solutions with multiple security levels, and this is common when there are several institutions sharing heterogeneous data repositories [179].

We also implemented an access control mechanism in the server-side module to assure users authentication and authorization before accessing the remote PACSs. This module provides transparent access to multiple data sources, using a role-based access control (RBAC) model for restricting access to authorized users regarding their role (i.e. hospital administrator, physician, assistant) - Figure 3.1.

The solution integrates a component that enables data sharing and access via short-link (Figure 3.2). Users need a pin code for a specific link to access the data. A link can give access to a medical report or a medical imaging study. This sharing method can be useful and straightforward in situations where it is hard to establish a shared network between institutions or a federated gateway to remote data access [180].

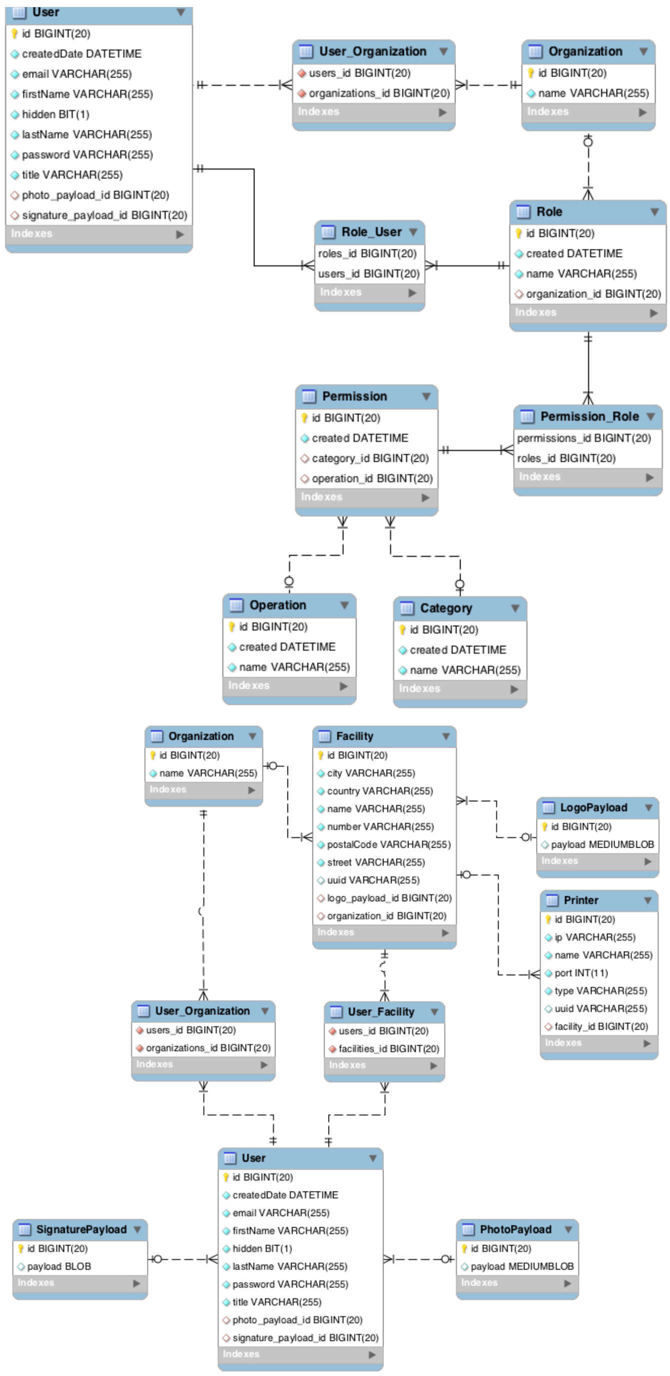

Figure 3.1 RBAC database model.

The exploitation of multimedia content in healthcare has shown potential to contribute to healthcare in many ways, including educational and professional applications. Regarding radiology reporting systems, Balkman et. al. [181] conducted a research to assess if multimedia reports can be an added value to clinical practice, and they found out that multimedia content brings more quality compared with textual reports, being helpful for trainee physicians. A reporting component is also included in our solution, allowing tele-reporting in the Web application. This component enables creating rich reports that support audio, text and film sheet construction. The reports can be exported as PDF and Word format. Figure 3.3 shows the data model used to support this module.

Figure 3.2 Data model to enable study sharing.

We also developed a printing component to support radiology workflow in the Web. It is a standalone cloud-based printing module which enables remote printing service, and it handles multiples modalities and multiple institutions. Film printing is important for the workflow of radiology modalities producing high resolution images. For example, screening mammography programs require distributing images and archiving printed films with the original image resolution. PACS and film printing mostly play together, allowing physicians to send images to DICOM printing devices after medical images acquisition and storage [182]. However, current evolution on radiology informatics indicates that new solutions like remote film printing may leverage radiology workflow, allowing improving communication and report delivery in scenarios with distributed healthcare facilities (e.g. hospitals in rural environments) [183].

In our proposal, we used Dicoogle [184] as the medical image repository. Dicoogle is an open source PACS archive which enables indexing of DICOM objects metadata using Lucene indexing engine, and enables Google-like searching experience. Dicoogle can be extensible via its plugin-based architecture, allowing implementation of specific features not directly supported in its core features. It supports all DICOM services, and there are plugins for QIDO, WADO and STOW services support. Also, it handles many kind of medical images modalities, including CT, MRI, US, XA. The archive has been well-tested and validated, being used to index millions of DICOM files in a regional hospital.

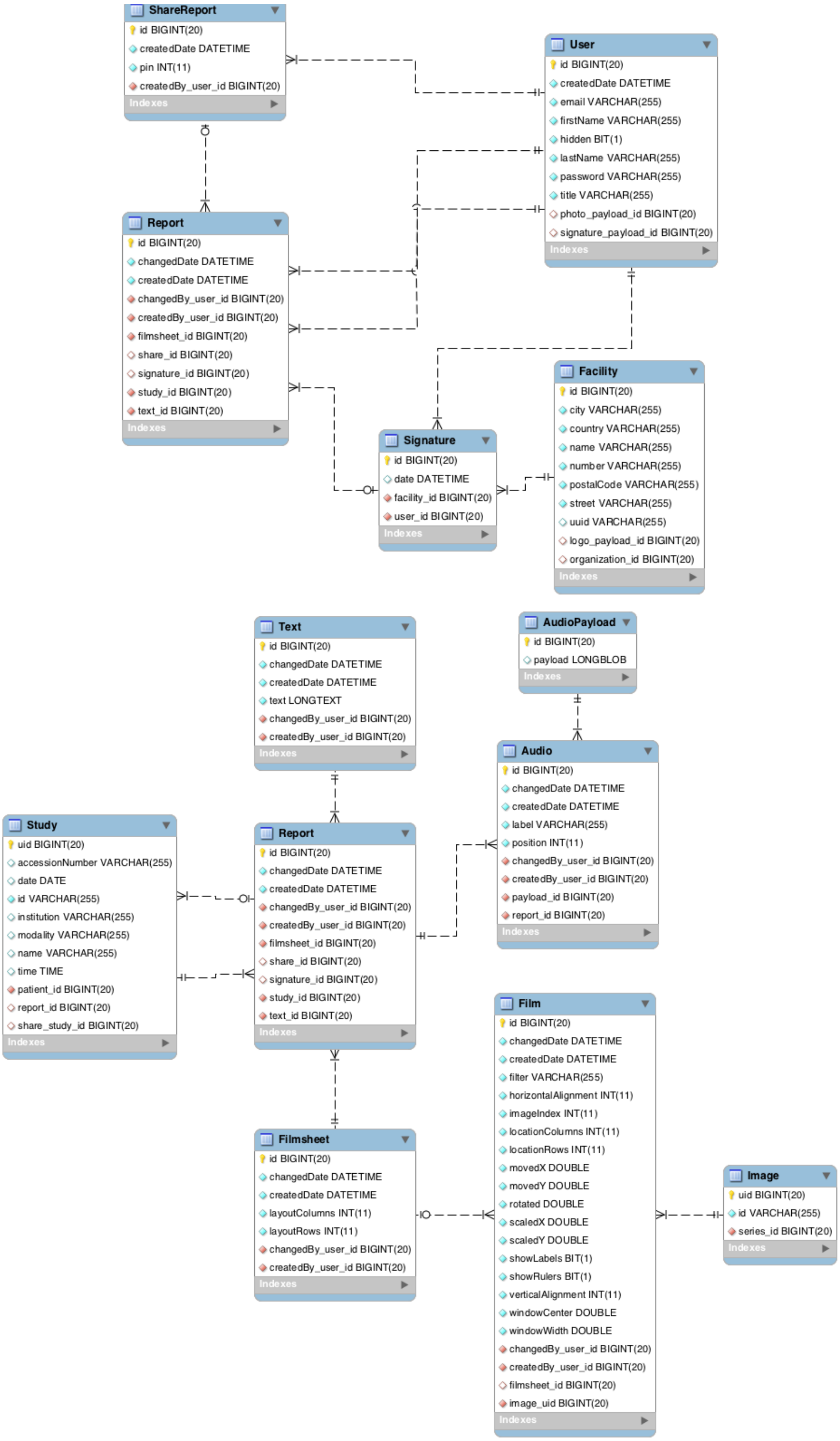

Figure 3.3 Data model implemented for the reporting module.

There also is a bridge module that enables connecting distinct DICOM networks in a single view. This module is fault-tolerant, and provides caching and anonymization of DICOM objects. It offers a REST API accessible through a secure communication channel using HTTPS protocol. Bridging DICOM networks via internet has appeared for a long time as a way to connect remote imaging centres, and to streamline teleradiology using the Internet as vehicle which reduce operating costs by many thousands of dollars [185].

3.2.2 Client-side Module Implementation

The client-side module is a Web application providing features for DICOM image visualization in a Web browser, thus being a solution accessible on any operating system (i.e. Windows, Mac OS X, Linux, Android and IOS) using an HTML5 compliant browser. This medical image viewer can display all kind of DICOM images format, including grey scale, coloured, single-frame and multi-frame. Since Web browsers, by default, only handle standard image formats such as GIF, JPEG and PNG, we had to implement the processes required to handle and display the DICOM image format, without losing image quality. We directly handle DICOM image pixel manipulation using JavaScript code, optimizing the process to obtain the best performance.

Several image processing functions were implemented on the client-side using JavaScript modules. We also used some components and features introduced in the HTML 5 standard specification. For example, the Canvas object was used for rendering the images. This component provides a set of useful function for drawing image, lines and texts, and for supporting directly manipulation of image pixel data. However, instead of directly using the Canvas API, we used the KinecticJS library. The KinecticJS is an HTML5 Canvas JavaScript framework [186], [187] which extends the 2D context of Web applications, enabling the implementation of interactive canvas solutions for desktop and mobile Web applications. Moreover, we used other HTML5 APIs such as Indexed DB [188] and FileSystem API [189] for storing relational information and caching data on the client side, respectively.

Additionally, we decided to execute some specific tasks on the server side. For instance, tasks that required more computing power, such as image compression, are executed on the server side. On the other hand, pixel manipulation runs on the user's Web browser. The server-side features are accessible through the REST API.

The Web application offers an interactive user interface (UI) that supports dynamic content, i.e. data can be asynchronously sent to and received from the Web server without interfering with the UI. Thus, we implemented a data-driven Web application, and we used the HTML and the Cascading Style Sheets (CSS) to provide an attractive UI.

Furthermore, the medical viewer module supports multiple modalities and implements several visualization modes for modality specific workflows, which is important to provide better interaction mode to optimize image visualization, navigation and analysis [190].

3.2.3 Deployment Models

The proposed architecture is modular and provides interoperability with any DICOM PACS. It is possible to arrange the visualization solution in different layouts to better fit to the requirements, providing distinct functionalities (e.g. visualization, reporting and printing). The architecture was designed to face cross-institution challenges, comprising cross requirements for operating and managing of medical imaging workflows. Hence, we identified the following usage scenarios for our medical image viewing service: institution-centric PACS; national/regional PACS; bridging multiple PACS; and embeddable Web viewer.

The institution-centric PACS is the traditional case where we have one PACS serving a specific institution (Figure 3.4). This solution has as target multi-side institutions which are looking to deploy a central archive to store studies from several facilities. This is the most common application for our solution. We can deploy the server in the institution network, i.e. same network as the PACS archive server. In this case, connection between the visualization server and the PACS is direct, and no bridging module is required.

The deploy of an institutional-centric viewing solution has as minimum requirement the viewer module and the archive module. This deployment model is designed to serve customers that have a middle-sized private imaging centre with one or more facilities under the same governance.

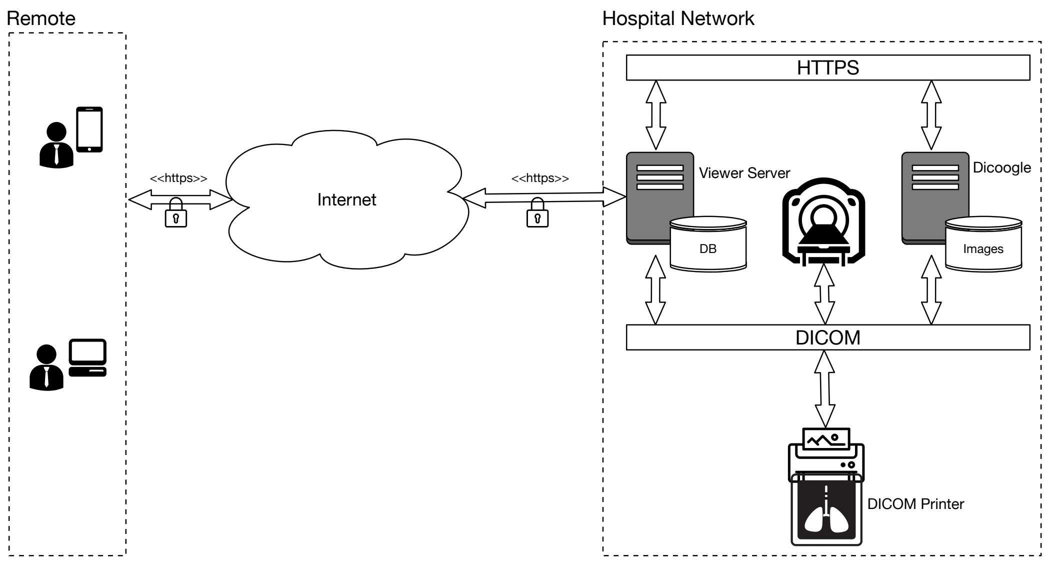

Figure 3.4 Deployment model for institution-centric PACS.

Additionally, as previously pointed out, resources can be shared via shared link to authorized users which can access the archive also outside of the institution, using the Web viewer or using third-party devices via WADO.

On the other hand, our proposal is also applicable when several institutions want to share data through a centralizer PACS (Figure 3.5). This is the scenario of having a regional or national PACS where the viewing server is centralized.

Radiology solutions are in a steady-moving pace from centred solutions toward integrated and inter-institutional solutions. The medical expertise is widely distributed around the patient, and healthcare services are mostly performed by heterogeneous teams of experts. In this sense, a regional/national DICOM viewing solution somehow requires a more complex deployment model, requiring a bridge module in each institution participating in the network. The bridge enables an efficient data sharing, where institutions can access the same archive. A centralized archive promotes a unique point, one PACS and DICOM viewing server, to find and retrieve medical studies, streamlining information access. Traditional cross-organization cooperation may deal with some political and technical bureaucracy (through port sharing or VPNs). Our solution offers a way to simplify patient-centric discovery of medical images and related reports. Nevertheless, it must be deployed in a trustworthy infrastructure to safeguard the confidentiality and integrity of patient's data.

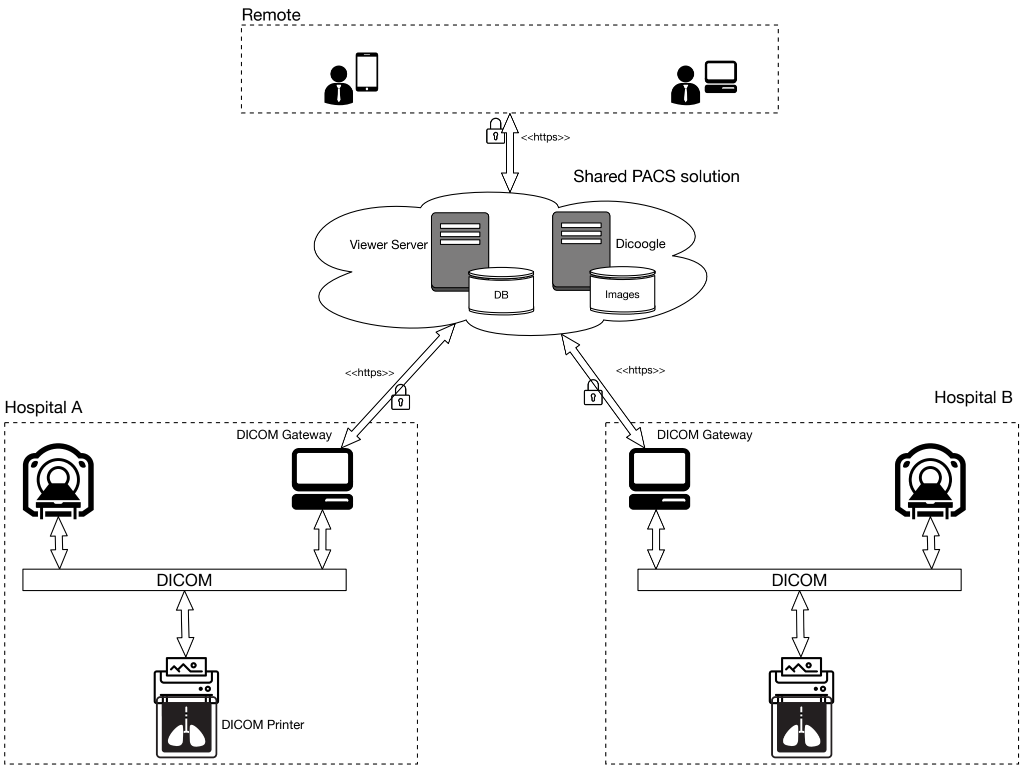

Figure 3.5 Deployment model for a regional/national PACS.

We also propose a bridging module which enables connecting independent PACS in a single view (Figure 3.6). This module is useful to connect distinct radiology network without changing the IT infrastructure, and having a centralized viewing point for image analysis.

Finally, there is the possibility to provide an embeddable DICOM viewer which can be integrated in third-party portals. This solution can be useful in Web portals for collaborative radiology where DICOM image visualization is a useful feature.

In each of these models, we ensure that an adequate access control is defined to cope with data access policies.

3.3 An Efficient Caching Module for DICOM Data in Web Browsers

The increasing adoption of Internet browsers as the new hardware independent "operating system" has potentiated the development of complex distributed systems running over these applications. Software developments based on Web technologies have opened also new possibilities for health information systems application. New application programming interfaces (APIs) proposed in the HTML5 standard bring capabilities needed to develop challenging healthcare solutions to Web environment. Although the HTML5 APIs provide powerful features, there are some challenging problems that software engineers should deal with when implementing such kind of solutions. The access latency is an essential requirement that cannot neglect if we aim at deploying the system in a professional environment. We observed the impact of this requirement when we implemented a Web-based medical image viewer for a mammography screening institution where physicians are used to analyse hundreds of studies per day in a desktop workstation. High amounts of readings per day requires small delays when accessing the studies. Since mammography images are typical of high-resolution, i.e. large volumes of data, it becomes challenging to cope with performance requirements [191].

In this section, we will present a model based on prefetching and caching mechanisms, which we developed, aiming at reducing medical images access latency in Web-based medical image viewers. We explored the new web technologies to build the caching system, and employed a prefetching module to populate the cache using information available in a revision work-list so that studies are downloaded ahead of time.

3.3.1 Caching and Prefetching Solutions

The distribution and regular remote download of data over the Web come with a price on performance, which boosted the research on caching mechanisms, aiming at reducing network bandwidth usage and data access latency.

These issues can be solved by caching the information closed to the clients using local memory and storage. Caching mechanisms also need to implement an index to hold the association between the data and the query. Several solutions keep this index in memory to allow fast responses, but this decision may become unfeasible in some environments due to memory constraints [192]. This limitation has drawn the attention of some researchers to the importance of implementing caching systems with an efficient memory management. Several solutions have been proposed, e.g. solutions combining memory and efficient flash storage to reduce memory footprint [193], [194], solutions based on distributed memory, or saving hashing scheme for reducing memory usage on key-value stores [195], [196].

One can reduce data access latency if able predict which information the user will need to obtain shortly. In this context, prefetching along with caching systems, they play a significant role identifying and storing the data locally. The effectiveness of prefetching systems consists on correctly identify and understand the user behaviour pattern, to build the most efficient prefetching rules.

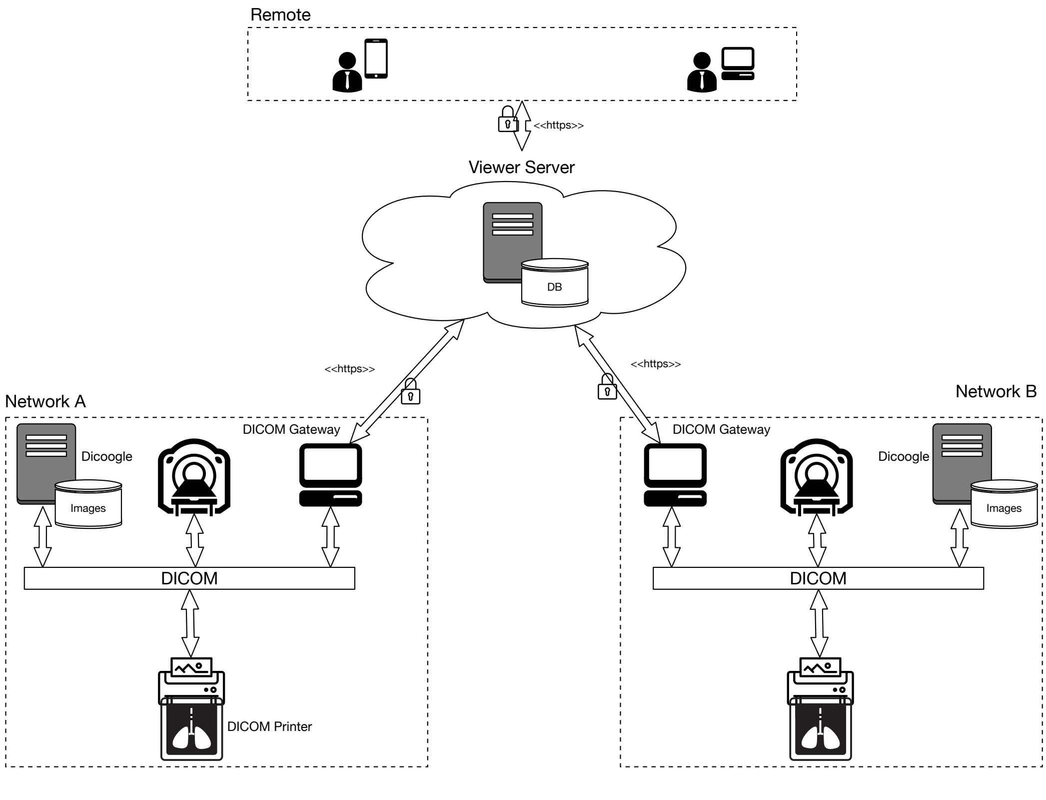

Figure 3.6 Deployment model for connection multiple DICOM networks.

To generate best prefetching rules, researchers have been proposing diverse techniques like dynamic web prefetching that applies rules according to the current bandwidth being in use [197]–[199]. Another method suggested is matrix prefetching, which consists of a matrix of probabilities associated with each item that may be retrieved [200]. The prefetching rules use the probabilities to predict which item is more likely to be accessed, and thus, the most probable elements are pre-fetched, and the system increases their probability if they are indeed accessed (successful prefetching) or decreases otherwise. We can also find other approaches, such as semantic prefetching, which fetches items based on their semantic similarity [201]. More recently, data-mining algorithms have been used to create prefetching models supported by decision-making modules that automatically identify usage patterns in the applications [202]–[205]. Also, some methods use temporal information in the prefetching module implementation [206], [207]. Hwang proposed a prefetching schema for distributed file systems where the users can select the data and schedule the appropriate time to perform the transfer [208]. The experimental results show that this kind of solutions has significant advantages concerning latency reduction and it also increases cache hit ratio. A similar idea was used in our approach, whenever the revision schedule for each examination is known in advance.

3.3.2 Data Prefetching in Medical Imaging

In some PACS implementations it is possible to find cache and prefetching modules to improve radiology workflows, using routines which transfer studies from a PACS and store them in diagnostic imaging workstations. Data prefetching is often limited to well-known patterns, such as filling cache with data from studies in a revision worklist. There are many cases where, for instance, radiologists may find relevant to access prior studies from the same patient. In this case, the PACS could make prefetching of prior studies ahead of time to reduce access latency when users request these studies. The implementation of prefetching algorithms for health information systems is a challenging task due to several factors such as data size and diversity, distinct modalities workflow and radiologists' experience. Several solutions have been proposed to handle these problems, including machine learning techniques [207] and automated learning [209]. Rule-based prefetching approaches can provide excellent performance due to the possibility to create rules which reproduce radiologist's workflow. Wei [210] proposed a decision-rule inductive learning approach where rules were based on three major indicators: temporality, modality, and anatomical side. On the other hand, Bui [211] focused on the problem specificities (e.g. patient within a limited age range or patient that a physician has diagnosed with a specific disease), and proposed a system where users can configure the rules for the prefetching queries. This problem-oriented prefetching module allows the users to define criteria that match a given problem.

3.3.3 Caching Module

Many challenging problems have arisen with the paradigm shift based on Web-based radiology applications, and data access latency is one of the main problems. Our DICOM Web viewing platform aims overcoming the main weaknesses of traditional DICOM viewing tools, namely making remote access to radiological patient images much easier and efficient [31]. However, we needed to build a solid solution for radiological data caching and prefetching for the DICOM Web viewer to ensure data availability and reduced latency.

The proposed caching and prefetching module (Figure 3.7) extends the Viewer REST interface by providing services such as: a) studies in the revision worklist; c) query and filter the prior studies needed for current review; d) retrieve medical images.

To build this module, it was necessary to efficiently implement image's pixel manipulation in JavaScript to ensure rendering performance and to preserve image quality. The rendering process needs information stored in the DICOM metadata to transform the raw DICOM image data into a visible image. The information needed in this process includes image dimension, pixel representation, row and column spacing, photometric interpretation, sample per pixel and the pixel data size. This means that we need to cache this information along with the pixel data to be able to render the image. Moreover, regarding data transmission, instead of transmitting all the data stored in the DICOM files, we transfer only the minimal information that is needed to display the images. The transmission of data is made as byte stream, allowing us to perform GZIP compression [212], which browsers transparently support at the network level.

We store data in the local caching module using the HTML5 *Filesystem* API, and the *IndexedDB* API to keep a mapping of cached images. This local caching module has shown very useful to avoid redundant access to the same file and to reduce data access latency.

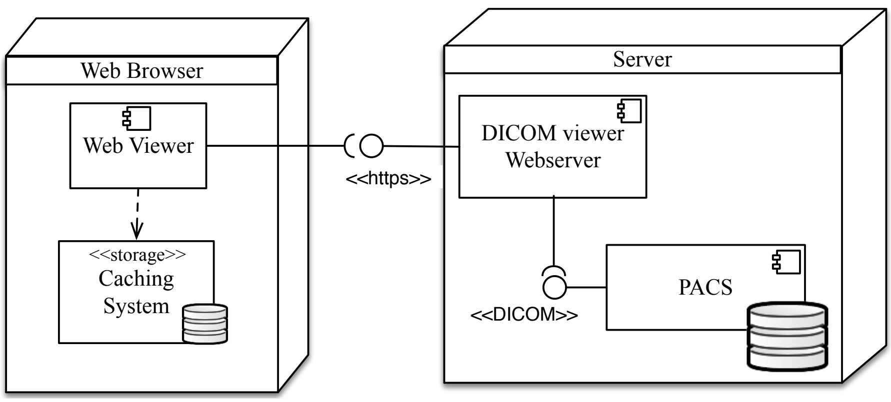

Figure 3.7 Schematic representation of the proposed system.

Furthermore, to improve the performance, we implemented a circular cache where we held in memory the most recently accessed images. If the application needs to obtain an image, and it is in the *Filesystem* cache, the image is pushed into the memory cache and the last used image in the circular cache is pulled out.

The *FileSystem* API allows Web applications to request quota for their own use, which can be unlimited for browser extensions or apps. In our DICOM Web viewer, we used 4GB space due to large size of medical images.

The *IndexedDB* API is another API which we used in the implementation of the caching module. This API allows storing on client-side large amounts of structured data. It also allows storing files and blobs, but browser limits the available capacity. One of the key features of *IndexedDB* is the possibility to make high-performance searches. It provides a transactional database where is possible to store JavaScript objects, which are indexed with a given key allowing the fast access for reading and updating records. In this module, we use the *localForage* library [213] to have an abstraction of low-level functions provided in the *IndexedDB* API.

The caching module was integrated into the DICOM Web viewer providing functions to read and to write information necessary for image rendering. The Web application queries the *IndexedDB* when accessing any examination; if is already cached, the information required for rendering the image is retrieved from the cache; otherwise, is downloaded from the server and subsequently stored in the caching module. By anticipating data transfers of large files, this module has a significant impact on the users' experience, since it reduces significantly the examination access time.

The data schema of the caching module is presented in Figure 3.8. The DICOM standard defines that each study, series, and image should have a unique identifier (UID). We create a hash based on these UIDs which is then used as key when storing image's data in the *IndexedDB*.

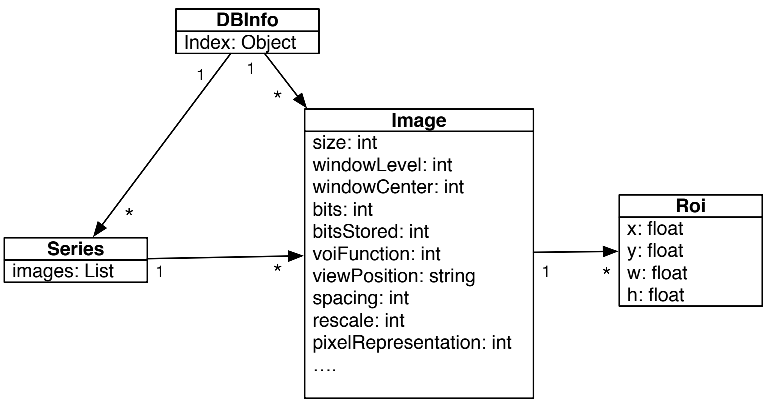

Figure 3.8 Data model organization.

Since a study may contain one or more series and series may contain several images (files) we also had to store the mapping between images and series in the caching information system, so that we can deal with all the files that belong to each series.

Furthermore, with regards to the management of cache usage, we replicate a file allocation table (FAT) to store information about each file, i.e. size and the overall quota currently used by the Web application. This information allowed us to automatically remove old images from the cache after reaching a certain amount of the *Filesystem* usage. Likewise, the application stores quota usage in the *IndexedDB*, and whenever we add a new file or remove a file from the caching system, we update the FAT by incrementing or decrementing, respectively, the quota usage by the file's size in bytes.

Aiming at improving the image browsing performance, we complemented the caching system with an in-memory circular cache which store recently accessed pixel data. This in-memory cache allows reducing disk access for data read and improves browsing performance due to faster access to data stored in RAM memory than reading from disk. Nevertheless, due to resources constraint at client-side, we restrict the number of images stored in the in-memory cache. This number depends on modality type due to variances in files size between modalities. For example, one ultrasound image may need 512 KB in memory while an image generated by digital radiology modality needs more than 8 MB. Therefore, memory usage is always under control with this controlling mechanism allowing us to use devices with reduced memory resources.

3.3.4 Prefetching module

A revision worklist (RWL) is composed of medical exams to be reviewed and reported by physicians. While in some medical specialties, medical images are visualized in acquisition order, others use a revised workflow where schedule is made considering doctors that might be available and priorities. Moreover, in the context of screening programs, such as breast cancer, the revision worklists make a huge difference because they allow balancing and scheduling exams and assign them to different physicians.

When medical exams enter in a PACS, they are scheduled for reviewing and assigned for a particular physician with an expected deadline to be reviewed. After revision, the exam is removed from the revision worklist, unless it needs to be reviewed by another physician. Generally, this module is associated with a RIS (Radiology Information Systems), which provides the capability to retrieve Patient ID and Accession Number of the studies.

To enrich our caching feature, we develop a prefetching module that takes advantage of the information stored in the RWL. This way, the viewer client-side can download the studies ahead and cache them. Besides, this module incorporates features that enable end-users to manually pre-fetch studies by patients' identifier or by acquisition date range.

The prefetching module uses three fundamental services available on the server's REST API (Figure 3.9). The first allows obtaining the studies scheduled to be read, by gathering information stored in the RWL and presenting it in JSON format. The second REST service allows searching for studies by given parameters, for instance by a patient ID or by date range. This service is available via the HTTP POST method, and the parameters are passed in the HTTP POST's body using JSON format. Also, this method returns the results as a list of JSON objects, where each object represents a study. Finally, the third REST service is used to obtain the series of a study. This service is available via HTTP GET method, where the unique study identifier is passed in the URL, and thus, the list of series with links to the DICOM images is returned. Then, the prefetching system accesses the links to download the images' pixel data and all information needed to perform the rendering in the display.

The prefetching starts with the selection of one prefetching mode which identifies how to obtain studies to pre-fetch, and can be from the RWL, from a date range or using patient identifiers. Given the selected mode, the system accesses the respective REST service and obtains a list of studies. After that, the prefetching module uses the REST API for gathering the series of each study. The prefetching module verifies if the application has cached the series on the client side before proceeding to the images download. This way, the module filters the lists of series to download remaining only those not present in the cache, which reduced unnecessary bandwidth usage. Next, the module moves to the downloading function and retrieves all images belonging to the series. The download task uses the caching system to store pixel data in the file system and additional information in the *IndexedDB*. Regarding this dependency, the caching system is fundamental in our proposed architecture, and it ensures the proper functioning of the prefetching module.

Additionally, to keep the file system usage under control, we must remove from the caching system studies which physicians have already reviewed. The RWL plays a significant role in addressing this problem because studies are removed from the RWL after being read out. A specific procedure is executed when prefetching studies from the RWL, to find out studies in the caching system which are not scheduled for review and removes them.

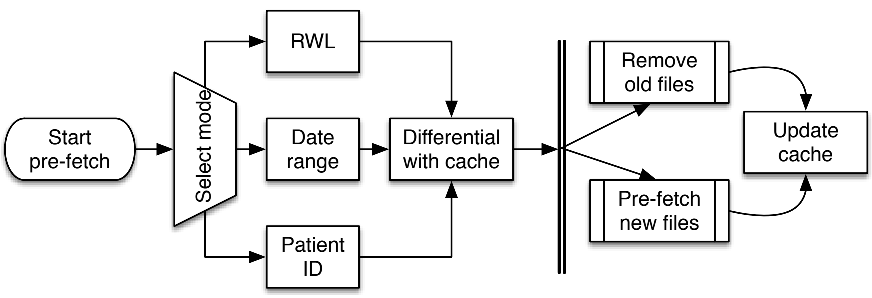

Figure 3.9 Flow chart of the prefetching process.

3.3.5 Evaluation

We tested the proposed solution in a clinical scenario, where it was used by radiologists for mammography screening. In this use case, physicians usually need to compare current exam with prior studies of the same patient. This implies that when prefetching a study for reading out, the system needs also to pre-fetch prior studies of the same patient. This rule can also be adapted to specific modality, and allowing us to define which modalities should be pre-fetched. In this setting, optimization tests showed that prefetching of ultrasound does not introduce many benefits when considering the trade-off between local storage usage and accessing files via network. The tests carried out to arrive to this decision can be found in Table 3.1.

The system manages automatically prefetching of studies using the RWL mode. Moreover, one can schedule automatic task in workstations to start the prefetching at a time.

To evaluate the impact of our caching and prefetching solution in the DICOM Web viewer we used a dataset composed of 100 studies, 84 MG (Mammography) and 16 US (Ultrasound). We indexed the dataset in the PACS, which was deployed along with the Web server in a virtual machine with 32 GB of RAM and with 4 Intel(R) Xeon(R) CPU cores at 2.67GHz. The tests were performed using a workstation with OS X Yosemite, 8 GB of RAM, CPU Intel i5 at 2.5 GHz and 128 GB solid-state disk. The connection between the workstation and the server was established through a 100 Mbps network.

In the first batch of tests, we evaluated how much is the impact of the caching module regarding studies' access latency. Therefore, we cached studies of the two different modalities and then we compared the time necessary to load a cached study with the time needed to load it from the network. Table 3.2 shows how much improvement we had for each modality. We used the following function to quantify the percentage of change in the access time:

$$f(access_{cache}, access_{network}) = \frac{access_{cache} - access_{network}}{access_{network}} \times 100$$

As we can observe in the results reported in Table 3.2, with respect to 10 different studies, we obtained on average an improvement of 82.93% when comparing the time needed to open an examination via the network and the time required to access it from the cache. This enhancement has a significant impact on the radiology centre workflow.

On average, each physician reads out 400 studies by day. If we consider that he/she takes approximately 3.5 seconds just to open a study, and it can be reduced to approximately 0.5 seconds when cached, we saved approximately 20 minutes from the time needed to review all the 400 studies. Consequently, it became possible to increase the number of studies read per day and improve radiology centre efficiency.

Table 3.1 Network access time by modality.

Modality	# of images	Average file size (KB)	Average download time (ms)
DR	10	7190 ± 291	3476 ± 2643
CR	46	2049 ± 1042	1420 ± 1200
US	28	106 ± 47	204 ± 270

Table 3.2 Data access performance analysis in the Web DICOM viewer.
Comparison between accesses from the cache after the prefetching versus access via the network.

Study	Cache allocation (MB)	Access time via network (ms)	Access time from cache (ms)	Change (%)
1	60.837	4998 ± 152	540 ± 24	- 89.13 ± 0.01
2	32	2157 ± 145	443 ± 31	- 80.12 ± 0.01
3	40	2482 ± 164	600 ± 21	- 76.08 ± 0.02
4	32	2258 ± 182	481± 18	- 78.49 ± 0.02
5	57.185	4453 ± 171	467 ± 15	- 89.56 ± 0.01
6	57.58	3811 ± 183	574 ± 29	- 85.31 ± 0.01
7	33.975	2828 ± 129	492 ± 12	- 82.36 ± 0.01
8	57.58	2923 ± 131	560 ± 16	- 80.66 ± 0.01
9	32.185	2600 ± 173	531 ±23	- 79.35 ± 0.02
10	68.185	6390 ± 134	758 ± 33	- 88.30 ± 0.01

We also evaluated the prefetching module performance by measure the time needed to pre-fetch 236 series present in the RWL. As a result, we observed that it takes almost 15 minutes to pre-fetch all the series, storing a total of 3 GB of data on the client side. As expected, for a considerable amount of pre-fetched studies, one would need more file system quota to cache all the information. If the application reaches the maximum quota available, the caching module removes older studies from the cache. This space can be adjusted in accordance with users' needs and average amount of studies in the RWL.

Medical imaging systems are demanding scenarios to explore the full power of web technologies. In this research, we presented a novel solution to enhance user experience in a Web-based DICOM viewer. We developed a caching and prefetching module supported by the *FileSystem* and *IndexedDB* APIs. Moreover, we also used of a revision worklist to support the prefetching module which was crucial to the module performance and system operation. An important conclusion comes out from its use in a real case scenario – the module significantly improved the revision workflow and increased the productivity of the radiology centre.

3.4 Collaborative Medical Image Visualization

The evolution of the health informatics in radiology departments has been strongly driven by the capability to interactively display electronic patient records including DICOM images. Novel PACS architectures are currently being proposed to comprise Internet-based collaborative applications for medical imaging visualization. With this, researchers have developed Web-based systems to interactively manipulate and display medical images, integrating multimedia data and remote control in interactive and collaborative applications for medical image viewing [214], [215].

These Internet based solutions for medical image viewing enable establishing collaboration between geographically distributed medical professionals, allowing the exchange of electronical medical records for collaborative analysis of medical studies. The use of online collaborative applications in radiology can be very broad including the medicine practices such as the teleradiology, and the teaching of radiology. For example, local and remote doctors can collaboratively discuss medical studies in telemedicine sessions. Also, collaborative medical applications often are used to establish interactive learning channels between radiology students and medical experts through Intranet or Internet [216].

Collaborative medical systems may provide support for video, audio, message communication and distributed medical data exchange to enhance collaboration environment, simulating a face-to-face contact between them and their colleagues during meetings for clinical cases discussing [217]. Moreover, tools like bidirectional remote control and multi-pointer are important to provide an interactive experience during collaborative medical imaging consultation sessions [218]. These tools allow multiple users to manipulate the images and to synchronizing actions in a session by capturing mouse and keyboard commands from a remote user, enabling the control of the viewing session.

The establishment of collaborative sessions in radiology face several challenges. For example, data transmission may hinder the establishment of collaborative consultation in cases dealing with high-resolution images. Also, it may be challenging to create a collaborative channel that guarantee the data exchange between physicians using different institutions' IT solutions without modifying the existent infrastructure.

3.4.1 Platform for Medical Images Analysis

After developing a solution for medical image visualization in the Web, we decided to make the solution more open and oriented to multi-user collaboration. Thus, we designed an architecture (Figure 3.10) for collaborative medical images visualization, supporting multiple users in a session. The users have a private area to which they can upload files for starting a collaborative viewing session with the others. In the backend, we used the Dicoogle PACS for storing the medical images.

By default, Dicoogle cannot handle private user areas because it was designed to be used as an institutional medical image repository. However, the Dicoogle is an extensible PACS, and we extended it to meet our requirements making the best use of its plugin-based architecture. We implemented a search and a storage plugin to support multiple virtual private area. The plugins implementation is described in section 3.4.3.

We also decided to decouple the user authentication and authorization from our Web viewer server using a dedicated authentication server – Keycloak. The Keycloak implements several useful and advanced features including user federation, social login and identity brokering. The user federation feature allows connecting the Keycloak authentication server to existing user directories using the Lightweight Directory Access Protocol (LDAP) or the Active Directory (AD). Moreover, we found useful to enable social login in our Keycloak server because the users can use their social login (e.g. Facebook account) to connect to our platform, without having to register new authentication credentials to access our service.

In the Web viewer server, we implemented some important modules to support the application logic. The module that enables the communication and the management of the virtual private areas is named as *Dicoogle Micro Archive Manager*. It implements the functionalities which allows uploading files to a private area in the Dicoogle PACS, and provides the functionalities to query and to retrieve files from a virtual private area. The communication between the component and the Dicoogle PACS is through Web APIs (i.e. STOW and QIDO) using a secure communication channel.

Also, we support an OAuth 2.0 provider to connect our Web server to the Keycloak authentication server. The *Keycloak OAuth* module has functionalities, such as authentication token management, user login and session management, that allow the integration with the authentication server. Moreover, resources access control is done by integrating the authentication module with the *Dicoogle Micro Archive Manager*, which uses this information to identify the data owner when uploading data to a virtual private area. Also, user identification is used to restrict the queries and data access to the owner only, unless the data are being shared in a collaborative session.

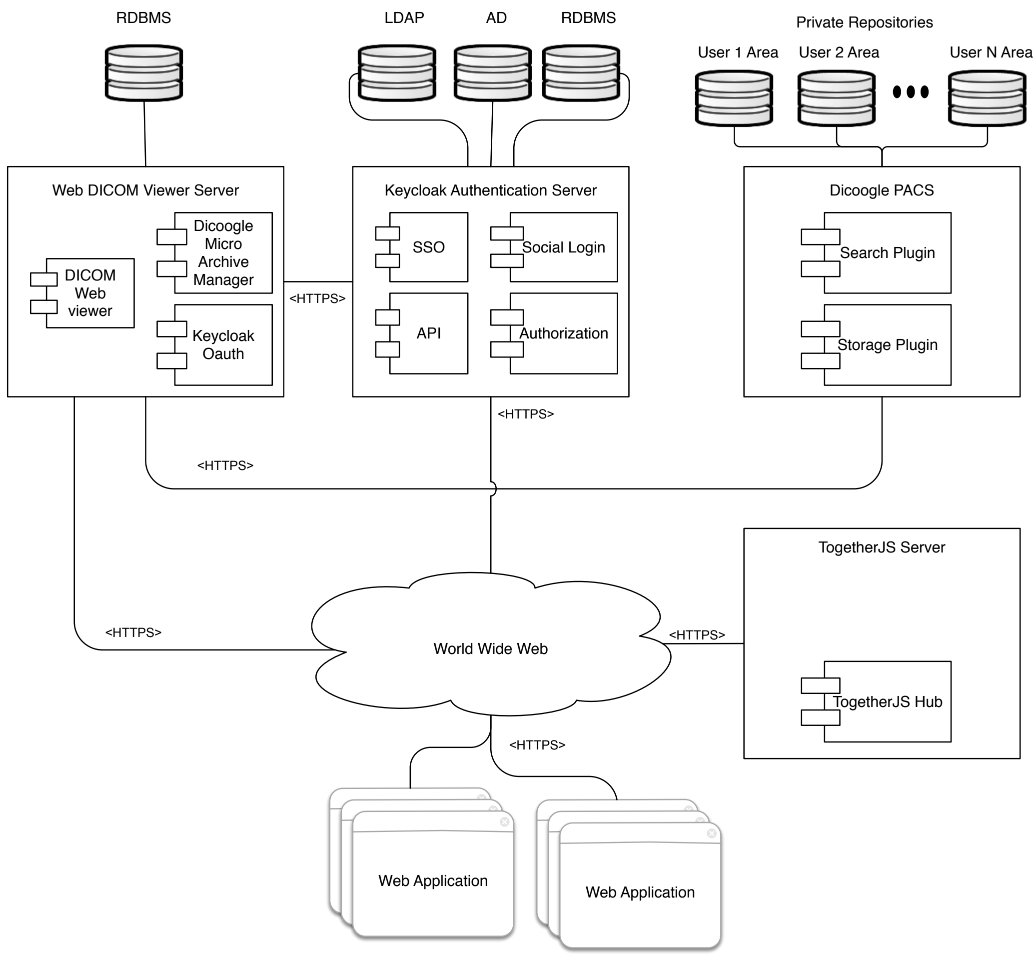

Figure 3.10 Architecture for an open collaborative viewing platform.

Another component is used to provide the required features for medical images visualization. This component is called *DICOM Web viewer*, and it provides the Web interface to access and visualize the medical studies. Moreover, it is the front-end to access our platform. The user access this Web interface to upload files, to search studies in their private area and to start a collaborative session. A viewing session can be established with other users already registered in the platform and with unregistered users via a short-link with PIN authentication. Besides the session establishment, this component also provides session synchronization and multimedia streaming between Web clients. The session synchronization is implemented using the TogetherJS server hub. Every client connects to this hub when joining a collaborative viewing session. This server only acts as a relay in the cloud that allows the exchange of synchronization messages between clients. Moreover, the server only echoes messages using Web sockets to every client participating in a session, therefore, without manipulating any message.

3.4.2 Users Registration and Management

The Keycloak authentication server was deployed in a Docker [219] container as a standalone identity management platform. This server was used to authenticate users, where they can choose to their social login or register new credentials.

We created a realm for our visualization platform, and configured a trusted Web application that can request a user login. The client was configured to use the OpenID Connect protocol [220] on top of OAuth 2.0 [221]. Therefore, Keycloak authorization server allows the verification of the end-user identity, and to obtain their profile information (i.e. user name, email and avatar) through a REST API. This profile contains settings for the specific user, including the user name that will be displayed, user's picture, signature, and visualization settings (e.g. automatically enable auto-hiding tools and menus, where to display tools and menus and other viewing settings).

3.4.3 Virtual Private Area Implementation: Micro PACS

The core storage and indexer/search plugins available in the Dicoogle PACS were designed to avoid data replication in the repository. It follows the DICOM information hierarchy (Figure 2.1), which is defined by a data model with four levels. In the first level, we have the patient that may contain, at the second level, one or more studies, performed at different times. The third level contains one or several series of each study, and each series has one or more instances (images) – the fourth level. Therefore, when storing a study in the repository, the storage plugins checks if a leaf (instance/image) already exists in this hierarchical tree structure and do not store it again. This behaviour does not meet our requirements because it was designed to support a central institutional repository and does not handle the scenario of virtual private areas.

Instead of an institutional-oriented central PACS, we were interested in a user-oriented micro-PACS. The main idea was that each user could have his private PACS where he can store and query medical studies. Therefore, we had to add an extra layer to the DICOM information hierarchy as depicted in Figure 3.11.

This new layer is composed of data owners. A data owner has one or several patients in the underneath layers. This feature avoids leaf replication in the hierarchical tree structure, and in this case the path to a leaf is defined by the following DICOM tags: Owner ID → Patient ID → Study UID → Series UID → SOP instance UID. The storage organization of the repository follows this hierarchy, where each node in this tree is a folder and the leaf are the DICOM files.

With this modification, we can have the same patient, study, series and image stored in different private areas, defined by the Owner ID.

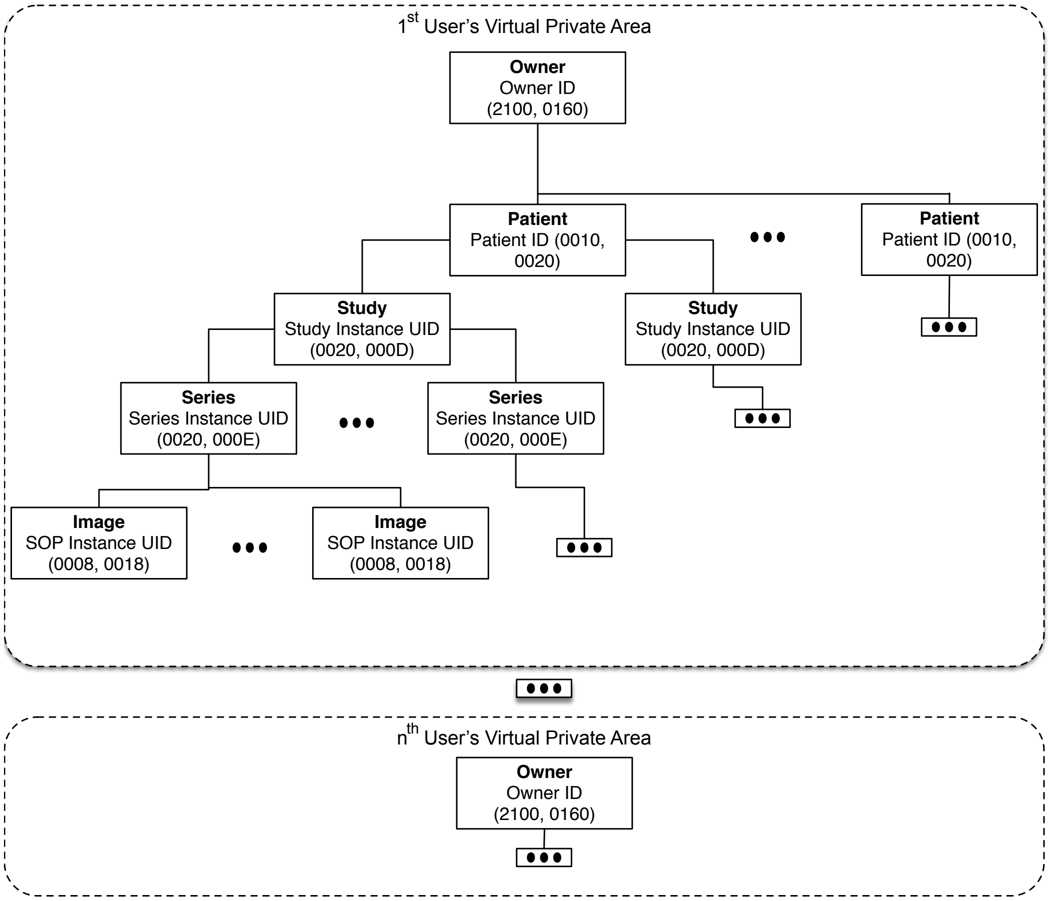

Figure 3.11 Storage hierarchy: Owner ID as root element of a virtual private area.

This means that to upload a study to users' private area the *Dicoogle Micro Archive Manager* component should add the DICOM Owner ID tag with the value used to identify each user. In this case, we used the user's email address that is provided by the Keycloak authentication server after the user authentication.

Additionally, to create the abstraction that supports the virtual micro-PACS concept we had to change the Dicoogle query filter to consider the Owner ID tag. The *Dicoogle Micro Archive Manager* has also to add the Owner ID tag to every query sent to the Dicoogle PACS to restrict the results to the data stored in the logged user's private micro-PACS.

3.4.4 Micro PACS Archive Management

The *Micro PACS Archive Management* is the component that provides the communication interface with the Dicoogle PACS. The Dicoogle PACS expose a REST interface implementing STOW and QIDO functionalities. In this sense, the component uses the REST API to interact with the PACS server.

The archive manager allows storing, querying and retrieving of medical studies under the abstraction of a virtual private micro-PACS. This component uses the end-user identity information to select to which private area the actions should be sent. Figure 3.12 shows two views from different users after searching for all studies stored in their archive. The storage flow and the search flow are depicted in the following sequence diagrams (Figure 3.13 and Figure 3.14). In the upload flow, the *Micro PACS Archive Manager* adds to each DICOM file the Owner ID tag. Regarding the queries and the retrieval of medical studies, every action is also filtered using the Owner ID tag. Therefore, regardless of the action that is performed at each level, this extra parameter restricts the actions performed by each user.

3.4.5 Establishing Collaborative Visualization Sessions

A user can start a collaborative session with other participants to analyse DICOM studies stored in his virtual private area. By default, the access to studies stored in other user private area is denied, unless the owner explicitly grant access via a sharing action. Figure 3.15 depicts the control flow for data accessing that was implemented. A sharing action generates a short-link and a PIN code which can be used by external collaborators to access the study. Therefore, the study becomes available for visualization both for the registered users and unregistered users.

Simple sharing of a study is enough to create an asynchronous collaboration between participants, because they can access the study in different periods to analyse, annotate and write a study report. The platform allows users to easily distribute the access link and PIN code to the participants through email notification. The sharing can be disable at any time the by the study owner, and he becomes again the only one allowed to visualize the study.

Moreover, after sharing a study, the user can also create a synchronous collaboration session with multiple participants, where they observe the same layout with synchronization of the participants' views and actions and videoconference (Figure 3.16).

A session is created by spawning a TogetherJS session bound to a study's uniform resource identifier (URI). TogetherJS generates a URL which is shared with the participants to join the collaborative viewing session. We used TogetherJS because it provides tools to easily add real-time collaboration features and tools to a Web application. For example, it is possible to add features including interactive pointers, text chat, audio chats using Web RTC technology for enriched communication between users, and features for real-time content synchronization.

3.4.6 Multimedia and Action synchronization

The DICOM Web viewer implements synchronization of actions, so that all users can see content changes at the same time. This feature is important to leverage real-time collaboration between users because it provides a more interactive experience, allowing users to observe others and interact in real-time when analysing a medical study.

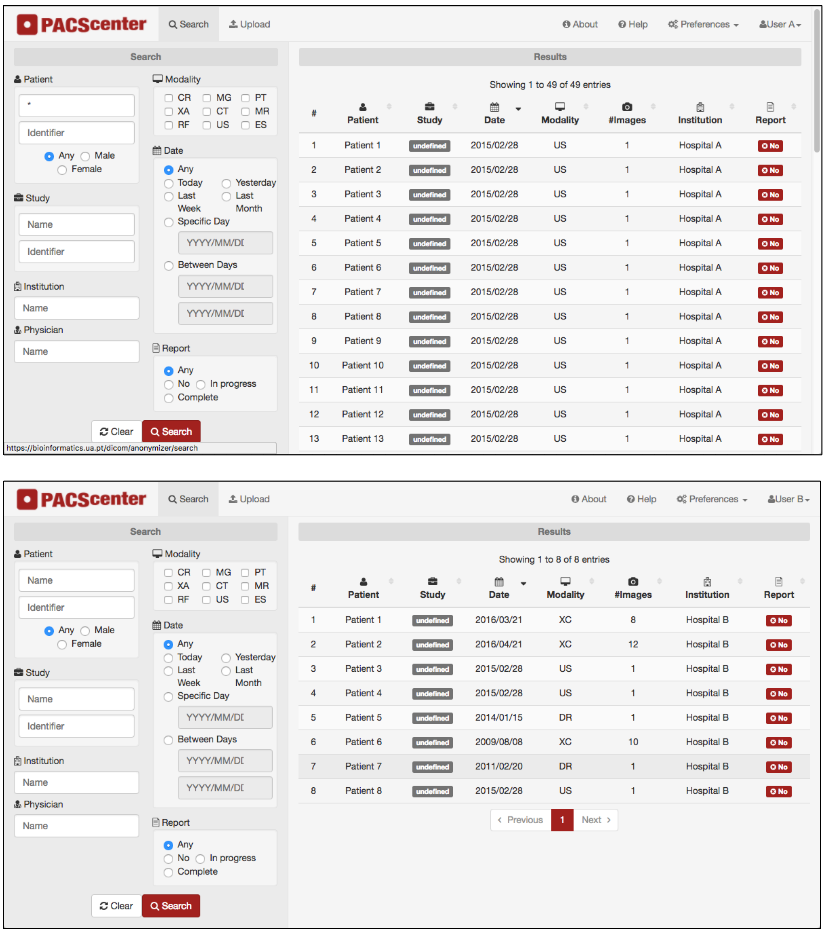

Figure 3.12 Users' virtual area.

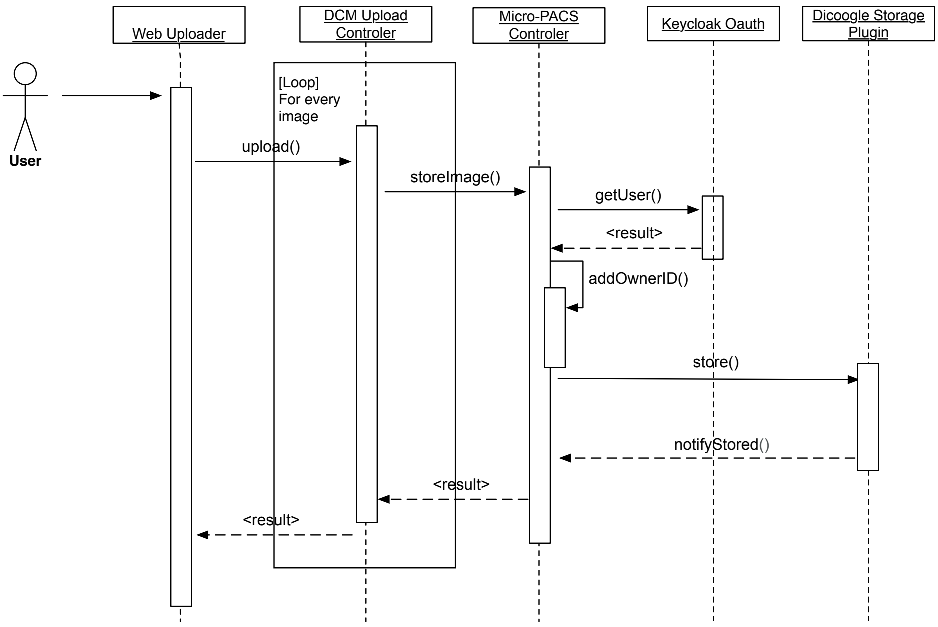

Figure 3.13 Micro PACS – data upload workflow.

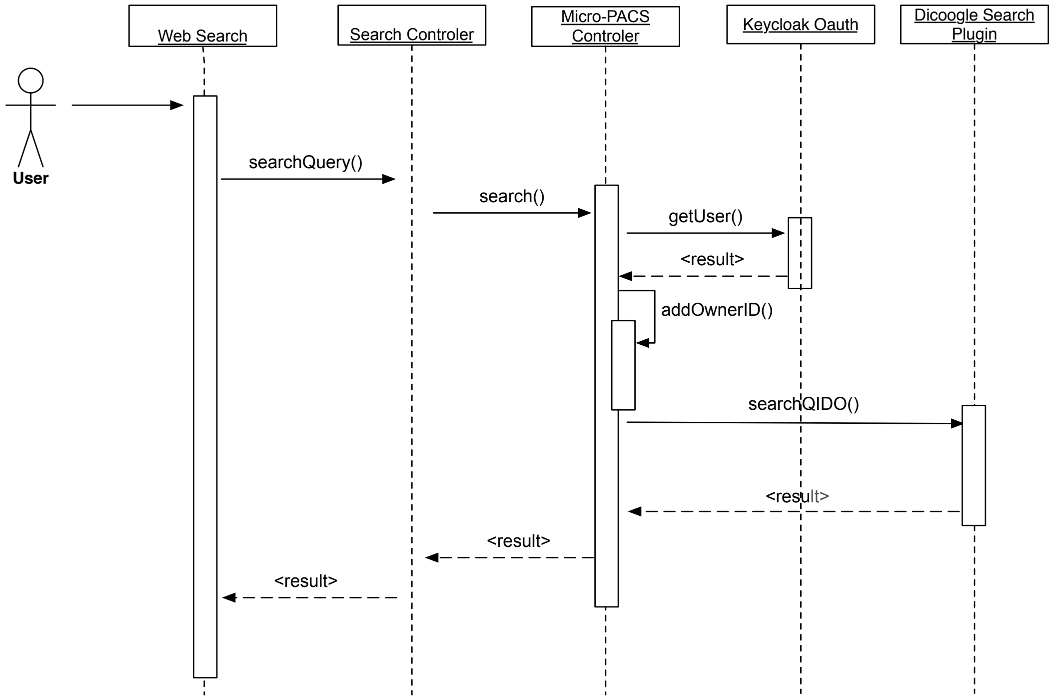

Figure 3.14 Micro PACS – search workflow.

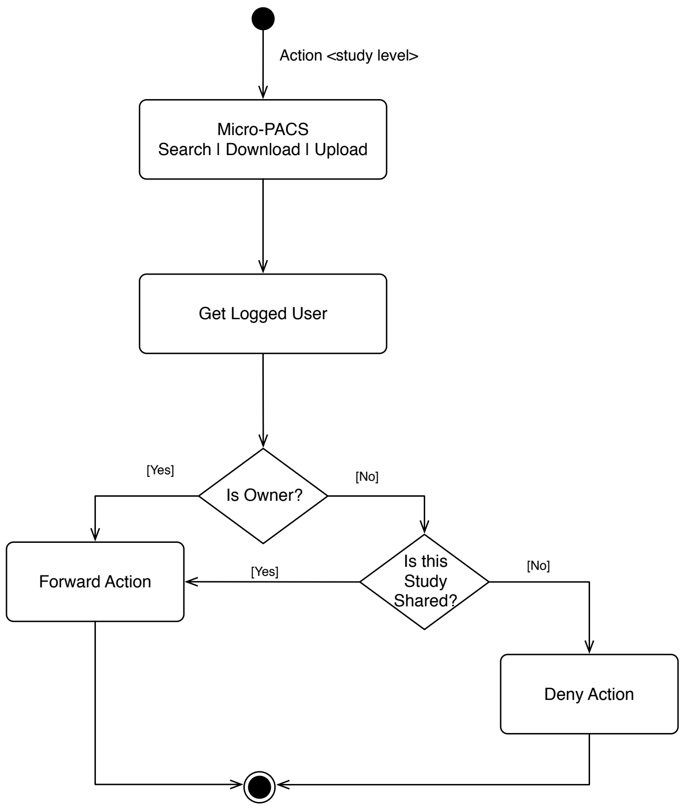

Figure 3.15 Micro PACS – resources access control.

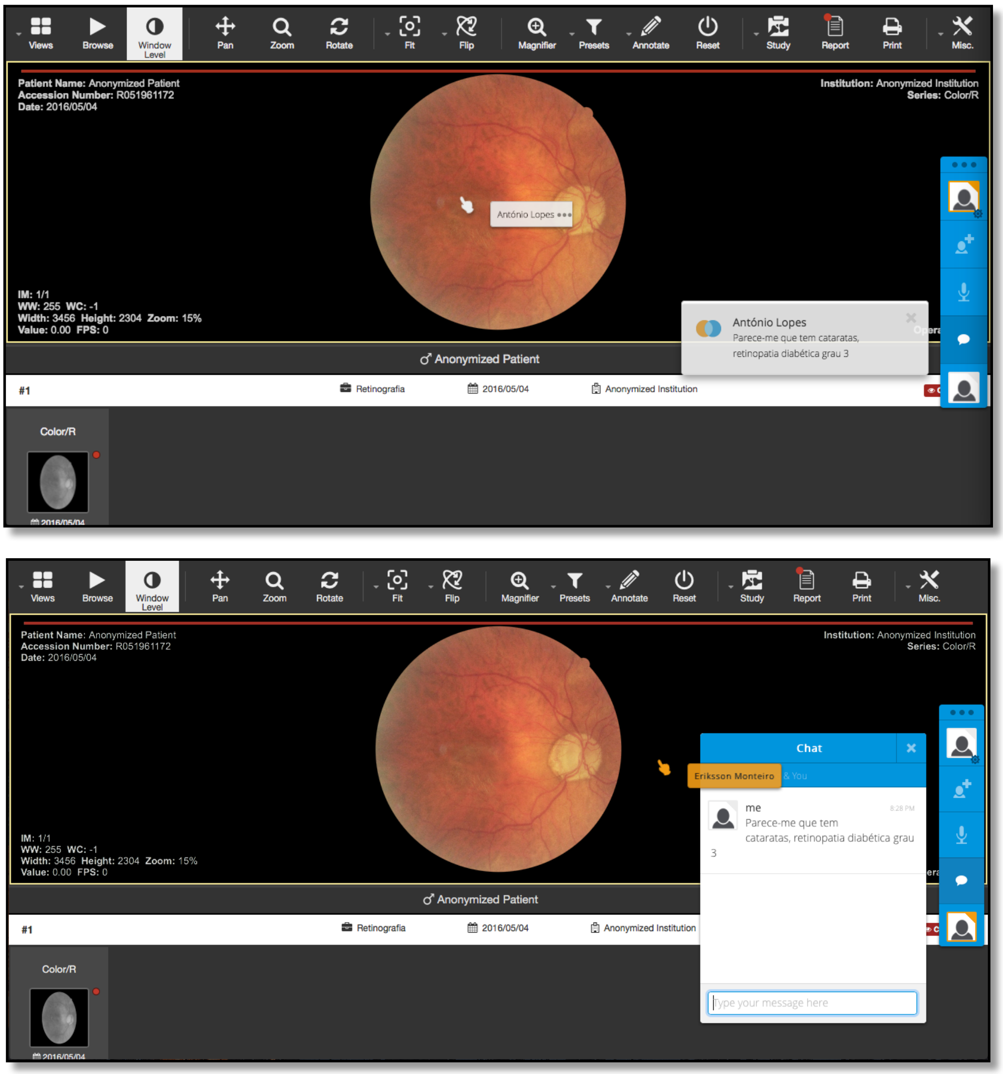

Figure 3.16 A collaborative viewing session with two participants.

We used an instance of the TogetherJS server to enable real-time content and actions synchronization using Web sockets. The communication hub allows the implementation of the publish-subscribe pattern for synchronizing action between views (Figure 3.17). All users joining a collaborative viewing session register in a room created for the session to receive update messages.

Every user in the room is also a publisher. Therefore, every client can change the current state of the view. For example, they can change the view layout, change current images being displayed and add annotations to the images.

Every action which change the session view is published in the room to synchronize other users' viewing state. The usage of a publish-subscribe pattern is known to be advantageous for system scalability compared with traditional client-server model. Using the publish-subscribe pattern allows us to easily broadcast update message to other participants without the need to explicitly know the subscribers.

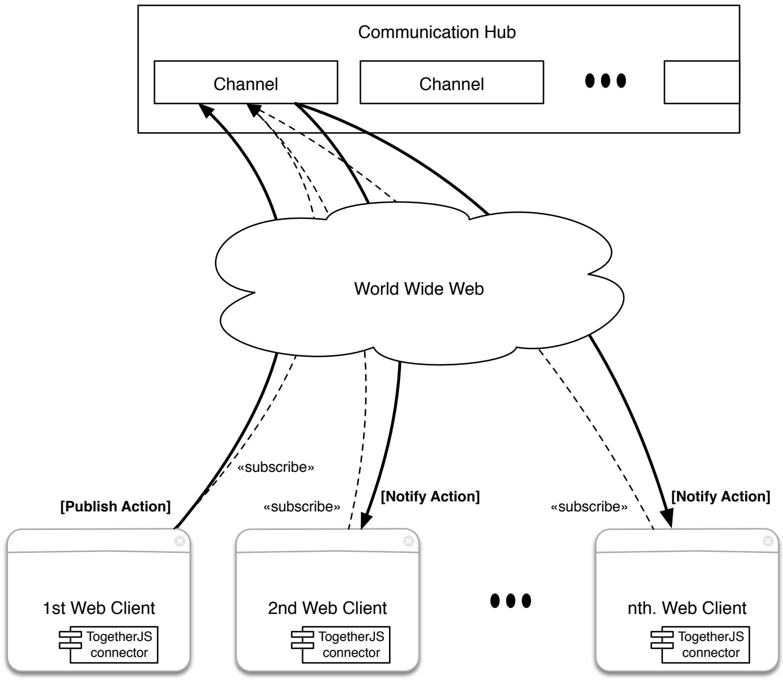

Figure 3.17 Communication channel subscription to synchronize actions and views.

Additionally, this messaging pattern allowed us to reduce the complexity of the synchronization method. We wrap the actions that change the viewing state in a TogetherJS event which is broadcasted to the other participants to describe the change that occurred in the viewing state. This broadcast process is described in Figure 3.18.

The publish-subscribe pattern can show some problems inherent from decoupling the publisher from the subscribers. Therefore, the publishers are not aware of current subscribers and this means that they cannot guarantee that the subscribers will receive every synchronization message. As consequence, this problem could have a negative impact in a system using publish-subscribe pattern to synchronize clients. It requires robust synchronization processes to ensure that all clients are synchronized and visualizing the same content. In this sense, we implemented a module that is responsible to keep every client synchronized. The module maintains the current viewing state updated by pooling the session creator to synchronize the view if not at the correct state. With this, all the participants will have their viewing state synchronized with the session creator. The synchronization flow is depicted in the following diagram (Figure 3.19), where we can observe that only the session creator replies to pooling events with the viewing state to which the other participants should be at.

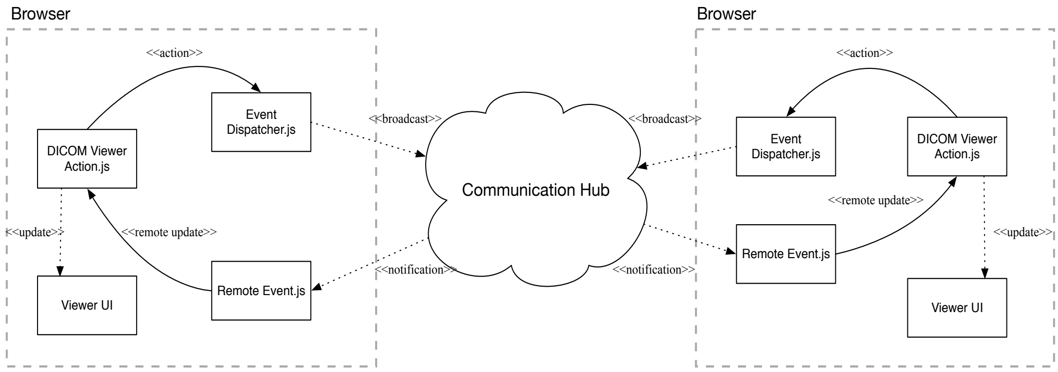

Figure 3.18 Action broadcasting in session synchronization process.

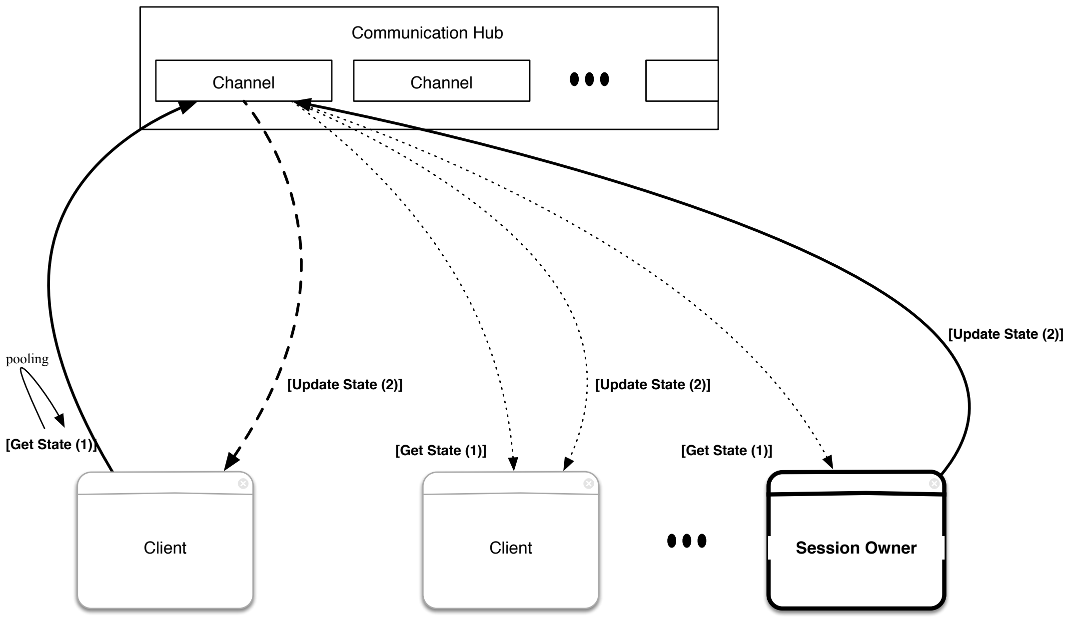

Figure 3.19 Client requesting the viewing state update.
This action may be invoked after reloading the application or after some time without receiving any update message.

Network security is usually very tight in health institutions and the connection to services hosted outside the local network is controlled by restrictive firewall rules. These rules may block services using data transport protocols other than the ones used to connect to the Internet, such as HTTP, HTTPS and Web sockets.

The synchronization process implemented in our platform transfers messages via Web sockets. With the TogetherJS server hub deployed in the cloud and because we used Web sockets, the users can connect to the platform and start a collaborative viewing session with others without changing any network configuration or firewall settings.

3.4.7 Performance Evaluation

Typically, cooperation in an inter-institutional radiology scenarios demands adopting a patient-centred solution and building means to distinct shared patient's data beyond institution's borders [222]. This problem hampers dataflow in inter-institutional collaborative environments. Considering this, we proposed a solution to streamline the collaboration in radiology, and targeting these cross-institution challenges. Our solution consists of a ready-to-go platform to promote collaboration between radiologists focusing on medical image visualization, essentially via interactive solutions based on synchronous collaboration sessions. The platform is hosted in a cloud-based infrastructure, and it is opened for every user under limited storage quota in the user's private virtual micro-PACS. Hence, radiologists or radiology institutions do not need to deploy and manage a radiology collaborative system to create a collaboration channel. They can take advantage of the platform, aiming at reducing complexity when creating collaboration channels between the radiology professionals.

Additionally, instead of only providing traditional one-to-one collaboration, the platform also supports many-to-many synchronous collaborative sessions which may be an added value for various collaboration scenarios including teaching of radiology.

The platform provides an easy solution to disseminate data between multiple collaborators through a private virtual micro-PACS where studies are shared with the collaborators. This Web-based solution simplifies data transmission, reducing the complexity inherent to solutions based on DICOM gateways for accessing data.

During the platform evaluation, we assessed the performance of the virtual private micro-PACS in terms of study upload, query and download. We used different modalities to assess the system performance when handling different file size such as small ultrasounds image and high resolution images like mammography. Also, we evaluated the collaborative viewing session performance, implementing a testbed in which we simulated multiple users in a collaborative viewing session.

To evaluate the collaborative viewing session performance, we tested the action synchronization scalability by simulating scenarios from one-to-one to 100-to-100 users in a viewing session. During the scalability test, we measured how the platform performance varies with the increasing of the number of users in a viewing session. We implemented several test bots which join a session a perform specific action in the session. The bots were deployed in several Docker containers. During the session, we log the delay that the platform has when synchronizing the action in each bot. In the end, we took the average delay for each kind of action. Table 3.3 shows how the delay varies by changing the number of participants in a viewing session. By analysing the results, we can observe that increasing the number of participants in a session up to 100 does not have a significant impact in the synchronization time.

3.5 Results and Impact

Healthcare institutions have experienced reforms to meet costs reduction measures taken by government due to the economic crisis [223], [224]. Radiology as well as other health areas has significantly felt this economic effect, resulting in many negative consequences including workload increase, equipment ageing, staff size reduction, retention in reimbursements and delegation of specialized task to professionals without required expertise [225]. On the other hand, the need to reduce cost has favoured the adoption of teleradiology services. But, regarding this fast adoption of teleradiology has been a consequence of costs reduction, we have to consider some negative effects like price competition between traditional health service and teleradiology, and acceleration of professionals outsourcing in radiology departments [225].

The costs to operate and maintain a radiology centre are somehow high due to very expensive equipment and special IT infrastructure, as also special physical infrastructure to comply with security guidelines such as radiation shielding. Moreover, highly qualified personnel are essential to establish a radiology centre, and this leads to high wage costs because radiologist is one of the jobs with highest income.

The advancements in ICT have contributed to cost reduction in radiology centres operation because nowadays almost every centre has a PACS to store and transmit medical images which contribute to saving of papers and traditional films having an economic and ecological impact.

Table 3.3 Message synchronization time.

Action type	Message size (bytes)	Synchronization time (ms)		
		2 Clients	10 clients	100 clients
Window/Level	±166	138 ± 4	155 ± 41	184 ± 41
Image Browse	±121	154 ± 29	182 ± 71	212 ± 83
Change Layout	±121	154 ± 29	189 ± 52	201 ± 62
Draw Line	±256	142 ± 10	194 ± 72	207 ± 28
Draw Rectangle	±277	140 ± 5	173 ± 89	193 ± 48
Draw Circle	±245	137 ± 20	149 ± 36	189 ± 38
Draw Arrow	±360	138 ± 5	157 ± 67	195 ± 22
Change Tool	±110	137 ± 4	159 ± 46	209 ± 72

We developed a solution for medical imaging diagnosis which stands out for being an eco-friendly solution by reducing the number of film sheet prints and DVD/CD burns. Every year, billions of film sheets and CDs are globally produced in radiology centres, representing an environmental threat and an avoidable waste. The associated cost for physically sharing a study – film sheet, DVD/CD and custom envelops – implies an average cost ranging from two to five euros per study. In this way, the adoption of our solution represents a potential saving of 50 to 125 thousand euros per year in a medical imaging centre which produces approximately 25 thousand studies per year.

We propose a paperless workflow where the studies and reports stored in the platform can be shared with other healthcare professionals, patients and insurance companies through a simple short link. The link allows us to properly authenticate and authorize users to access the target study – and not the entire PACS archive. This way, the user will have access to the same information that would have before, but in an eco-friendly and less expensive manner.

Slow applications are frustrating specially when they are operating as working tools. Therefore, the implemented platform takes the overall system performance seriously, and we have invested a lot of effort turning the solution instantly responsive to the users. The result is user experience equivalent to a desktop workstation, even if the archive is in a remote site (e.g. *cloud*). Besides being developed with the most efficient technologies – e.g. RESTful services, Lucene, MySQL – the backend relies on caching mechanisms that pre-fetch the information before it is needed in the frontend based on Modality Worklist (MWL), or, if not available, in the background in parallel with the first user request.

Furthermore, zero-footprint viewers rely on frontend technologies such as HTML5, JavaScript and CSS. Although, these state-of-the-art technologies bring significant advantages in terms of access convenience, they can degrade the user experience if not implemented properly. The solution stands out from the remaining viewers since it uses frontend multi-threading technology: HTML5 Web Workers. Web workers run in the background, independently of other scripts, without affecting the performance of the page. This multi-threading technology is supported by all the major browsers and improves significantly the user experience.

The platform follows well-established security guidelines on the communications between system nodes, addressing the following requirements:

- Authentication: verifies if the entity in the HTTP requests is the claimed one.
- Authorization: Based on RBAC, which evaluates the user permissions before granting access to the protected resource.

- Channel integrity: ensures that HTTP messages do not suffer modifications in the channel.
- Channel confidentiality: ensures that data in transit is not disclosed to a third entity in the middle of communications.

In the proposed solution, the exchanged messages are transmitted over HTTP/S channel. A certificate X.509 is emitted for each platform's component and used in context of SSL/TLS connections.

From this research, we could conclude that Web technologies, namely HTML5, are already sufficiently mature to permit the implementation of professional medical image viewers for Web environment. A first prototype solution was installed in a radiology clinic, where radiologists' feedback allowed us to tune some aspects associated to usability and improving system robustness. Consequently, many of the tools commonly used by physicians during medical images reporting are already available in our application.

3.6 Final Considerations

As a first contribution, in this chapter, we introduced the architecture of a DICOM Web viewer which promotes telework by supporting multi-PACS connections and allowing visualization of distinct medical imaging modalities. The proposed solution can be used in common Web browsers and can be accessed using mobile devices, like Android and iOS based tablets, establishing a novel ubiquitous solution for medical image analysis.

As second contribution, we proposed a prefetching and caching solution to reduce medical images access latency when accessed through Web-based viewers.

Finally, a third contribution, we extended the DICOM Web platform to allow the creation of collaborative sections between multiple users and institutions.

The validation of our ubiquitous DICOM Web architecture was performed in two distinct assessments. On the one hand, to validate the web solution, it was deployed in a mammography screening scenario, which is one of the most demanding medical imaging modalities. On the other hand, we performed experimental tests to assess the application performance in terms of access time for image rendering, and we obtained good results when compared to native DICOM viewers.

4 A Collaborative Radiology System with Data Reuse[1]

"If I have seen further than others, it is by
standing upon the shoulders of giants."
Isaac Newton

Teleradiology has been promoted by healthcare professionals as an efficient way to obtain remote assistance from specialised centres, to get a second opinion about complex diagnosis or even to share knowledge among practitioners. The current economic restrictions in many countries are increasing the demand for these solutions even more, to optimize processes and reduce costs. However, despite some technological solutions already in place, their adoption has been hindered by the lack of usability, especially in the set-up process.

In this chapter, we will propose a telemedicine platform that relies on a cloud computing infrastructure and social media principles to simplify the creation of dynamic user-based groups, opening opportunities for the establishment of teleradiology trust domains.

The implemented collaborative platform is provided as a Software-as-a-Service, supporting real time and asynchronous collaboration between physicians. To evaluate the solution, we deployed the platform in a private cloud infrastructure. The system is made up of three main components - the collaborative framework, the Medical Management Information System (MMIS) and the Web application - connected using a message-oriented middleware.

The platform allows physicians to create easily dynamic network groups for synchronous or asynchronous cooperation. The created network improves dataflow between colleagues and knowledge sharing and cooperation through social media tools. The platform was implemented, and it has already been used in two distinct scenarios: the teaching of radiology and tele-reporting.

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[1] This chapter was based on the following publications:
A Cloud Architecture for Teleradiology-as-a-Service. Methods of Information in Medicine, 2016 [126];
Semantic Knowledge Base Construction from Radiology Reports. In Proceedings of the 9th International Joint Conference on Biomedical Engineering Systems and Technologies, 2016 [345]
A Recommender System for Medical Imaging Diagnostic. Digital Healthcare Empowering Europeans: Proceedings of MIE2015, 2015 [346]

4.1 The Evolution of Collaborative Work in Radiology

Medical imaging laboratories are complex environments using very specialized equipment, from image acquisition to visualization. The IT infrastructure, namely storage units and communication layers, needs to be prepared to deal with a large amount of produced data that can reach terabytes per year in a central hospital [226], [227]. Usage of PACS has been handy not only to manage and store medical imaging data, but also to integrate health solutions allowing remote access to patient information and to set-up teleradiology workflows, telework and collaborative work environments [126], [228], even in mobile platforms [36], [170]. Consequently, even though medical imaging repositories were initially designed to be accessible through the DICOM services [24], [27], [184], currently, due to technological evolution (e.g. Web technology), these repositories can in many cases be available through other APIs such as REST services [170]. In this sense, technological changes have paved the way for innovation in radiology informatics favouring data sharing and remote data access which have empower adoption of collaborative work in radiology.

Generally, computing devices and Internet access are now very widespread, creating new opportunities to share and use online resources. A tremendous amount of computational power (e.g. Google Compute Engine and Amazon Elastic Compute Cloud) and an unprecedented number of Internet resources and services are used every day as an ordinary commodity. In this sense, cloud computing has emerged to deliver computing as a service rather than a physical product (e.g. physical servers) [49]. With the rise of cloud computing, many services are being outsourced - data are stored in the providers' infrastructure and the information accessed anywhere through a Web browser, even on mobile clients. Without a doubt, these features are also an opportunity for teleradiology. Furthermore, the social media paradigm [229], which consists of online social interaction where individual users become part of an online community, generating content and interacting with other users via messaging channels and engaging forums, has become increasingly popular among Web users. As a result, it is also explored in health informatics communication aiming to identify novel interaction models between patients and physicians [230].

In this research, following the Teleradiology-as-a-Service concept, we propose a collaborative architecture that offers secure and private spaces where physicians can store exams, establish collaborative groups and share data without complex configurations or set-up problems. The platform facilitates real-time and asynchronous collaboration, making also use of social media tools. For example, a radiologist can import a study to his personal archive, anonymize the images, append annotations and start a case discussion with a colleague, powered by a set of collaborative tools such as synchronized image visualization and videoconferencing.

In addition to this novel architecture, we also studied how to exploit the information stored in this kind of systems which includes multi modal data such as clinical textual reports and medical images. As a result, we developed a clinical recommender system where we integrate textual information and image features to find similar clinical studied which may assist physicians in the decision-making process. Moreover, we designed a pipeline to transform textual information in radiology reports into semantic knowledge. This knowledge base can be integrated into a recommendation engine to support a semantic recommender system for radiology.

Finally, the built system deals with private and sensitive information, and, therefore, one cannot afford to lose control over the data access or having flaws that allows disclosing private information about patients' records (i.e. health condition or zip code). This issue was also addressed in the system architecture, restricting user access to data using a RBAC mechanism, and having supports for data encryption.

4.2 Architecture of a Collaborative Framework for Radiology

The architecture of our collaborative solution for radiology is based on three main components: the collaborative platform, the Medical Management Information System (MMIS - a gateway for mediating communication with a PACS inside a healthcare institution) and the Web application for accessing the platform (Figure 4.1).

The collaborative framework is the architecture core component. The framework is hosted on the cloud, and is composed of four components (Figure 4.2): Openfire server, the cloud archive, the cloud database and the XMPP communication middleware.

Openfire is a real-time collaboration (RTC) server which allows registering, managing and establishing communication between users [231]. It uses an open-standard communication protocol, the eXtensible Messaging and Presence Protocol (XMPP) [232], for message exchange between clients and the server. We chose Openfire as our backend server because it inherently supports instant messaging, collaborative interaction and collaborative workflow, and works perfectly in cloud-based environments [233].

The server architecture supports extension via plugins, and allowed us to develop plugins for enhancing the communication middleware with capability to handle new functionalities built on top of the XMPP protocol. Thus, enhancing the protocol for a medical scenario with features like encapsulation of DICOM services into XMPP messages.

A user must be registered in the Openfire collaboration server to access the functionalities available.

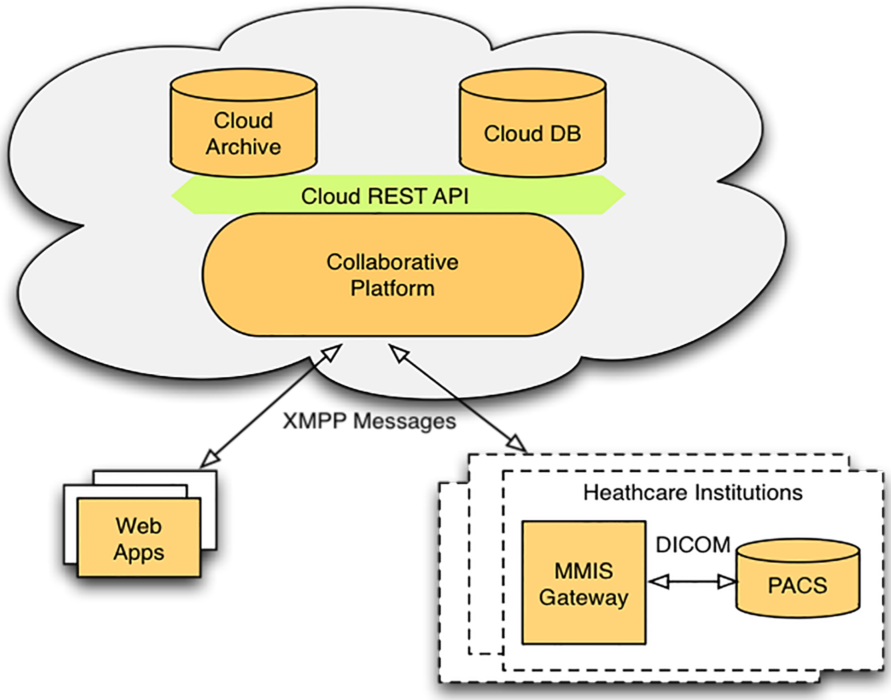

Figure 4.1 Architecture overview: the collaborative framework for radiology.
The cloud infrastructure (cloud database, cloud blobstore) supports the collaborative system. There is an MMIS gateway for mediating communication with a PACS. A message-oriented middleware supports communication between all entities in the platform.

The server also provides social media features including management of friends list and groups. Users can add others to their roster or create affinity groups, based on social network interaction models. The platform allows physicians to create easily dynamic network groups (Figure 4.3). Thus, cooperative groups can be created to assist social relationships among physicians. This cooperation can be synchronous or asynchronous. The facility of creating ad-hoc networks (or trust domains) has the potential to improve professional workflows where radiologists can cooperate and share knowledge through interactive tools.

The cloud archive module is responsible for managing the system storage area. The platform uses this component to store the users' DICOM images in the cloud. This component is seen as a pointer to a given cloud storage, or as a stream used by the system to write and read files from and to the cloud. The cloud archive and the cloud database were implemented as plugin-based components, and they can be developed to use any desired cloud provider. The plugin-based approach also gives us more flexibility in the deployment of our system.

4.2.1 Personal Remote Archive

The cloud archive and the cloud database gave users the abstraction of a Personal Remote Archive (PRA) to store private studies, which were accessible anytime and from anywhere.

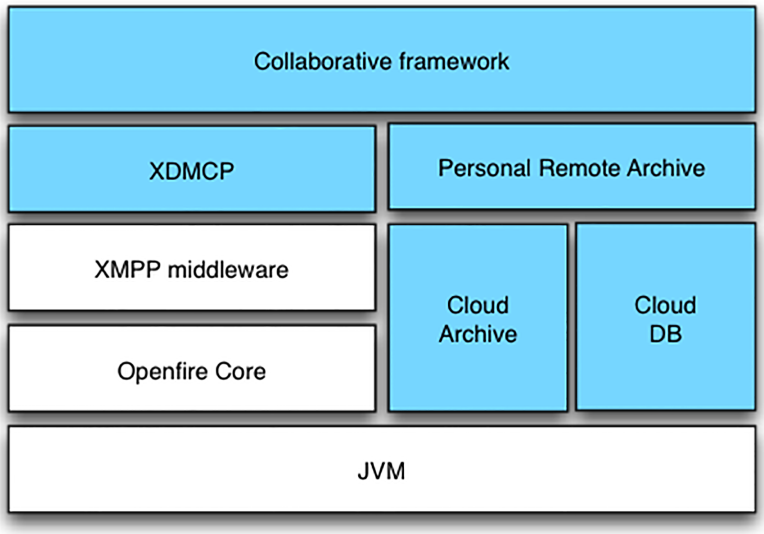

Figure 4.2 The core components of the collaborative framework.
The Personal Remote Archive (PRA) and the eXtensible DICOM Communication Protocol (XDMCP) are the components responsible for providing the data persistence and the communication middleware of our system.

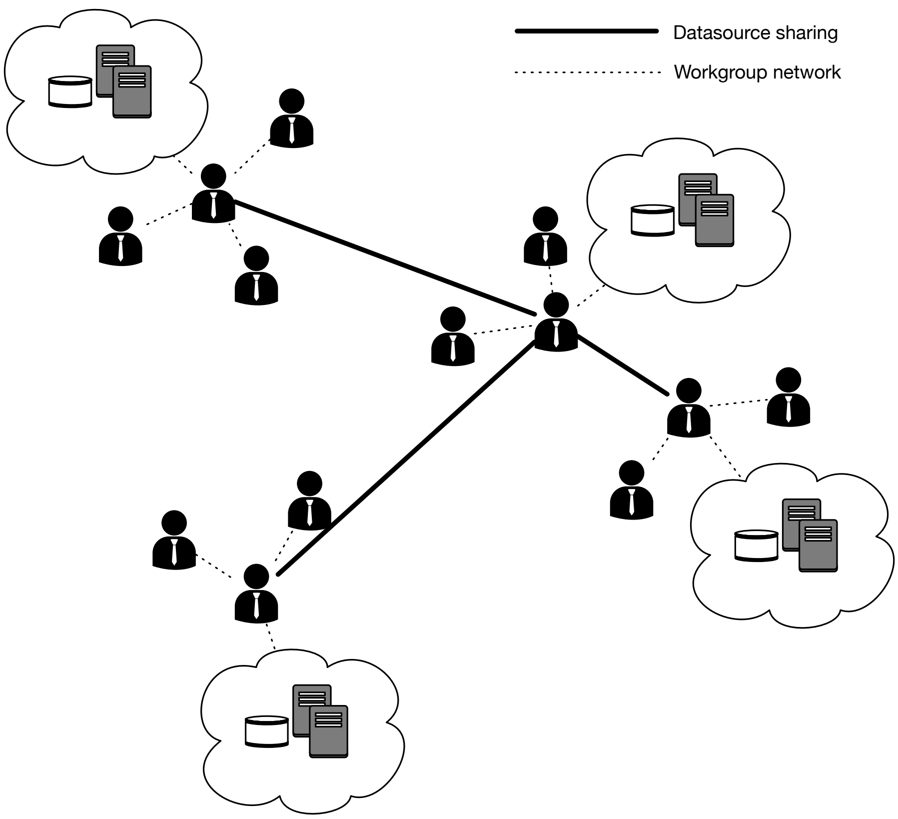

Figure 4.3 Social media network for data sharing and work group management.

These files could be shared with other users or groups. Each resource has an access control list stored in the platform database (i.e. the cloud database). This feature was important to promote collaboration between users.

An instance of the Openstack Swift blobstore [234] was deployed in our private cloud infrastructure to handle the PRA, but it could also be hosted on any cloud storage provider supporting a blobstore mechanism.

4.2.2 XDMCP - eXtensible DICOM Communication Protocol

Focusing on the communication layer, we implemented an extension of the XMPP protocol that supports custom XMPP messages with features addressing the medical environment. XDMCP enriches the messaging middleware to satisfy the system requirements. Particularly, Info/Query (IQ) messages were created to allow XMPP clients to manage their PRA. This includes features like sharing, obtaining and putting medical images into the PRA. Also, using specific pay-loaded messages, any XMPP client can send a DICOM command to a given MMIS gateway. This allows clients to access remote DICOM repositories. All system entities must implement specific IQ handlers and IQ providers to understand the new features added to the XMPP protocol.

4.2.3 Medical Management Information System (MMIS)

We implemented the Medical Management Information System (MMIS) module to ensure interoperability between the collaborative platform and institutional PACSs. It allows remote access to standard PACS (Figure 4.4), and is extremely important to the overall architecture. For example, it is used to query and to import studies from remote PACS into user's private area (PRA).

We used Java programming language together with useful libraries such as the XMPP smack client [235] and the dcm4che DICOM library [236] to develop the multiplatform MMIS module. The module consists of an XMPP client, developed using the Jive Smack library, which connects to the Openfire Server and receives messages from users, controlling their access to the DICOM network where it is deployed. These messages can be custom XMPP stanzas [237] that are translated to DICOM commands (e.g. c-find, c-move).

Access to the PACS is restricted based on the MMIS access list, and each institution system administrator can manage this list by adding or removing users. The component must be installed on a server inside the radiology institution network. Users with granted access to an MMIS may execute commands to retrieve medical imaging studies. In addition, images can also be stored in the cloud, allowing users to share them with others.

An automatic process is provided to allow anonymous sharing of examinations. This anonymization process changes the patient identification, demographic information and institutional information stored in DICOM metadata aiming at removing data which can reveal person's identity [238].

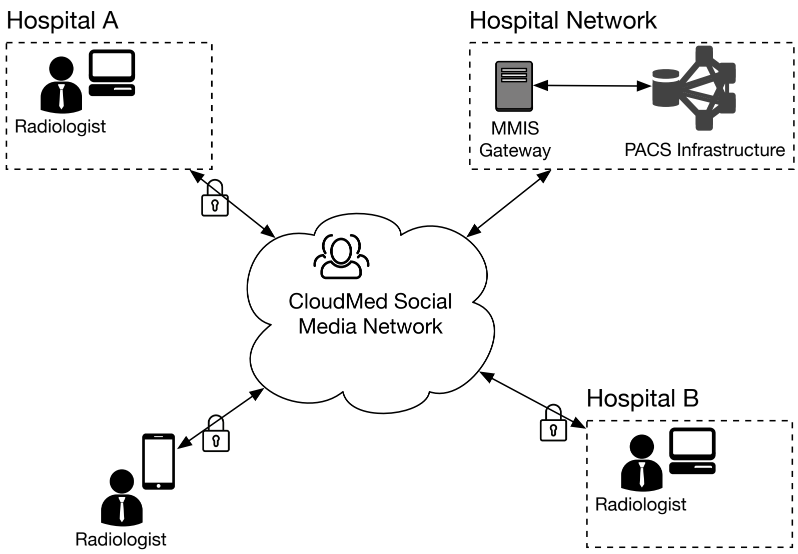

Figure 4.4 MMIS - PACS Interoperability.
The MMIS gateway plays an important role in establishing interoperability between PACS infrastructures and the Web platform. It enables physicians to access data stored in their PACS through our platform.

Moreover, our system does provide pixel data anonymization, and we will further discuss in details all the aspects of this subject (chapter 5).

4.2.4 Collaborative Web Application

After deploying the teleradiology infrastructure as a cloud service, we also developed a Web application to enable the remote access to the platform. This application offers the UI to manage private repository, manage contact list, visualize images, discuss clinical cases and share clinical cases.

This Web application uses HTML5 APIs for many advanced features including audio/video communication stream. The Strophe XMPP JavaScript client [31] was used to support communications with the server. The client supports bidirectional-streams over synchronous HTTP (BOSH) to transport XMPP stanzas. Traditional collaboration in radiology is somewhat limited to use store-and-forward technologies, which may have disadvantages compared to real-time technologies. Therefore, we chose to implement real-time interactive tools for collaboration, using the XMPP and the WebRTC technologies (Figure 4.5).

User interaction with the Web application is very similar to their interaction with a desktop viewer. For instance, they can simply drag and drop DICOM files into the Web application to make the upload to their private repository.

XMPP supports the main interactive tools including messaging and presence exchange. In addition, we also used WebRTC to enhance collaboration with features like video and audio stream in the browser without the need to install any plugin.

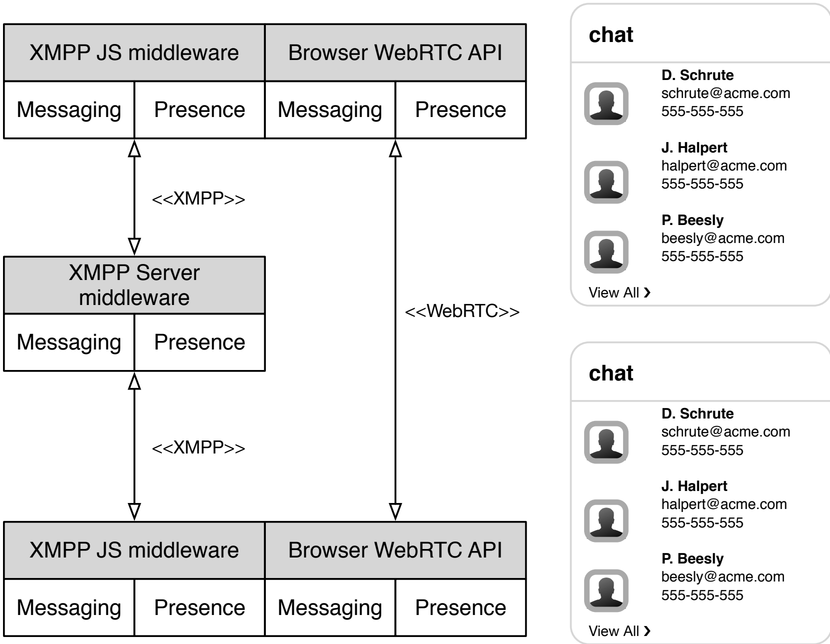

Figure 4.5 Middleware for handling interactive collaboration in Web applications.
The system uses the WebRTC for audio and video call and the XMPP for messaging and presence exchange.

For instance, in the collaborative mode, it is possible to have synchronized visualization of medical images supported by interactive pointers and videoconferencing.

For medical images visualization, we integrated the DICOM Web viewer (Figure 4.6) introduced in chapter 3. By integrating the DICOM Web viewer into the collaborative radiology platform we built an 100% Web solution, which is platform independent and with support for mobile environments. It provides a set of common functionalities, including surface and angle measurement tools, graphical annotation, window/level manipulation and image processing.

4.2.5 Privacy and Security

Privacy and security are main concerns related to medical data access, and many researchers are targeting these problems [239], [240]. It becomes more critical when medical data are transmitted over the Internet or stored outside institutions' physical domains. In these environments, confidentiality, integrity and even the authenticity of the data source are important. In many cases, access control mechanisms and strict security policies are mandatory [241].

Security and privacy were considered of major importance in design of the proposed architecture. For that we implemented important mechanisms including event logging, data encryption, image anonymization, and the enforcement of secure communication channels through HTTPS.

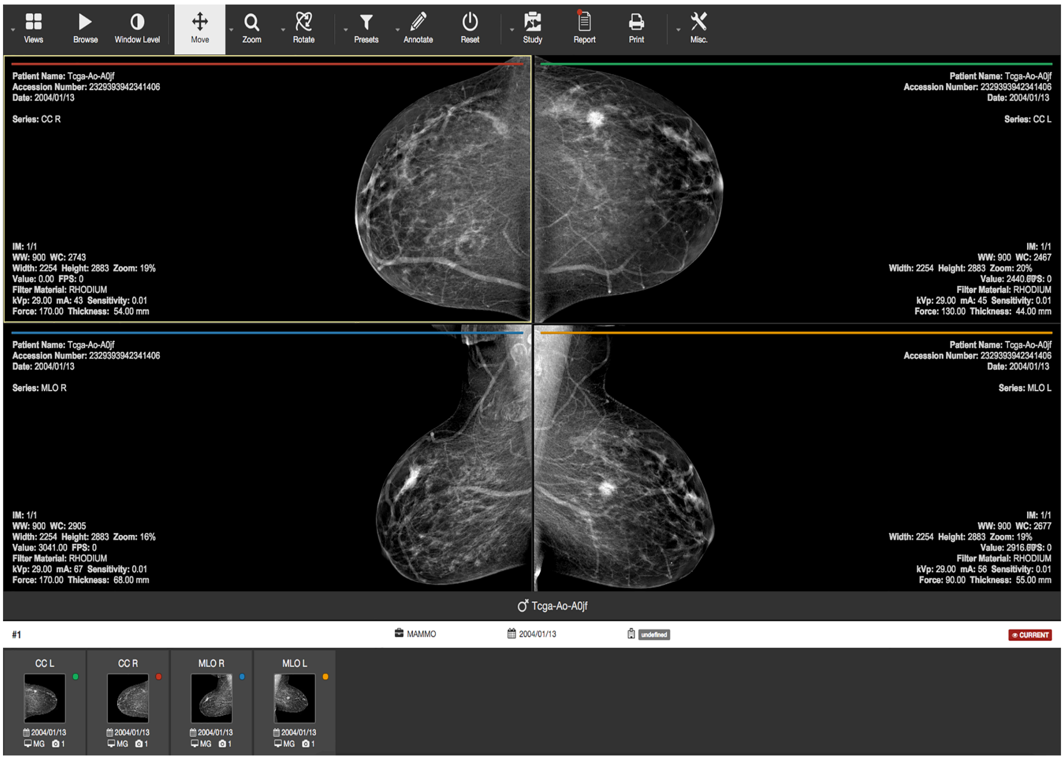

Figure 4.6 Web client application.
This figure depicts the use of our DICOM Web viewer for analysis of a clinical case.

An access control list (ACL) was implemented, and only users belonging to the MMIS' ACL are able to communicate with it. A role-based access control (RBAC) module is used to define roles (e.g. administrator, healthcare professional, student, teacher, etc.), resources (gateway and uploaded study) and permissions (read, write, remove). A set of permissions is associated with each role, defining the kind of interactions the user could have access to. Then, resource owners can identify the roles required by each user to access the resources. The ACL is also synchronized and stored on the cloud collaborative framework so that any XMPP message is analysed before being forwarded to its destination. All the access control mechanisms were implemented on the XMPP communication middleware. The data source, i.e. the archive, can also be configured to provide access just to a sub-set of the data stored in the PACS, e.g. to ultrasound studies performed during the last week.

Using a public cloud to store and manage clinical data is a sensitive issue and must follow national legislation. The public infrastructure may bring security concerns associated with the loss of full control over stored data. Hence, it is difficult to conciliate and ensure both the confidentiality and the search ability in cloud environments.

The proposed architecture uses the cloud to relay all messages exchanged between entities. Thus, clients behind corporation firewalls may establish (or receive) connections with (from) external resources without problems. This approach is fundamental to ensure communication with MMIS gateways located inside healthcare institutions.

4.2.6 System Evaluation

To evaluate the feasibility, usability, and performance of the proposed platform, we deployed two use cases:

1. ***Teaching of Radiology***

One major problem of teaching radiology in health schools is that traditional PACS solutions are very limited in supporting the classroom's workflow. Besides training the radiology trainees with the workflows they will face in their professional future, the technological solution should also support e-Learning. Namely, by providing individual user areas, i.e. private DICOM archives, sharing of resources and supporting collaborative work environments.

The proposed framework was associated with the Dicoogle PACS archive to support the Radiology classrooms of ESSUA (School of Health, University of Aveiro). On the one hand, lecturers need to upload case studies (i.e. DICOM exams) to be analysed by a student group. Thus, a public repository owned by the lecturer is required. This repository is shared with class students (read-only permissions). On the other hand, there are acquisitions performed by the students, for instance, CT or X-Ray in phantoms. Only the student (or group member) should be able to see the acquired examinations. Next, students annotate and apply transformations in these studies, which can be performed collaboratively. The final work needs to be submitted for evaluation, i.e. shared with the lecturer.

During one semester, a class of 21 students used this platform for having access to medical imaging studies shared by the lecturer. In some assignments, they also used the platform for adding CT acquisitions that were later shared with the lecturer. All actions were logged for evaluation purposes. We have registered 1921 DICOM actions between the teleradiology platform and the Dicoogle PACS archive. Several operating systems (Windows, MAC, and Linux) and Web browsers (Mozilla Firefox, Safari and Google Chrome) were used, in the university campus and at home.

At the end of the semester, a questionnaire was given to the students to evaluate the impact of the platform during their classes. Overall, the users' interest confirmed that the proposed platform is extremely useful in an academic tele-teaching scenario. The direct contact with students during the classes also provided an important feedback for improving some functional aspects.

2. ***Tele-Reporting Service***

Existent statistical data and productivity studies showed that medical imaging data can be generated in practically any healthcare institution, even one with limited human or financial resources [242]. Nevertheless, highly skilled physicians are usually concentrated in a reduced number of specialized medical centres. The asymmetric distribution of equipment and service providers across countries typically leads to the need to hire third party reporting services outside the institutions where the exams were made. In the past, our workgroup developed a tele-ECG platform that is being used by cardiologists to support examination reporting [31]. The tele-reporting service presented in this use case has a similar aim, but the technological approach is very different. In this case, the information is not pushed to a central repository but remains in the remote institution PACS. The technician makes the examination in the modality, and the exam is stored in the institution's PACS archive, connected to the review platform through an MMIS gateway. The physician uses the platform to query, retrieve and visualize the examinations produced in the institutions. The examinations are temporarily cached in the PRA, but the data are deleted after user logout.

We also deployed this use case in a scenario connecting two geo-distributed institutions sharing a private regional repository. They belong to the same owner, and the radiologists can practice in both institutions and report examinations remotely. These institutions deal with different modalities, handling an average of 3000 examinations monthly, with a combined volume of around 60 GB. Previously, the visualization workstations used DICOM communications, supported by a routing mechanism with cache, to connect with the central archive. Our platform was installed in their private cloud infrastructure, and they started to use the DICOM Web browser for tele-work reporting. During 6 months, 23164 DICOM actions (c-move and c-find) were performed between the teleradiology platform and the central archive. One of the most used functionality was the ability to collect interesting clinical cases, which can be anonymized, annotated and stored in their personal archive.

4.2.7 Performance Measurements

The cloud infrastructure provides response capacity in case of high demand for storage and processing power. However, the latency associated with remote retrieval and visualization of medical imaging studies is the most critical issue in the platform. To demonstrate the performance of the proposed platform, trials consisted of recording the delays in moving, parsing and displaying several medical imaging studies between the PACS-cloud archive and the remote Web client application. The studies must be retrieved from a remote PACS archive server using the DICOM standard, stored in the cloud container and parsed to extract the pixel data. Next, the pixel matrix is transferred to the remote Web client application that applies transformations to the original pixel data according to the DICOM standard specifications regarding image presentation [243] before displaying it.

The teleradiology platform was deployed in a private cloud infrastructure and several instances with the following characteristics were used: 16Gb of RAM, 4 vCPU at 2.6GHz and a network connection with 24Mb/s of upstream bandwidth. The clients were connected through channels with a downstream of 40Mb/s. The studies information (image matrix, the number of DICOM files and the total data volume) and average access times are presented in Table 4.1. The results allow us to observe that the proposed platform provides an approximate throughput of 2.5 MB/s. We also observe that the access time varies between 4 and 50 seconds for the studies available on our platform, which may be considered acceptable considering the overheads associated with DICOM communications, disk I/O operations, communication latency and image processing.

We also performed a stress test to assess the impact of multiple clients using the platform simultaneously and intensively to retrieve and visualize studies from their cloud archive. In the trials, each client was programmed to request studies and perform searches continuously. We used Locust [244] to simulate user behaviour in our system. This modern load-testing tool allows us to define and simulate a set of tasks performed by each user when accessing the system. The tasks defined consist of accessing the home page, performing the login, accessing the profile, accessing static contents, performing a search and downloading a set of images for visualization. The results obtained are presented in Figure 4.7.

As expected, increasing the number of concurrent users in our platform affected the server response time. The most important observation is that the maximum response time, considering 250 concurrent users, could top 1.2 seconds, which is very acceptable taking into consideration the limited resources of the virtual machine used in the tests.

As expressed previously, the search and retrieval of medical imaging studies are CPU intensive tasks with direct impact on platform scalability.

Table 4.1 Access time measurements of different modalities.
The size of the study is the factor that has the most impact on access time. The latency introduced by multiple files is residual as can be observed when comparing the access time of one CT containing 25 slices with one CR containing 1 slice and all studies with a size of approximately 7 MB.

Modality	Number of files	Volume (MB)	Time(s)
CT (512x512)	65	33.4	12.4
CT (512x512)	195	100.2	41.5
CT (512x512)	24	12.3	5.9
CR (2370x1770)	4	32	12.8
CR (4740x3540)	4	128.4	49.0
CR (2140x1760)	1	7.2	4.1
US (1024x768)	25	7.5	5.2

The stress tests also provided data that allowed us to analyse the impact of Memcached system during downloads and searches. To simulate a real scenario where it is not possible to have everything in cache, the system was tested with distinct percentages of data (images and query results) in the cache, i.e. using missing percentages that vary from 10% to 50%. Figure 4.8 and Figure 4.9 present the impact of the caching mechanism on the download and search response times, respectively.

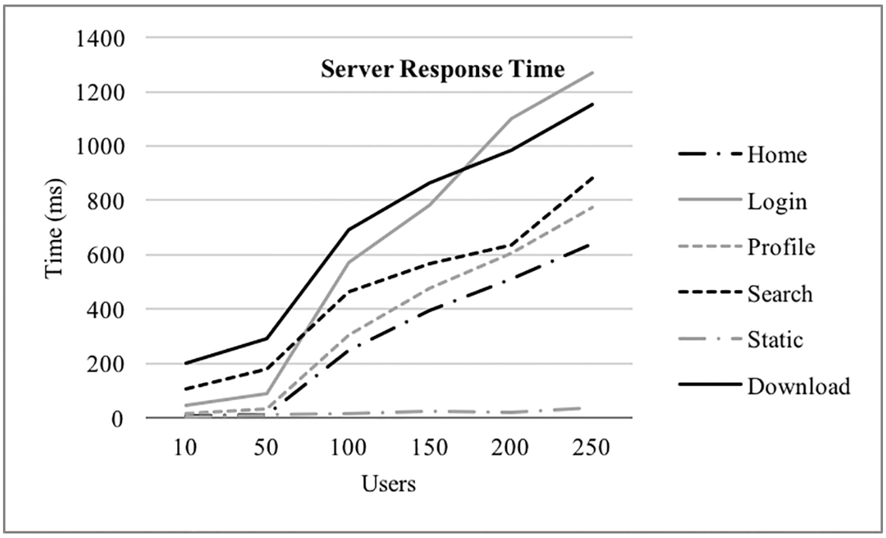

Figure 4.7 Average response time in milliseconds for each task:
varying the number of concurrent users.

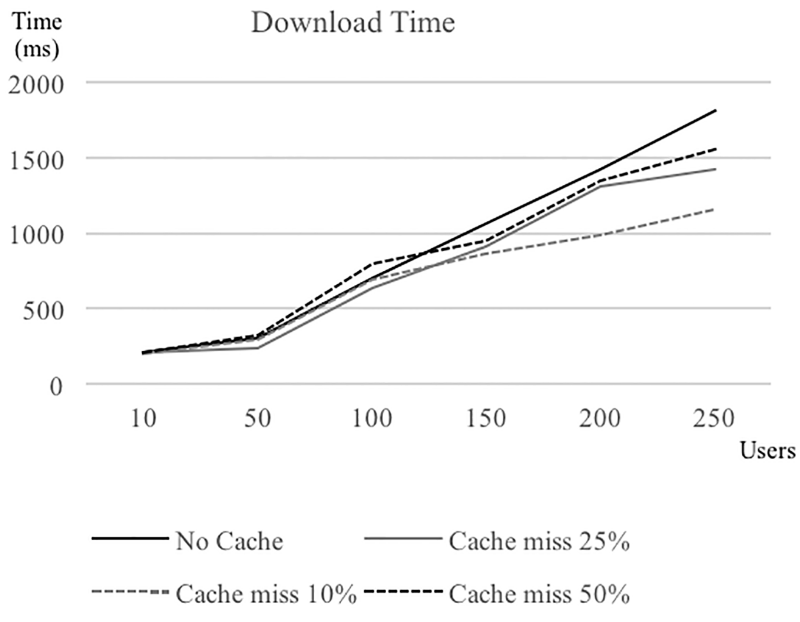

Figure 4.8 Performance improvement using Memcached (image download):
Average response time for image downloads with cache and without cache, varying the number of concurrent users.

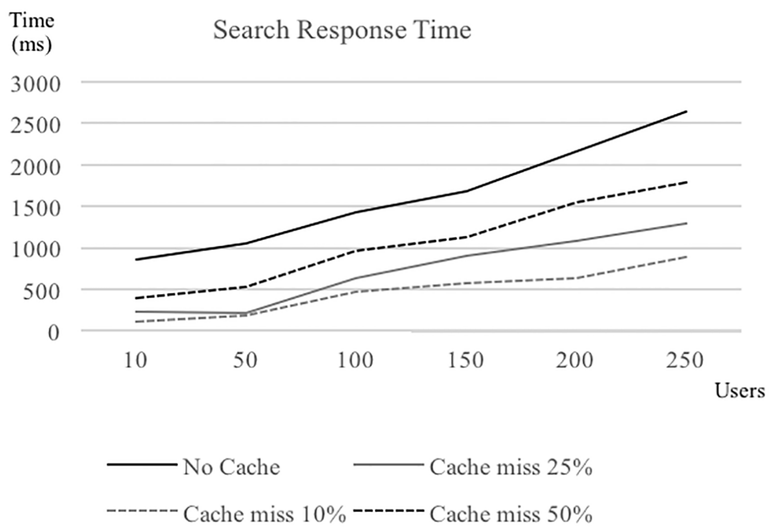

Figure 4.9 Performance improvement using Memcached (study search):
Average response time for study search with cache and without cache, varying the number of concurrent users.

The results obtained clearly demonstrated the importance of the caching mechanism to reduce the download and query response times in the proposed platform. The impact is most notable when the number of concurrent users is high and when the missing percentage is small. For the best scenario, where we had 90% of data cached and considering 250 concurrent users on the platform, the proposed caching mechanism improved the search response time by 66% and the download time by 36%.

4.3 A Pipeline for Knowledge Extraction

In the previous section, we have described an architecture that aims simplifying the creation of spontaneous collaborative groups in radiology. While the solution was being validated in two distinct scenarios, a major issue appeared, related to the effective use of the data. The tremendous quantity of data stored daily in radiology institutions demands the development of new methods to summarize and reuse available information in clinical practice. Novel radiology information systems must address challenges such as extraction of relevant information, data redundancy, and the lack of associations within the data.

To address this demand, we propose a strategy for knowledge extraction and representation, through a pipeline which transforms clinical free text from radiology reports into a semantic knowledge base. Furthermore, considering that our collaborative platform handles data from images and text, we also propose a model to use this information to build a multimodal clinical recommender system to improve the collaborative platform which can physicians to easily find similar cases.

The proposed pipeline automatically extracts and summarizes natural language reports into an ontology model. To test the effectiveness of the implemented model we used data from

Physionet MIMIC II database. As a result, we created a semantic knowledge base with more than 6.5 millions of triples obtained from a collection of 16,000 radiology reports. The main idea was to apply the same transformation on textual information generated by users in the collaborative platform, and allow them to explore the information generated via a semantic search engine.

In the following subsection, we will present related work in the field of biomedical text mining and semantic Web. Next, we will describe the proposed method to extract relevant information from clinical reports and the resulting semantic knowledge base structure. Last, we will discuss the results obtained with the implemented pipeline, summarizing the contributions.

4.3.1 Biomedical Knowledge and Representation

Researchers have developed diverse solutions for improving information storage, management and retrieval in healthcare scenario [245] [246]. However, the tremendous heterogeneous clinical data produced in distinct healthcare centres is a critical issue [247]. Digital repositories containing clinical information, assessment reports and guidelines are usually available for consultation in those centres. Still, these data are not always structured and organized, hindering information retrieval and knowledge extraction. Furthermore, even though it is currently possible to find multiples sources of medical information in healthcare centres, there is a lack of integration between these data sources. For example, traditional clinical information retrieval systems are usually connected to a single type of data source and do not support information from heterogeneous data sources to be connected and queried. Additionally, online platforms such as Radiopaedia [248], GoldMiner [249] and AuntMinnie [250] provide rich collaborative repositories of radiology cases and articles, but these systems do not exploit linked data across similar online platforms. Linking the information available on these kinds of systems has great potential for knowledge discovery in radiology.

One of the main issues that limit the implementation of a solution that contemplates the linked data scenario is related to how the information is stored and provided. Typically, most clinical information is commonly stored using relational databases (e.g., Microsoft SQL Server, MySQL) and queried through SQL (Structured Query Language). According to Pathak et al. [251], relational model has several limitations when compared to RDF (Resource Description Framework) based solutions. Firstly, in terms of data management process (i.e. add, update, delete), RDF does not differentiate ontology classes and properties from the instances of the ontology classes. This makes it more flexible when compared to relational models, which need to be reorganized if database schema changes. Second, RDF resources are identified by a globally unique URI, making it possible to create references between two different RDF graphs, even in completely different namespaces, therefore enabling data linkage and integration processes. Third, the relational model does not have notion of hierarchy, which makes difficult to apply SQL queries for reasoning purposes. In opposition, these types of queries are natively supported in RDF (RDF Schema) and OWL (Web Ontology Language). Lastly, there is a lack of a formal temporal model for representing relational data. For instance, SQL provides minimal support for temporal queries natively, in contrast to SPARQL (SPARQL Protocol and RDF Query Language) [252] that already provides these extensions.

Regarding the healthcare context, these semantic web technologies (SW) have been applied for transforming the enormous quantity of data produced in useful knowledge capable of improving clinical methods and workflows. For instance, the development of ontologies [253] and semantic frameworks allowed answering time-oriented queries through temporal relation inference in clinical narrative reports [254]. Another study shows that SW inference and federated querying mechanisms can be used for cohort identification from Electronic Health Records (EHRs) [251]. Finally, other studies demonstrate how SW can provide semantic interoperability between disconnected clinical domains [255] or different healthcare systems [256], as well as aiding and supporting clinical diagnosis through well-structured ontologies [257]. Healthcare systems are adopting SW for building better solutions to represent and discover knowledge contained in clinical data. However, its integration with healthcare state-of-the-art systems is not trivial. Current solutions are based on a set of ETL (Extract-Transform-and-Load) techniques to elevate the data to SW standards, requiring a significant effort in data transformation and ontology mapping processes. Regarding the integration of text-mining results in SW, several ETL procedures have been applied [258] in order to translate information. Concluding, Semantic Web technologies provide an enhanced model for making clinical and research data available for secondary use and exploitation.

Besides relational databases, a huge amount of textual resources are available. In the biomedical field, important text mining contributions have focused on named entity recognition [259], which aims to identify chunks of text associated to specific biomedical entities of interest. Usually, it is a complex task due to the domain specificity – large set of terms, heterogeneous and ambiguous concepts, dynamic terminology [260]. Several tools, such as Whatizit [261], NCBO Annotator [262], GIMLI [259], Neji [263] and cTAKES [264], apply machine learning and dictionary-based methods, or a combination of these approaches to solve this issue.

Some frameworks already provide services for text analysis and knowledge extraction. For example, UIMA [265] and GATE [266] are general frameworks for developing complex information extraction systems. These frameworks also provide enough flexibility to build custom processing pipelines based on software modules. Nevertheless, they are too general and need to be tuned, or extended, for improving their performance in specific domains.

Currently, it is already possible to find modules optimized for the biomedical domain (e.g. JCoRe [267]), which are built on top of one of these frameworks. There are also libraries such as NLTK [268] and OpenNLP [269] that provide several natural language processing, machine-learning and text-mining methods. Finally, tools such as Neji and cTAKES were specifically developed for the biomedical domain, aiming to provide a user-friendlier framework for building text-mining solutions.

The following section presents a complete pipeline that comprises biomedical information extraction from unstructured textual reports and the creation of a knowledge base using Semantic Web and Linked Data standards [270]. Text-mining techniques were used to extract relevant information from clinical reports. Next, those information elements were mapped to an adequate ontology. The result is an enriched knowledge base (in RDF format) from radiology reports. It aims to support knowledge discovery processes and to serve as a basis for the construction of decision support systems.

4.3.2 A Radiology Semantic Knowledge Base

The pipeline architecture is illustrated in the Figure 4.10 and it consists of five main blocks. In the first stage, clinical records are selected and extracted from a public database. Next, clinical free-text is obtained from each record.

In the third step, the free-text is annotated through a dedicated service and the results stored in separated objects. Later, a semantic layer engine converts the annotations to the RDF format using advanced ETL features. Finally, the resulting RDF file is uploaded to a triple store database named COEUS [271], which allows performing SPARQL queries for exploring the information available in the knowledge base. The pipeline modules and respective workflow will be described in the next sections with more detail.

The development and validation of our system was performed using the radiology reports extracted from the Multiparameter Intelligent Monitoring in Intensive Care II (MIMIC-II) database. MIMIC-II is a joint project of the MIT, Philips Medical System, Philips Research North America and Beth Israel Deaconess Medical Center. It aims to promote and assess advanced patient monitoring systems [272]. MIMIC-II is a PostgreSQL database that contains data from more than 30,000 patients, collected between 2001 and 2008. In our project, we were interested in the information of 384,000 radiology reports. Moreover, we selected a subset comprising approximately 16,000 of the latest reports.

In this data gathering process, it was necessary to select and collect a subset of records to build our case study. Next, the proposed pipeline processed them, extracting information about concepts and identifying respective relations for building the knowledge base.

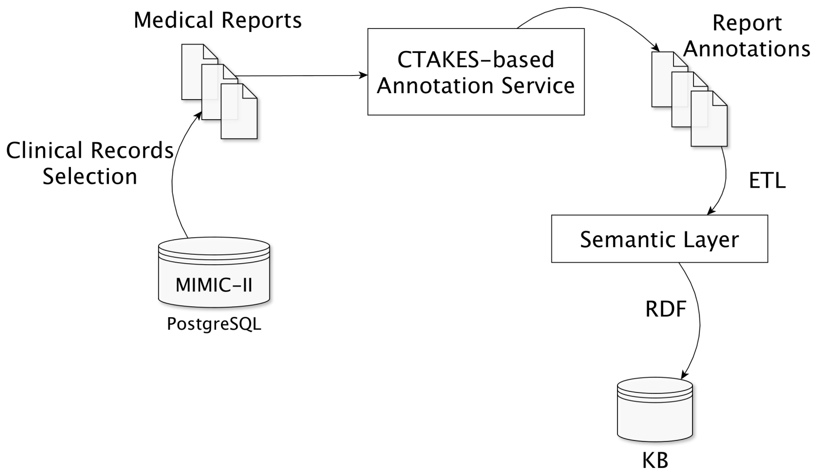

Figure 4.10 Pipeline overview: from clinical text to semantic knowledge base.

The proposed pipeline contemplates a biomedical clinical text annotation service that performs named-entities recognition, concept recognition and relation extraction (i.e. identifying relations between concepts mentioned in the text). It was implemented as a Representational State Transfer (REST) API where the annotations are retrieved by making HTTP POST requests to that service (Figure 4.11).

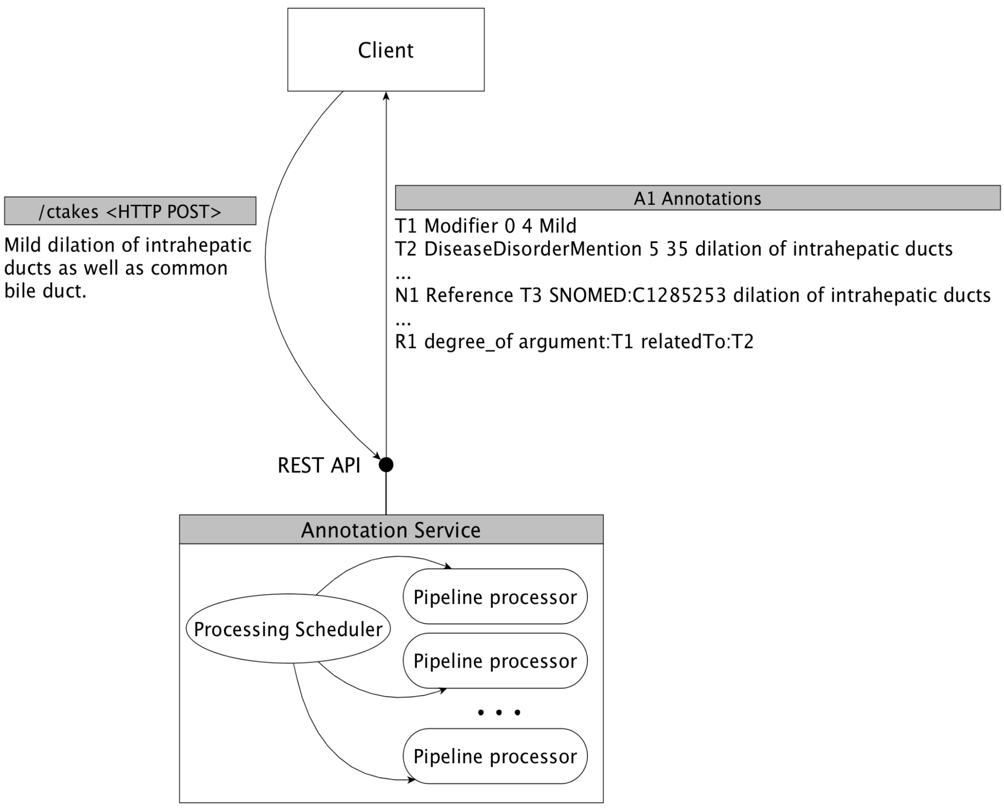

Figure 4.11 The REST service for annotating biomedical clinical free-text.
The client sends the texts using the HTTP POST method and receives annotations in standoff format.

Scalability of the solution is ensured by dynamically launched workers, named *Pipeline processors*. The maximum number of workers used to handle the annotation requests can be configured when launching the service. There is also a *Processing Scheduler* that manages the requests distribution according with workers' load, improving the service throughput. This is a very important issue, since the annotation process is relatively time consuming. On average, it takes 1.5 seconds to annotate each report in our dataset, when executed on a virtual machine with 8 vCPU Intel(R) Xeon(R) X5650 @ 2.67GHz and 8GB of RAM.

Regarding the format used to provide the annotations, we decided to use a standoff format similar to the one used in the BioNLP Shared Tasks [273], where the annotations are stored separately from the document text. It follows a simple structure where each line contains one annotation that has associated an assigned identifier restricted to an entity (T), normalization (N) or relation (R). An entity corresponds to a text-bound annotation found on the plain-text report. If the system can semantically classify the recognized entity, it then associates a normalization annotation. This corresponds to a semantic identifier of a given database (e.g. Unified Medical Language System (UMLS)). Additionally, a relation annotation can be established if the system detects a relation between two entities.

The system uses Apache cTAKES to implement the entire clinical text processing. It is an open source natural language processing tool for extraction of information from clinical texts of electronic medical records. Figure 4.12 depicts the pipeline implemented using several components of the Apache cTAKES. Firstly, the document processing stage includes segment detection, sentences detection and tokenization, using the OpenNLP Maximum Entropy package. In addition, the SPECIALIST NLP Tools are used for dealing with lexical variations in the clinical texts. Moreover, to annotate syntactic structures and to perform concept recognition, it was also used specialized components provided by cTAKES, namely annotators that combine rule-based with machine-learning techniques. For example, the cTAKES *DictionaryLookup* annotator used for concept recognition tries to match spans of text to dictionary entries.

In our case, it was used a dictionary built from the 2014 UMLS Metathesaurus database. It contains key terminology, classification and coding standards assigned to terms. Each term has a concept unique identifier (CUI) and an identifier for the semantic type (TUI). The dictionary comprised terms from five distinct semantic groups, each composed by a set of semantic types (Table 4.2). The terms used to define the medication semantic group were obtained from the RXNORM database [274] while the other terms for the remaining four semantic groups where gathered from the SNOMED CT database [275].

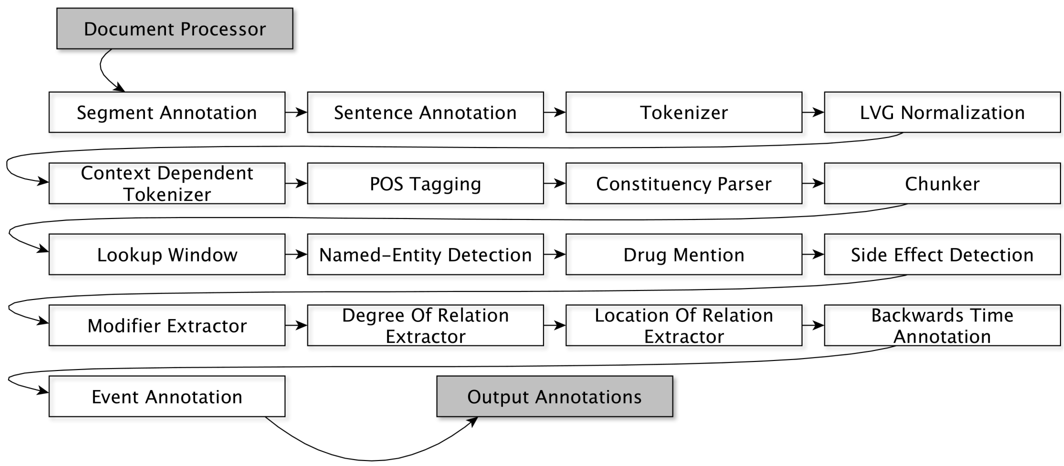

Figure 4.12 cTAKES pipeline.

Table 4.2 Sets of semantic types used for defining the semantic groups.

Semantic Group Name	UMLS Semantic Types
Medication	T073, T103, T109, T110, T111, T115, T121, T122, T123, T130, T168, T192, T195, T197, T200 and T203
Anatomical site	T021, T022, T023, T024, T025, T026, T029 and T030
Clinical procedures	T059, T060 and T061
Clinical disorders	T019, T020, T037, T046, T047, T048, T049, T050, T190 and T191
Clinical findings	T033, T034, T040, T041, T042, T043, T044, T045, T046, T056, T057 and T184

In addition to concept recognition, the system performs information extraction regarding clinical site effects of drugs using the cTAKES *SiteEffectAnnotator*. This component uses rule-based methods for annotating site effect relations, allowing us to recognize site effects and causative drugs in the clinical texts.

The extraction of binary relations between concepts identified in clinical free-text is another important feature for information retrieval systems and was also exploited to enrich the quality of the knowledge base resulting from our method. The components used for binary annotation are described in Table 4.3.

The model adopted for entity and normalization employs domain ontologies and vocabularies, creating extremely rich stores of metadata on Web resources.

Table 4.3 cTAKES annotators used to extract binary relation between concepts.

Binary Relation Annotator	**Description**
DegreeOfRelation ExtractorAnnotator	The component identifies “degree of” relation between an event and a modifier. As example, degree of pain.
LocationOfRelation ExtractorAnnotator	The component is used to recognize the “location of” relation between identified concepts. For instance, location of pain.
EventEventRelation Annotator	The pipeline used this component to annotate relation between two consecutive event mentions. The following are some event samples: stable, change, evident and process.
EventTimeRelation Annotator	The component identifies temporal relation between a time mention and an event. For example, for how long the patient has been sick.

The pipeline uses the AO (Annotation Ontology) model to represent the clinical reports annotations, producing enriched data with the fragments of the annotated resource and respective associated terms.

Figure 4.13 shows an example of an annotation for the word “chest” (i.e. the upper part of the trunk between the neck and the abdomen) detected on a medical report. The representation includes the annotation URI (*ao:Annotation*), the clinical report source (*pav:SourceDocument*) and the respective data (*ao:TextSelector*). The model stores information regarding the context of the annotation (e.g. *ann:T1_context*) such as location of the detected text in the report, the semantic group (e.g. *AnatomicalSiteMention*), the semantic identifier (e.g. *C0817096*) of the recognized text and the source report identifier (e.g. *480*). The *ao:exact* data property denotes the entity recognized by the text-mining tool. The concept normalization output is defined through the *ao:hasTopic* property, representing the semantic identifier of the annotated entity. The *ao:body* property represents the entity tag or domain detected by the text-mining tool.

An adaptable model that links and describes each interaction is also used to establish relations between them. Relation annotations are simple AO annotations with the addition of two object properties. The addiction of these properties allows us to establish binary relations between entity annotations and associated roles. Hence, we can identify the source entity annotation through the *ann:argument* property, and the respective target by using the *ann:target* property. By using the *ao:body* data property, we can establish the type of associated relation. An overview of this model is represented in the Figure 4.14 example, where a unidirectional relation between a “CT” (Computed Tomography) and the “abdomen” (portion of the body that lies between the thorax and the pelvis) is established. Basically, it shows that a CT was performed in (*location_of*) the abdomen.

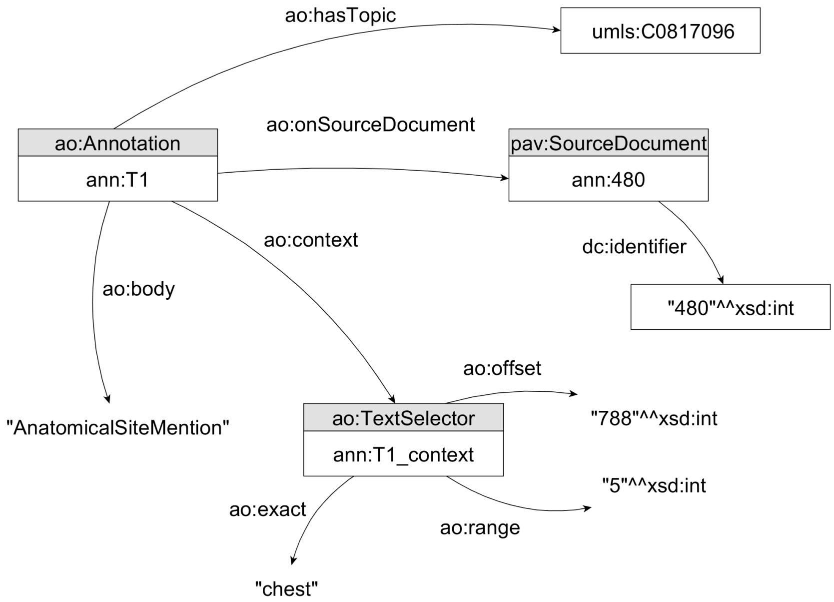

Figure 4.13 Entity and normalization annotation model.

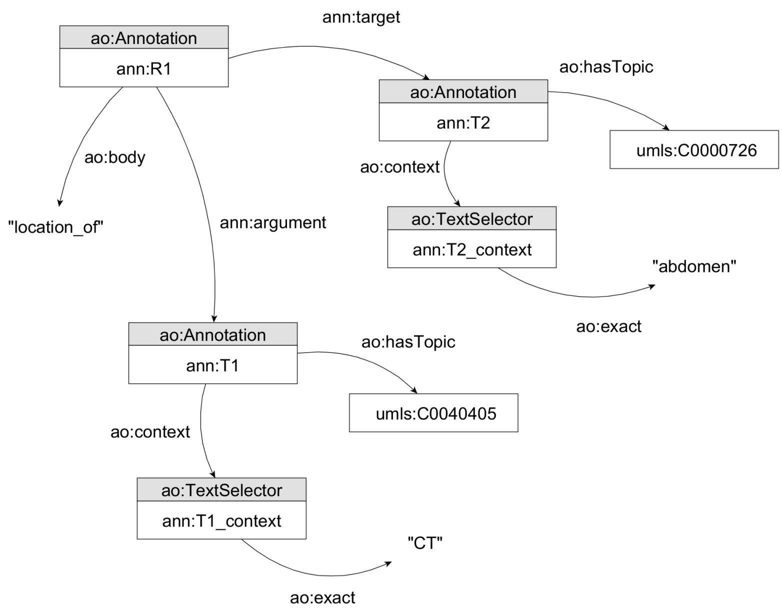

Figure 4.14 Relation annotation model.

The pipeline validation was achieved through a case study that aimed to create a semantic repository from a dataset of radiology clinical reports. Moreover, it is expected to use the facts represented in the knowledge base to serve in an inference engine for reasoning. The dataset contained approximately 16,000 clinical free-text documents and our pipeline constructed an associated semantic database with more than 6.5 million triples that were stored in a triple store database using COEUS.

The REST service for annotating the biomedical text is the most time-consuming component of our pipeline. So, during the development of the solution we had this fact into consideration. The service uses a processing scheduler that was implemented to take advantage of multiprocessing. It is possible to define several pipeline processors to handle the requests. Each pipeline processor runs in a thread, which allows us to take advantage of the multiple cores available in the server. The impact of implementing this kind of solution for our cTAKES-based annotation service was evaluated. We tried several set-up configurations, using different number of launched pipeline processor. It was measured the timespan to annotate 100 reports using the annotation service. Furthermore, for each experiment, we did 5 runs aiming for analysing the standard deviation and to be more confident with the results. The following picture (Figure 4.15) shows the annotation service performance while varying the number of pipeline processors from 1 to 10 processors.

By analysing the results, we can observe that using 8 processors we decreased the time needed to process the reports by 74% compared with the default usage of one cTAKES pipeline processor.

Also, we observed that using more than 8 processors did not reduce the processing time in a single computer. Therefore, a solution to improve the performance should use clustering computing for large-scale data processing.

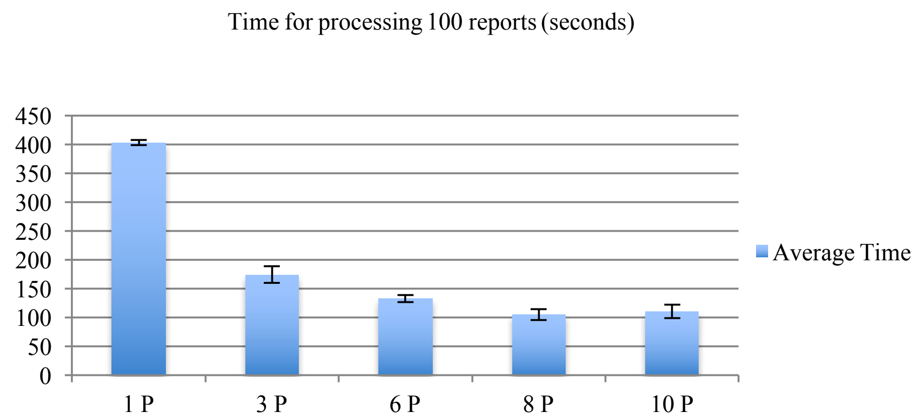

Figure 4.15 The annotation service performance:
This picture shows how changing the number of pipeline processors can improve the service performance.

After processing the reports using our pipeline, we retrieve information stored in the knowledge base using SPARQL queries contemplating semantic identifiers and semantic relations. Therefore, we could retrieve all distinct reports where specific UMLS CUIs are present. We were also able to exploit semantic properties associated to relations established between concepts.

4.4 Clinical Recommender System for Radiology

The need for better information management of medical images has fuelled the desire to bring more advanced query mechanisms, based on content. While the motivation to organize things is inherent to ourselves, it is paramount in medical institutions where data must be further categorized and placed at the disposal of practitioners for referral in order to maximize the usage of their time.

There are several reasons why there is a need for more advanced data query mechanisms in a clinical context.

One such reason is the need to handle the steady growth rate of medical images within a PACS. While is unlikely that alphanumerical query/retrieve in DICOM will be phased out, directly querying the DICOM headers may contain a fairly high rate of errors. For example, error rates of 16% have been reported in the field anatomical region [276]. This hinders the correct retrieval of relevant images when using only text-based methods. Content-based Information Retrieval (CBIR) systems have also been trialled as support tools for help in clinical decision-making. This can be achieved by using the CBIR to provide a set of images to be used as evidence to support a diagnosis or as a quick way for a practitioner to access a second opinion Figure 4.16. The potential for this type of assisted interpretation is motivated not only by time constrains, but also by the recognition that variations in interpretation between practitioners, commonly based on perceptual errors, lack of training, or fatigue, do exist [277]. Significant inter-observer variation has been documented in numerous studies [278] and in [279] it is pointed out that approximately 4% of radiologic interpretations rendered by radiologists in their daily practice contain errors.

Recommender systems (RS) have been widely explored in many information systems aiming to advise users about items related to their interests. Usually, to achieve this, RS get insights from past experiences of the users [67]–[69]. For example, decision-making processes can be fed by what the users listen to, what they buy or what they usually do in each situation. The data collected permits the creation of ground knowledge necessary to create useful suggestions [67]–[69] (Figure 4.17).

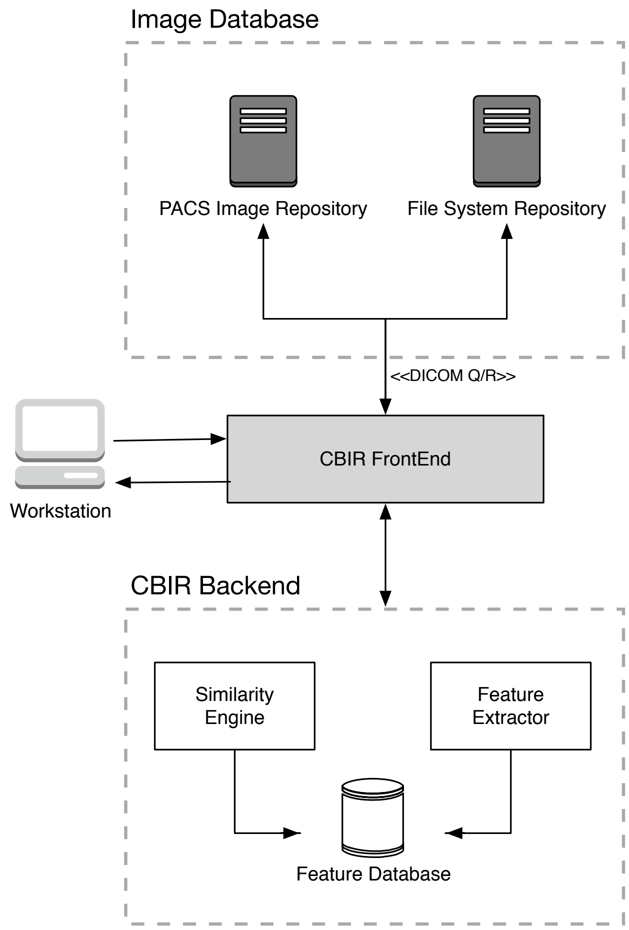

Figure 4.16 Generic CBIR system.

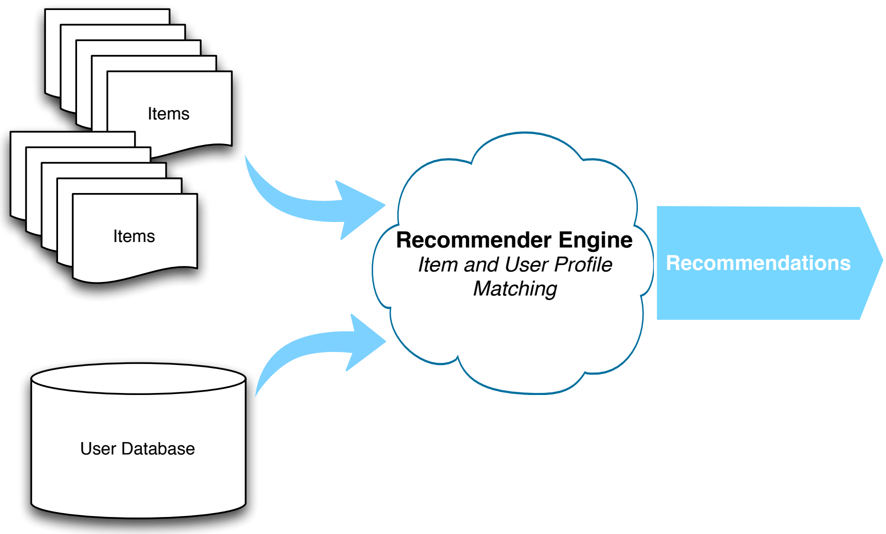

Figure 4.17 Generic recommender system.

Recommender systems have been successfully implemented in many ecommerce applications, in order to stimulate increased profits [71], [106]. Early solutions for RS were based on simple observations of users' basic daily activities [68], [73]. For example, if a costumer frequently buys books about a certain subject, there exists a high probability of acquiring another book related to that topic. Usually the knowledge built into the RSs is incrementally improved by feeding the system with feedback obtained, for instance, from the users. This feedback may be obtained from an explicit or an implicit way.

Recently, RS have been also applied to healthcare services and although this may be extremely advantageous, it may also raise some concerns related to privacy issues [280]. Some researchers argue that RS have great potential to improve healthcare informatics solutions, and they have been using them in several applications; e.g. nursing care planning to provide clinical decision support, nursing education and complement existent practice guidelines [74]; and to make recommendations and suggestions for preventive intervention [75].

Moreover, social networks together with RS have the potential to be an added value to healthcare information systems. On the one hand, the combination of social networks information and RS have been shown to be useful for supporting patients with chronic diseases [76]. For instance, this can be also useful for creating social links between patients with similar assessment reports, and also to assist physicians in their assessment [77], [78].

According to Herlocker *et al.* [79] there is a set of fundamental features for any recommendation systems. For some systems where the items suggested by the RS can be critical (e.g. medical applications) or the number of items is small, it seems better to recommend all the important items instead of a few, which the RS thinks to be relevant – maximize the recall. In this situation, the RS can be useful because it recommends all the important items in a ranked order. The order is frequently valuable when the users need help to identify which items are more important.

4.4.1 Recommender System Architecture

To support physicians while reviewing clinical cases by providing them useful information that may be used in decision-making process, we propose an architecture that leverages the clinical data present in a PACS to generate recommendations (Figure 4.18). The generated recommendation may increase the physicians' confidence if they provide added-value information such as previously clinical cases that are like the one they are analysing. Moreover, these advises can be seen as second opinions available on reviewed and trusted clinical information repositories.

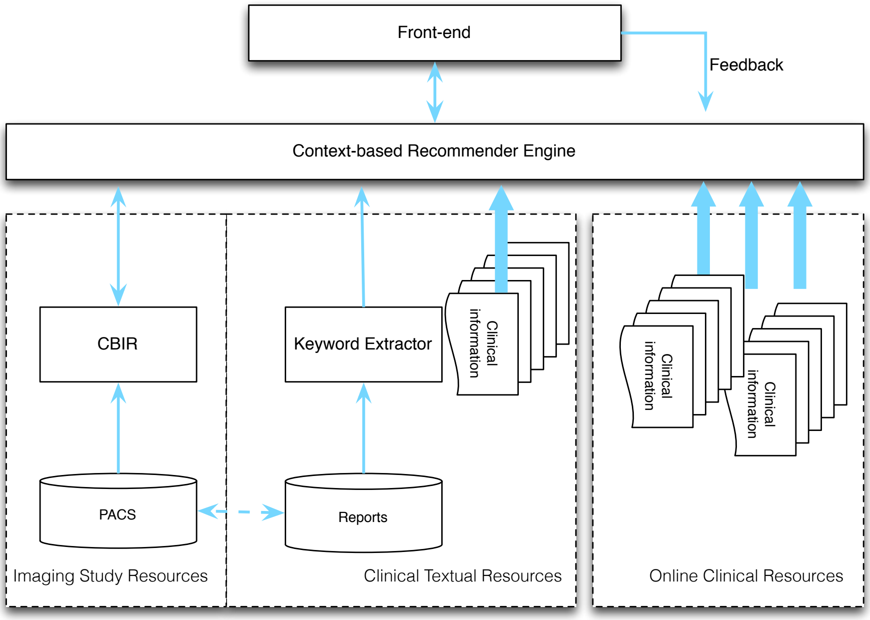

Figure 4.18 The clinical recommender system architecture.

The integration of a recommender system in the medical image viewer (clinical workstation) appeared as a potential tool for providing valuable knowledge to the physicians. This knowledge may be used to aid them while performing a clinical case analysis. However, the diversity and amount of information available nowadays is immense, which means that the identification and recommendation of useful articles is a difficult task. So, to overcome this problem we used current context information to extract features aiming to improve the precision while finding useful documents.

The resulting system was planned as a component to be integrated in the Web-based DICOM Viewer used in collaborative medical imaging environment [126]. Nevertheless, its architecture may have may application in other radiology systems.

In the back-end, we use Dicoogle-PACS as the medical images repository [184]. Besides common functionalities available in a standard PACS, this open source PACS also provides a CBIR component that extracts and indexes image-based features, which are used to find similar studies. Moreover, the CBIR implements a plugin-based architecture that makes possible the development of algorithms optimized to find similar studies in a specific problem domain. Currently, we have already deployed a plug-in implementation for mammography exams. By analysing tissues anomalies, for instance, it can identify similar studies aiming to faster recognize breast cancer exams.

The RS engine is deployed along with the DICOM Viewer server (Figure 4.19). The communication between the viewer and Dicoogle is made using the DICOM protocol, while the CBIR component offers a REST API that allows querying for similar studies. The RS uses this API to recommend similar studies to the users.

The front-end is completely developed using Web technologies. The Web-based DICOM viewer provides a plug-in interface that enables the injection of custom tools in the Web viewer application. Thus, we used this feature to insert a custom tool that provides a list of recommended items, e.g. similar studies, with reports and links to clinical resources available online.

The proposed architecture uses the CBIR to extract several features from the current study being analysed, and to create a feature vector representation of this study. While indexing images in Dicoogle, the CBIR extracts the features to build the feature vector that will be used to find similar studies to the one being reviewed. When the radiologists are reviewing a case, similar studies can also be provided, to complete the knowledge or the report about the current study (Figure 4.20).

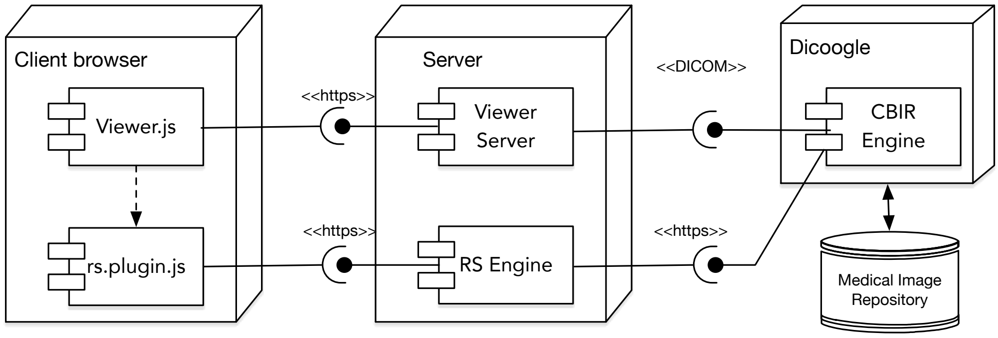

Figure 4.19 The client-server communication architecture.

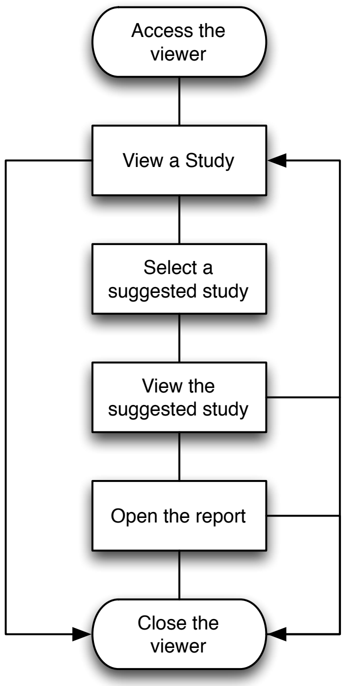

Figure 4.20 Accessing reports of related studies.

Moreover, aiming to improve both the CBIR performance and the textual information engine, feedback is collected from radiologists to confirm the similarity of the studies. By default, we rank the study as important if the physician use it for accessing further information. However, the physician can remove a study from the recommended studies or do nothing. All, these actions are used as positive or negative feedback for further improvements in the ranking process while searching for similar studies.

The CBIR plays an important role while finding useful studies that are relevant to the current review context. Besides the previously identified advantages of accessing related studies, these studies are also important for the recommender system engine. The texts extracted from their reports are then used to design the feature vector that is sent to the recommender system engine for retrieving relevant suggestions. The Keyword Extractor uses CTAKES framework to annotate and extract clinical knowledge from those reports. From the annotations, we get important keywords that describe the reports' main topics.

The extracted keywords define the knowledge domain and concepts that describe and contextualize the study being analysed. If the reports belong to studies that are similar the one in the current presentation context, we infer that the domain and concepts identified in the reports can also be descriptive for the current study. So, the system uses this information to query the recommender system for relevant information considering the knowledge extracted from those reports.

The recommender system provides access to knowledge that can come from heterogeneous locations. This knowledge is integrated into the RS by using connectors that have the role to extract information from a specific data source and to the index the data obtained (Figure 4.21).

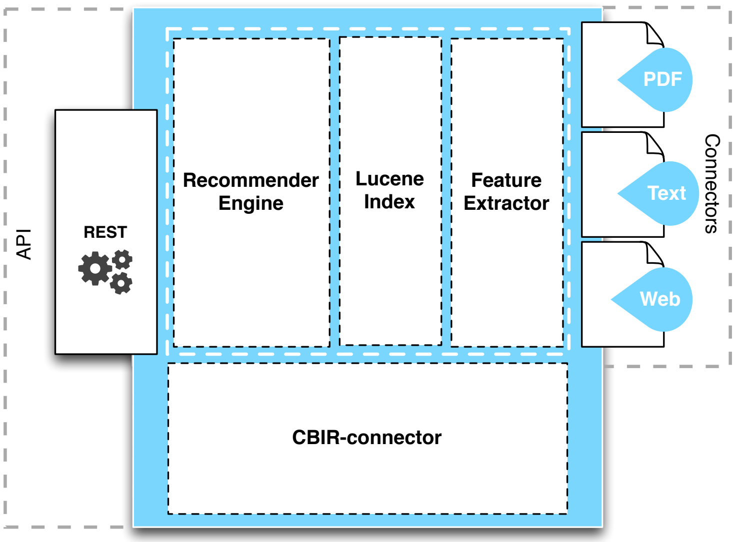

Figure 4.21 Recommender system engine.

The information is indexed using Lucene [281]. Before indexing documents, our RS annotates those using CTAKES. The annotations are indexed as keywords aiming to improve the recall and precision while searching. To generate suggestions, the RS uses the information gathered through the Lucene engine. Studies similarity score is based on document Cosine Similarity (1) of weighted vectors V(q) and V(d), where q is the query and d is the document.

$$document\_similarity(q,d) = \frac{V(q) \cdot \mathrm{V}(d)}{|V(q)||V(d)|} \qquad (1)$$

Lucene provides also some other features for computing the similarity. The engine allows boosting specific terms of the query and of the documents. We take advantage of this feature to improve the performance by giving a boost for the annotated keywords. Moreover, the system makes query refinement using the feedback obtained from the users. The refinement pushes toward a vector of relevant documents and subtracts the non-relevant ones. The query refinement is based on Rocchio's query expansion with pseudo-feedback (2) [93].

$$q_{i+1} = q_i + \frac{\beta}{R}\sum_{j=0}^{R} r_j - \frac{\gamma}{S}\sum_{k=1}^{S} S_k, \text{ where:} \qquad (2)$$

R: # relevant documents; S: # non-relevant documents; r: relevant documents vector; s: non-relevant documents vector; and $\beta + \gamma = 1$.

4.4.2 Case Study

As a case study, we implemented a connector for indexing biomedical literature present in PubMed that is related to the mesh term "radiology". The indexed dataset contains near 650,000 documents.

The relevance feedback from CBIR helps improving the quality of the suggested information by correctly find similar studies, and better define the topic of the study being analysed. On the other hand, feedback obtained from users contributes to improve the performance of the recommender system.

This scenario provides an example of the key features of user interaction with the system. The problem considered in this scenario represents common needs that physicians may have while reviewing mammography studies in day-to-day work.

Physicians usually review many cases a day. However, even being relatively expert in reviewing mammography exams the physicians may face some rare cases that may raise doubts in the decision-making process, even though they have already reviewed a similar case. The rare cases are hard to diagnose and even if there are similar cases it is difficult to recall which are the studies and where they can be found. In this case, the system may prove to be helpful aiding them in the analysis. For example, if the physicians are analysing a rare case, like lobular breast carcinoma that is a sub-type of breast which diagnosis is not easy and straightforward, they can access the recommender tool to obtain recommendations to support their decision. The recommender tool gets information about the current study and send this information to the Context-based Recommender Engine, which uses the CBIR component to find studies that have similar image features to the current one (Figure 4.22). Thus, the system streamlines access to related studies, which contains image features related with lobular breast carcinoma, and the physicians do not have to waste time to remember and find those studies. On the other hand, the physician may find second opinion within the documents that are also suggested by the RS. For instance, from the indexed PubMed documents the system may suggests some documents like:

- "Invasive lobular carcinoma of the breast: spectrum of mammographic, US, and MR imaging findings", Lopez JK et al;
- "Management of breast lobular carcinoma in situ: radio-pathological correlation, clinical implications, and follow-up", Capobianco G et al.;
- "Pure lobular carcinoma of the breast presenting as a hyperechoic mass: incidence and imaging characteristics." Jones KN et al.

4.5 Final Considerations

Collaborative systems can simplify the establishment of teleradiology expert groups with tools that enable improving clinical practice. The usage of collaborative systems in radiology can be potentially streamlined through the adoption of Web technology, increasing the quality of current solutions, facilitating the sharing of clinical information, of medical imaging studies, and of clinical cases diagnostics among collaborators through social media platforms.

The purpose of the conducted research was to improve medical information availability and simplify the establishment of teleradiology expert groups. The research has shown that it is possible to take advantage of cloud-based services and emerging Web technologies to leverage collaboration among physicians and to offer rapid access to clinical data, leading to improvements in clinical practices. It proved to be flexible and useful in different teleradiology scenarios including tele-reporting service and teaching of radiology. We have used the platform to connect two geo-distributed institutions promoting tele-work and tele-reporting. In addition, due to the fact of being a cloud-based architecture, it deals seamlessly with the increase in storage demand, being capable to handle tens of GB of data that institutions monthly generate. The storage growth is a problem that these institutions have always been facing, leading to the need for a hardware upgrade and replacement.

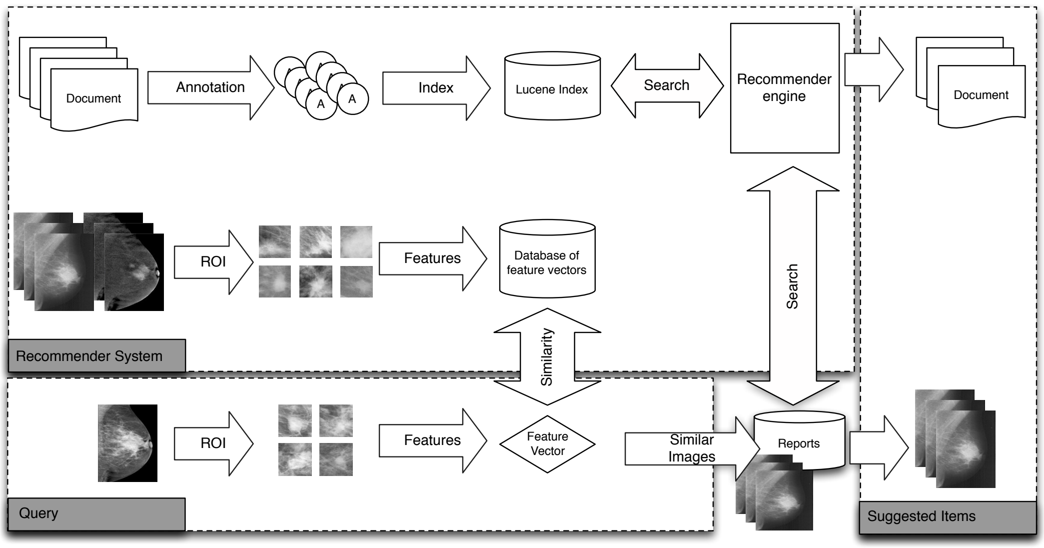

Figure 4.22 Case study example.

In this sense, our use case has brought another practical perspective to deal with the problem by outsourcing the infrastructure to public or private cloud vendors, thus being able to increase the storage as needed without being concerned with hardware management.

Further, we have customized the platform to work as an e-Learning platform for a radiology class, where the radiology trainees have their individual user areas. They can share resources, do collaborative work and access visualization tools for supporting the classroom's workflow. The platform was confirmed to be useful in a tele-teaching scenario where students can remotely access the clinical cases, which the teachers share in the platform. These advantages become more convincing when we analyse the students' difficulties in former classes where, to perform the same kind of analysis of clinical cases, they had to install visualization software on their computers or they needed physical access to the workstation in their classrooms. Moreover, the management of assignments become much easier, since teachers and students can now access them directly in the platform.

The results of this research support the idea that efficient dataflow and availability of medical records are key factors for the success of telemedicine. Moreover, to be effectively adopted, technical solutions need to follow current trends in software applications – ubiquitous and easy to use. We believe that solutions like the one we proposed in this research will have an important role in the future of healthcare systems, where knowledge sharing and collaboration is becoming increasingly relevant.

Also, we see great potential in exploring the data generated in collaborative radiology environments, and therefore, we implementing algorithms that use multitude of clinical data available on our platform to create semantic knowledge base for radiology and to generate recommendations useful for users in the platform. For example, by extracting several features from the medical image repository and from textual reports, similar studies are highlighted when a physician is performing a clinical analysis.

We developed a complete text-mining solution to extract meaningful information from clinical narrative reports. This solution was implement “as-a-service” using the cTAKES framework. The main goal was to provide an easy and functional service that can detect relevant clinical concepts and their respective interactions. As such, the developed tool can easily detect entities, concepts and relations contained in clinical text-reports. This contribution empowers the emergence of novel knowledge discovery methods through well-structured clinical report data in radiology.

We also presented a solution to deliver important clinical information to the practitioners while performing a clinical analysis. We focused on the development of a modular architecture that explores state-of-the-art solutions to build an integrated clinical recommender system. The architecture combines features extracted from images and reports to build a useful tool for practitioners. The proposed system may benefit physicians, either by giving them more confidence in the decision-making process, providing them a quick access to important information that may be helpful for their current needs, or by expediting the search for related studies that were gathered and analysed in the past.

The integration of clinical information and recommender systems in clinical workflows will play an increasing important role to simplify physician’s tasks and to leverage the quality of healthcare services. The clinical knowledge that results from previous EHR and from research is clearly relevant for healthcare practice. Meanwhile, as recommender systems evolve novel applications are expected. We believe that these systems can be a key component and will have wider application in biomedical informatics.

As expressed in previous sections, a special care was taken on data protection, regarding information stored and transmitted in the collaborative platform. Therefore, we developed features to improve the anonymization of DICOM images regarding annotations in the pixel data, which will be present in the next chapter where we will approach problems like patient privacy and data security in collaborative radiology systems.

5 Patients De-identification in Collaborative Medical Systems[1]

"A computer would deserve to be called intelligent if it could deceive a human into believing that it was human."
Alan Turing

The protection of patient privacy is extremely important for any EHR system. It becomes even more imperative in collaborative environments or clinical research trials [282], [283]. In the medical imaging field, removing patients' sensitive information from imaging objects' metadata is possible using available tools [284]. Additionally, there are solutions for data sharing safeguarding patient' privacy, allowing authorized users only to access the private information [285], [286]. However, these tools are inefficient in cases where patients' demographic information is present in the image pixel data. For example, modalities such as ultrasounds (US) have textual information (including patient's name) burned in the image, which may lead to the disclosure of patients' information in some usage scenarios. Therefore, medical image anonymizers should remove any sensitive information from both metadata and pixel data to be compliant with the HIPAA (Health Insurance Portability and Accountability Act) privacy rule which establishes standards for full de-identification of the patient [287].

In this chapter, we will discuss some of the security and privacy issues that may hinder collaboration in radiology, and we will propose a novel method for de-identification of medical images' pixel data. As main contribution, we developed a service which can be used do de-identify data and streamline data sharing in collaborative radiology environments.

5.1 Security and Privacy Issues in Medical Systems

Information security is a growing issue in health informatics because nowadays it is increasingly common to find electronical medical records storing a huge amount of sensitive information that needs to be secured. As such, medical systems increasingly require stronger security models to prevent data disclosure.

[1] This chapter was largely based on the publication *A machine learning methodology for medical imaging anonymization*. In 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2015 [347]

This subsection will address important measures adopted to preserve information security in medical systems, namely we will discuss the usage of encryption models in data storage and transmission and we will also present authentication and authorization schemes used to safeguard data access to authorized persons only.

5.1.1 Data Encryption

There are several well-known cryptography algorithms for securing communication and encrypting data storage [288], [289], relying mostly on symmetric-keys or asymmetric-keys. The usage of these methods in medical systems may depend on different factors, including if it is or not required data authentication, communication performance, access model and storage limitations [288]–[291]. Regarding data communication, medical systems can secure data transmission through communication encrypted using SSL or TLS, which are well-known standard security technologies for establishing encrypted link between computer nodes [292].

Modern Key-based cryptography is used to ensure high-security level when performing data encryption [293]. Key-based cryptography algorithms use a key (encryption key) to encrypt data and resulting ciphertext can be converted back to plaintext using a key-based function (with a decryption key) [293]. Usually, these algorithms' strength is related to the key length (i.e. larger key is better). There are three types of key-based cryptography: secret-key cryptography, public-key cryptography and digital signature [293], [294].

Secret-key cryptography requires that the encryption key and the decryption key are the same, which means that there should be a key agreement between actors before sending data. The main concern behind secret-key cryptography is that anyone with access to the key can cipher and decipher confidential messages. This means that all security level of symmetric key algorithms relies on the key, therefore, it should be kept in secret avoiding it to be intercepted by unauthorized actors.

Viana et al. proposed a method to secure medical data in a cloud-based architecture for medical systems which uses a symmetric encryption [295]. They used a security server to securely store the cipher parameters used to encrypt and decrypt data stored on the cloud. The security server controls the access to the cipher parameters via user authentication, to decide if a user has access or not to cipher parameters required to access specific data in the medical system.

The usage of symmetric encryption in medical imaging systems is applied to cipher image metadata and image pixel data [288], [290], [296]. However, storage of image metadata as ciphertext brings some challenges including searchability, requiring that each search query word is encrypted with the secret-key [290]. Though, the main problem relies in secret-key distribution, which represents a risk for the key interception by unauthorized users. This is risky because the system needs to send to the secret-key along with the ciphertext to enable decrypting the data. In this sense, the usage of public-key cryptography is preferable but these cryptography scheme requires more computational power in the encryption process, being much slower than encryption with symmetric algorithms [294]. Wong presented a hybrid cryptography solution where he explored the best features of secret-key and public-key cryptography, using symmetric algorithms to encrypt the data and using public-key cryptography to reduce key management complexity [288]. The secret-key used to encrypt the data is encrypted with the public-key of the receiver and sent to the receiver. Therefore, the receiver uses its private-key to decipher the ciphertext and retrieve the secret-key and then decipher the medical image data.

5.1.2 User Authentication and Access Control Models

Access to medical systems storing patients' EHR can be regulated via user authentication and access control models designed to preserve privacy requirements such as to restrict user access to the EHRs of specific patients, to control access to data based on users' role in the organization and to control users' data access rights (e.g. read, write).

User authentication in medical system is important to ensure rigorous user identity and authentication methods, which can go from simple user/password authentication method to complex method using user's biometric data for authentication [154]. Public key infrastructure is used to develop reliable solutions for rigorous user authentication based on digital signature scheme [297]–[300]. Moreover, the combination of two or more authentication methods like PIN, fingerprints, smart cards and digital signature can improve the security level in terms of user authentication [301]–[307]. Also, authentication methods may provide some versatility in terms of data access in medical systems, such as combining use of username/password authentication method for permanent access to data and PIN for single access to a given information, which access right may expire after some time.

Authentication methods allow user identification, but access to resources must be controlled using access rights to guarantee data privacy. Role-based access control (RBAC) is one of the most used access control method in medical system [308]–[312]. This model defines roles, which have permissions and restrictions. A user may have one or more role in the organization, which define what access rights he has. Extensions to the RBAC model has been proposed to specific use-cases in medical systems [313]–[315]. Peleg et al. designed the Situation-based access control (SitBAC) model for healthcare scenarios of data access where access to patients' data is regulated according to the context of the request [315]. This model has as central concept the *Situation*, which defines formally the representation of a patients' data access context. The context in a system implementing the SitBAC model is defined by the entities data requestor, patient, EHR, access task, legal authorization, and response. Health organizations define different access scenarios by the means of *Situation instances* controlled by data access policies. Moreover, Beimel et al. established a knowledge framework to represent and implement SitBAC policies as a knowledge model with an inference method [316], using Web Ontology language (OWL)-based *Situation* classes and Semantic Web Rule Language (SWRL).

In the RBAC model each role has predefined permissions which should always be obeyed restricting users' action. However, it represents a constraint in health organizations where can be necessary to bypass access control rules in case of emergencies to deliver healthcare. Therefore, medical system may allow exceptions for disclosure of data in emergency scenarios (*"break the glass"*), which may bring some issues regarding patients' data security and privacy. Ardagna et al. addressed this problem and proposed an access control method which covers *"break the glass"* exceptions under complex policies regulating these actions and classifying requests as abuses or planned exceptions [317]. The proposed access control model consists of four policy spaces defined by denied accesses, authorized accesses, planned exceptions and unplanned exceptions.

In another perspective, medical systems may implement patient-centric authorization models allowing patients to specify access policies to enable authorized and discriminatory sharing of patients' EHRs. In this way, patients control which authorized users have access to their critical EHRs. Jin et al. show an application of a unified access control model with patient-centric authorization for selective sharing of virtual composite EHRs, enabling access to data following a unified logical EHR model with special attention to distributed data integration and patients' privacy protection [318].

5.1.3 DICOM Security Specifications

Public-key cryptography can be used to ensure data security regarding confidentiality, authenticity and integrity [293], [294]. Cao et al. investigated the application of public-key cryptography to transmit medical images as data envelop which cannot be decoded by anyone other than its correct recipient [289]. They also specified a way of assure the integrity of medical images and patient information via digital sign, which they suggest to be embedded into the image in a form of steganography without affecting the diagnostic quality of the image.

Regarding networking, the DICOM standard includes specifications to assure security in terms of secure communications and digital signature [319]. The standard focuses on a set of security profiles including secure use profiles, secure transport connection profiles, digital signature profile, media storage security profiles, etc.

The DICOM standard also comprises communication security, which is analogous to VPN connection or SSL used to extend a private network to remote areas. It uses public-key cryptography to ensure that the receiver is the only one able to read encrypted messages. There are two cryptographic protocols, the TLS and the ISCL (Integrated Secure Communication Layer V1.00), which provide communications security and message integrity check over a DICOM network [320].

Besides security on the communication layer, the DICOM also defines mechanisms for data integrity validation of SOP instances through digital signature. The digital signature is performed over a subset of DICOM elements, calculating a hash value of the data which is then signed using sender's private-key. The integrity of the DICOM elements can be verified by comparing the hash value of the elements with the hash value in the digital signature.

The DICOM standard defines security mechanism to avoid unauthorized access to data in media storage. It proposes security aspects to assure DICOM files security regarding confidentiality, integrity and data source authentication. Files are sealed into a cryptographic envelope which may contain signed-data content or simply digested-data content. The DICOM standard defines the Advanced Encryption Standard (AES) and the Triple Data Encryption Standard (3DES) [294] as the algorithms that should be used for content encryption.

5.2 A Methodology for Medical Imaging Pixel Data De-Identification

The use of medical images beyond the institutional border, for instance, to build phenotype-specific databases, for teaching and even for research purposes has been increasing. Thus, efficient tools to perform patients' de-identification are required. The anonymization process should remove or replace any information elements that may lead to patient identification. There is well-known protected health information (PHI) in the standard DICOM attributes [321], [322]. However, some manufacturers also use private attributes to store complementary information, thus requiring manual processes to make this data anonymous [323].

Although earlier research outlined the importance of creating mechanisms to verify and remove PHI from DICOM metadata [324], there are still gaps regarding the removal of PHI annotations burned into the image pixels. Tools for this task already exist, but they are based on manual processes for identification of image areas containing PHI annotations [284]. Newhauser et al. [321] automated this process using Optical Character Recognition (OCR) to detect text burned into the images. Nevertheless, the proposed algorithm removes all alphanumerical annotations. This is not desirable in some situations where some important annotations must be preserved, for instance, examination parameters and measurements in echocardiography.

The sharing of de-identified medical images retaining useful values for research is a challenge. Huang et al. [325] have proposed a method for preserving the privacy and security of patient medical records in this scenario. They followed the HIPPA privacy rule to design a solution aiming to protect, recover and verify patients' identifiers in EHRs. De-identification of medical images using pre-defined area filters and OCR to recognize and remove patient identifiers was also considered. They applied OCR in the image to recognize burned identifiers. After OCR, they obtain the text words and the positions of words in the image and then remove them from their related position. The authors reported a 65% success rate when de-identifying image pixel data. The OCR process aimed to recognize and remove HIPAA identifiers from image pixel data. The pixel data de-identification was not reliable due to errors when recognizing ambiguous characters such as "g", "9" or "1", "l" or "0", "o"; and due to medical image background, which complicates the character recognition processes.

Another challenge is patient privacy protection in medical images containing facial features. Li et al. [326] pointed out the need of DICOM brain images defacing and proposed method to remove facial features without remove brain tissue to ensure correct brain images de-identification.

Chen et al. have developed important work in text detection and recognition in images and video frames [327]. They propose one methodology for text detection using machine learning, and one for text recognition supported by segmentation and the traditional OCR algorithm. This work has guided numerous research projects in this area. In medical imaging, radiation dose information extraction and modality categorization are examples of applications that take advantage of text recognition [284]. Florea et al. [328] implemented a rule-based algorithm for modality categorization of medical imaging that automatically interprets burned annotations in the images. Nowadays, many new challenges have arisen in text recognition, for instance, to deal with real-time scenarios and handwritten forms of languages, such as Arabic, Japanese or Chinese.

The research presented in this section was guided by the following questions:

- Is it possible to implement an automated process using machine learning for the identification of patients' information in pixel data?
- Does this methodology provide acceptable accuracy while identifying and removing patient information from the medical imaging?
- Can this method be successfully applied for removing burned annotation from any kind of medical imaging?

The proposed methodology uses end-to-end text recognition based on machine learning algorithms and models, which were built using data collected from a medical imaging centre, namely ultrasounds (US) produced by modalities of distinct manufacturers. The approach taken in this study is a mixed methodology based on image processing techniques and machine learning algorithms (linear models, neural networks, and random forest classifier). Based on the anonymization results, we have also developed public Web services for developers, to promote the use of the proposed methodology. These include methods to upload images and launch the de-identification task, follow the task progress, and download the results. In addition, we developed a Web application which offers a user interface (UI) to access the available functionalities, an individual storage area with search functionality, and a Web viewer for medical imaging.

The proposed methodology for de-identification of pixel data in DICOM medical images follows a pipeline composed of 6 steps, which are presented in Figure 5.1. The first step consists of extracting PHI elements from the DICOM metadata. We extract the following sensitive DICOM attributes: patient name, ID, gender and accession number. This information is used to fill the set of words that need to be removed from image pixel data. In the next step of the pipeline, image pre-processing algorithms, such as adaptive bilateral filter and total-variation de-noising [329], are used to prepare the image for the character detection and recognition tasks. Once we obtain the pre-processed image, the object detection step is performed using functions to identify contours and detect objects [330] through bounding rectangles that are subsequently normalized. Next, each object is classified using a machine learning-based OCR system that returns the identified character. After classifying the objects, the words present in the image are reconstructed, considering the objects' position and their classification. The next step detects which of the reconstructed words are present in the set of sensitive information.

To reduce OCR misclassification, we use a method based on the Levenshtein distance between the reconstructed words and the words present in our set of sensitive words extracted from DICOM metadata. Finally, sensitive words found are removed from the image pixel data by drawing a white rectangle over them. The next subsections will describe in more detail the several steps of the proposed pipeline.

5.2.1 Image Pre-processing

The pre-processing pipeline step is applied to increase image contrast and is a process that improves the precision of object detection. In this step, three pixel-based transformations are applied to the image pixels. The first transformation applied to images is a total-variation de-noising function. The second step consists of performing an adaptive bilateral filtering that reduces noise while keeping the edges. It is a linear filter that computes the value of a pixel in the image location (x,y) using the value of the neighbouring pixels.

Lastly, a binary threshold is performed. So if the pixel intensity at location (x,y) is higher than the value of the threshold, the new pixel intensity is set at 255.

Otherwise, the pixels are set at 0. This allows us to sharpen objects' contour, improving their identification and segmentation (Figure 5.2).

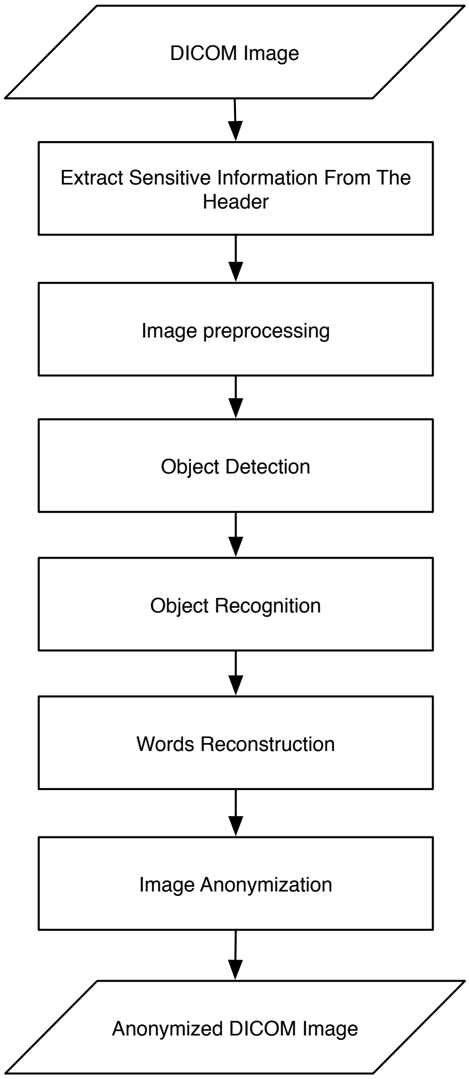

Figure 5.1 Anonymization pipeline for pixel data in DICOM images.

a)

b)

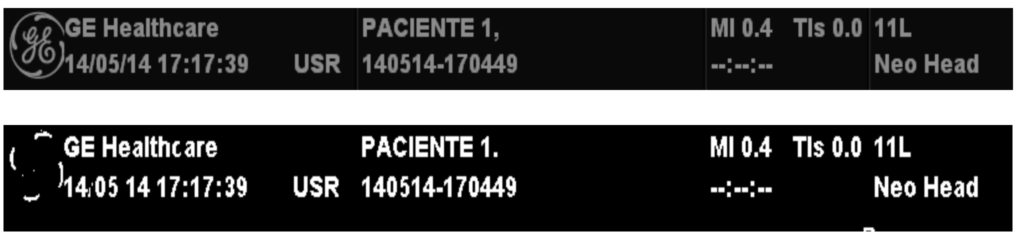

Figure 5.2 Pre-processing step: a) original image; b) pre-processed image.

5.2.2 Object Detection and Recognition

Object detection follows the pre-processing step and aims to identify objects' contours and to create a rectangular bounding box for each object (Figure 5.3). These tasks are performed using the OpenCV 2.4 library [330], [331] (functions *findContours* and *boundingRect*), and in the end, each contour is defined using only its end points, i.e., a rectangular contour is encoded with 4 points.

After obtaining the set of points that define the contours, the system computes the minimal bounding rectangle for each contour.

Objects with very small or too big bounding boxes are discarded to minimize the noise in the word reconstruction process. The remaining list contains the objects which are candidates to be classified as characters. The objects' coordinates are stored to allow subsequent word reconstruction.

Finally, the objects' dimensions are harmonized by resizing them to a patch with a pixel area of 32x32. The resulting elements are used as an input feature vector in the object recognition step.

A classification task consists of creating a model that correctly assigns pre-defined classes to samples, in our case, automatically labelling the images' patches with an alphanumeric character. Whatever the specific method employed, a data mining classification task starts with a training set $D = (d_1 , . . . , d_n)$ of samples that are already labelled with a class $C_i \in C$ (*e.g.*, a-z and 0-9). The challenge is to determine a classification model that can assign the correct class to a new image patch *d*.

We implemented an OCR system based on machine learning classifiers to be able to perform object recognition in the pipeline. Implementation of this character recognition tool required the study, selection and experimental evaluation of several specialized algorithms. In this process, four different strategies using machine learning algorithms and ensembles were proposed and evaluated. The models were built targeting our specific problem, i.e., the de-identification of US medical imaging. This decision was due to the fact that this modality represents the vast majority of cases requesting pixel data de-identification [332].

Figure 5.3 Object detection.

5.2.3 Character Dataset

We extracted 62992 character samples from the *73K Character* dataset [333] (including numbers, lower case and upper case letters) to generate the dataset we used to train and test the OCR system. When building our dataset, we discarded the handwritten characters and Kannada characters present in the 73K Character dataset because in our problem these types of characters are not likely to appear. We used the resulting dataset to model a multiclass classification problem. Each image in the dataset is labelled with the respective alphanumerical present in it (i.e. 0-9, a-z and A-Z).

In our approach, upper case and lower case characters were counted as belonging to the same class. So, the classification problem had to deal with alphanumerical classes.

Extra noisy data were artificially generated by performing morphological transformations of the images (i.e. erosion, dilation) and applying a convolution (linear shifts of 1 pixel in each direction) to the samples in the training data.

The final dataset comprised 944880 labelled samples. The process to generate these 944880 samples is depicted in Figure 5.4. We split the dataset between a train set and a test set through stratified sampling where we took 90% of the samples to build the train set and the remaining 10% of the samples was left for the test set.

5.2.4 Building the Model for Character Recognition

The development of an efficient model for character recognition is crucial in our proposal. Based on state of the art models, we tested four different strategies, as presented in Figure 5.5. The classifiers use as input a feature vector with 1024 features extracted from the raw image data (32x32 matrix) identified in the object detection step. The input value of each feature may vary from 0 to 255 representing the pixel intensity in grayscale.

A Random Forest (RF) [334] with 100 trees was the first classifier model that we tested. The RF algorithm consists of an ensemble of decision tree classifiers that are fitted on sub-samples of the dataset and uses a voting method based on the prediction of each decision tree to improve the predictive accuracy and to control over-fitting. The decision trees in the RF are trained independently, in a randomized way. The RF algorithm uses a random sample of the original training data to train each tree in the forest. Another specificity of RF is that the trees use a random subset of the features to determine the best split at each node instead of all the features.

Usually the trees in RF grow to their full extent without pruning, but some implementations allow the trees' maximum depth [334] to be defined. The RF classifier fits well in problems such as the one we were dealing with because it is known to be capable of handling a large dataset and high dimensionality of data well [334].

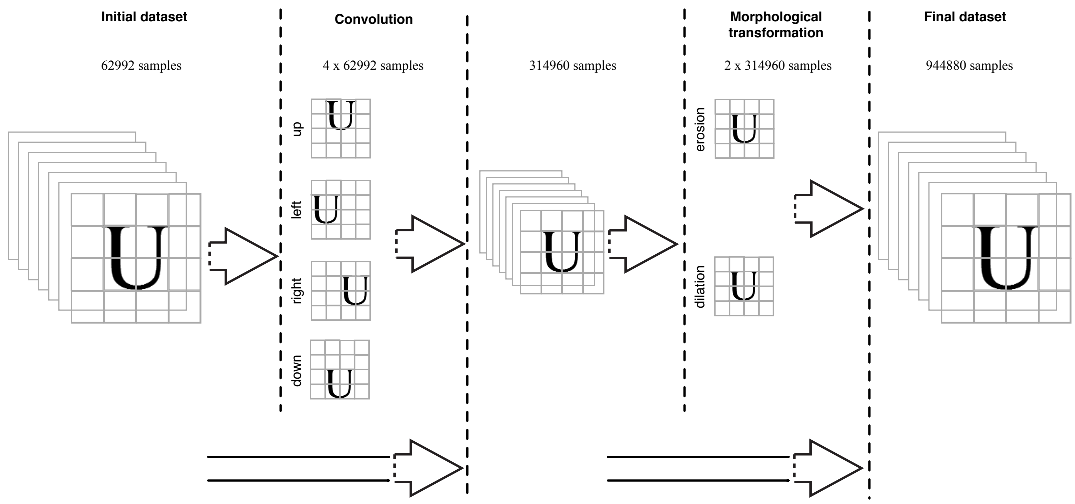

Figure 5.4 Dataset generation process.

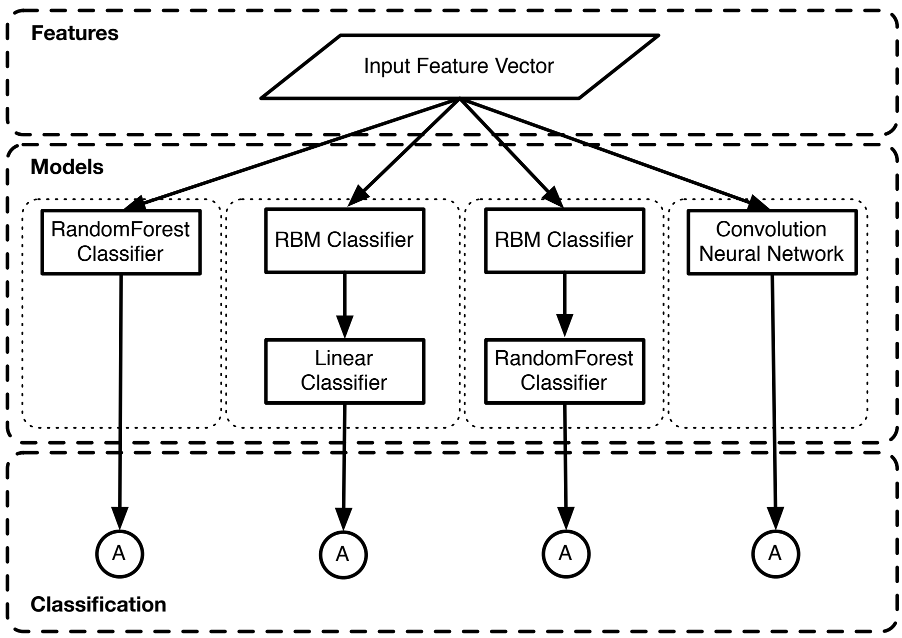

Figure 5.5 Implemented classification models.

The second model used a more complex approach combining a neural network with a logistic regression in an ensemble. Bernoulli Restricted Boltzmann Machine (RBM) [335] was used to fit a learning model using the raw input data. This neural network extracts non-linear features that describe the input data [336].

RBM is a stochastic neural network with binary input units and binary hidden units. The activation of neuron units depends on the state of their neighbours, and also depends on a probabilistic component due to its stochastic nature. In our problem, the RBM has 1024 input units and the network has 200 hidden units that are connected to all input units. The activation state of each unit depends on the unit's activation energy, which is computed based on the value (pixel value intensity) of the connected unit and the connection weight between this unit and the others. The connection weights are adjusted during several training epochs until the network converges or the maximum epochs are reached. The Bernoulli RBM extracts 200 non-linear features from the 1024 inputs. Then, a logistic regression classifier [337] is attached to the RBM output to predict the input vector class.

The third model consists of an ensemble comprising an RBM and a random forest. In this case, we replaced the logistic regression classifier with an RF in the decision layer. As in the second model, we extract 200 non-linear features using the RBM and use them as input features of the random forest. Using these features as input features provides a non-linear description of the raw input vector, which may have more predictive value and may be more informative regarding the raw input vector. Therefore, these features may improve the model's accuracy in comparison with the previous one where a random forest was trained directly with the raw 1024 input features.

We used Scikit-learn library [338] to implement the first three models. Scikit-learn is an open source library for data mining and data analysis in Python. In particular, it provides the RF implementation proposed by Breiman [334] and the RBM implementation proposed by Tieleman *et al.* [335]. The last model is a more complex approach that uses Convolutional Neural Network (CNN) [339]. CNN is a variant of Multilayer Perceptron (MLP) network [340] and is one of many deep learning algorithms [341]. CNN exploits spatially-local correlation and it has been found effective in general image classification tasks [339] (including character classification). The network has convolution layers where the inputs of the hidden units are generated by spatially continuous units in the adjacent layer. CNN classifiers tend to outperform other classifiers when dealing with image classification problems because of using spatial information generated by convolution of the input image in the convolutional layers. The convolutional layers and the max-pooling layers are the most important characteristics of the CNN [339]. Max-pooling is used to reduce the dimensionality of the signal by a given factor, which may vary according to the image size or the amount of information we can afford to throw away. This layer splits the image into non-overlapping areas and for each area it picks the higher value. Thus, this layer performs a non-linear down-sampling to the input image. CNN consists of alternating convolutional layers and max-pooling layers and at the end of the network it has fully-connected layers as in traditional MLP. We implemented our CNN using Theano library [342], and it consists of 6 layers (2 convolution layers, 2 max-pooling layers and 2 dense layers) depicted in Figure 5.6. One of the important advantages of using Theano was the ability to build our model using the GPU. This feature allows us to reduce significantly the time needed to learn the model by taking advantage of the process parallelization in the GPU.

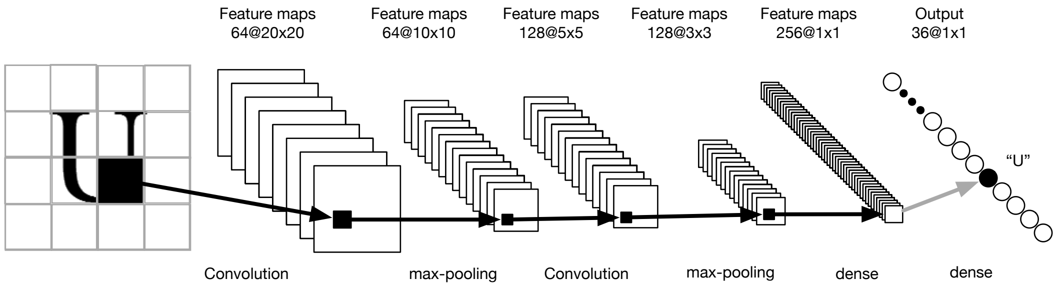

Figure 5.6 The implementation of the convolution neural network.

For each model, we used the test set composed of 94488 samples to evaluate its performance in terms of precision, recall and F1-score. The results obtained are discussed in section 5.4.2. This evaluation supported our selection of the best model for current imaging modality. The best model is then used to perform object recognition in the proposed pipeline.

5.2.5 Word Reconstruction

The word reconstruction algorithm uses the spatial information of the recognized objects to identify the words present in an image. A rectangular bounding box delimits each object found (see section 5.2.2). Therefore, the system measures the distance between objects using the coordinates that define the rectangle's position. The spatial distance between objects enabled us identify the relation between them and their position in a word. To group the objects in words, we ordered them according to their coordinates in the image pixel data. After that, they are arranged by the distance between an object and the next neighbour in the ordered set. If the distance between an object A and its neighbour object B is less than γ, then they belong to the same word, otherwise, the object B is identified as the start of a new word (Figure 5.7).

5.2.6 Image Anonymization

In the image anonymization task, we identify the sensitive words that were found in the word recognition task and remove them from the image. However, word reconstruction is likely to be highly influenced by the object detection task and the object recognition task, and it may identify words with some mistakes. For example, the object detection task may not be able to segment a given character in the image. This problem is likely to occur when segmenting characters like *"l"*, *"i"*, causing mistakes such as identifying the name *"MARA"* instead of *"MARIA"*. Another problem with an impact on word reconstruction is character misclassification, which is inherent to the classifier performance. Usually, machine learning models are not sufficiently accurate to correctly identify the correct class of a given sample. Therefore, an error rate must always be considered when implementing a system supported by a machine learning model. So instead of identifying the name *"MARIA"* the system may identify the name *"MAR1A"*, replacing I with 1. To overcome the problem of misclassified objects and wrong reconstruction of words, we consider the edit distance between two words. The system uses the Levenshtein distance [343] and if the distance between a recognized word and a word present in the set of sensitive information is less than α, the match is positive and this word will be removed from the image pixel data. Table 5.1 presents some examples for word recognition using α = 1 when performing word matching using the Levenshtein distance.

If a recognized word has a positive matching, the area occupied by this word in the image must be obfuscated, drawing a white rectangle in this area (Figure 5.8). The coordinates of the "black out" shape are defined by the first and last objects of the recognized word.

5.3 Providing Services for Medical Imaging De-identification

After implementing the anonymization system, we saw the opportunity to offer it as an independent service that could be integrated into other solutions. In this connection, we decided to provide a Web service to the community, which would facilitate the usage of the proposed system.

Therefore, we implemented a REST API that can be used as a service for automatic DICOM image de-identification. The API provides 3 methods: *anonymize, status, download*. The *anonymize* method allows the client to upload a set of DICOM images that will be de-identified. Each upload submitted creates an anonymization task that will run on the server. As this de-identification task is time-consuming, we decided to make the tasks asynchronous, executing concurrently using multiprocessing. After submitting an anonymization task, the service responds with an HTTP header containing the *Location* attribute with the URL that can be accessed to query the anonymization progress. The returned URL points to the *status* method of our REST API, passing the correspondent anonymization task ID as a parameter to the REST service. Then, the service returns the task's status (PENDING, FAILURE, PROGRESS, COMPLETED).

Figure 5.7 The word reconstruction algorithm.
γ is the maximum distance between adjacent characters within a word.

Table 5.1 Matching table for word recognition using the Levenshtein distance.

Recognized Word	Word	Distance	Match
silya	silva	1	True
concelcao	conceicao	1	True
concelcoo	conceicao	2	False

Figure 5.8 An example of an anonymized image.

A client can use *pooling* to find out the task's progress and to know when the anonymization task has finished. When the anonymization task finishes, the API returns in the *status* response a URL that can be accessed to download the de-identified DICOM images. This URL points to the *download* method of our API. Besides *pooling*, the API also provides the possibility to indicate a URL that will receive the de-identified images after fulfilling the task – this use case is depicted in Figure 5.9.

Besides the REST API, we provide a Web application oriented to end-users (Figure 5.10). The Web application offers a private box where users upload DICOM studies, and use the de-identification feature to anonymize the studies. Our solution can de-identify the images before storing them, using the REST API services previously presented. The application integrates a Web application for DICOM image visualization named PACScenter [344][42], which allows users to search, analyse and download DICOM studies. Moreover, Dicoogle archive [184] is used as a backend to store and manage the studies.

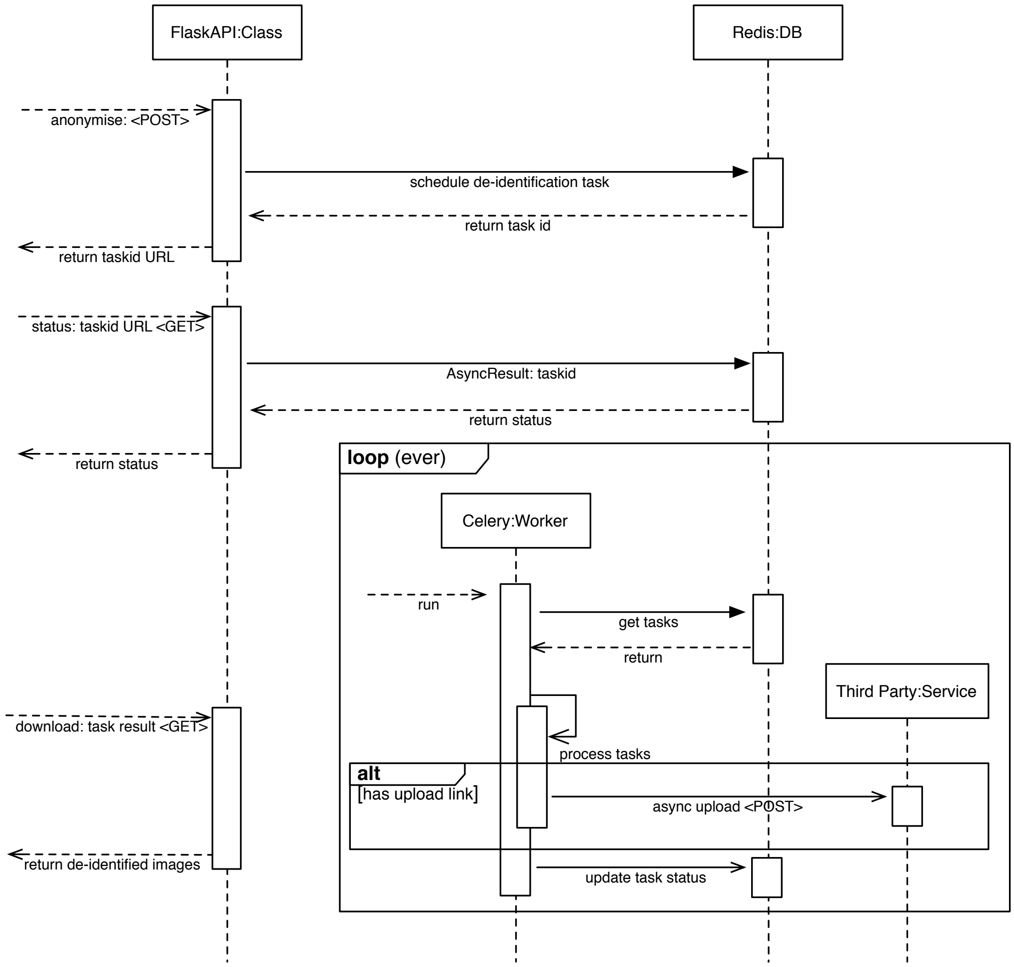

Figure 5.9 The life-cycle of the de-identification service.

5.4 Validation and Discussion

5.4.1 Experimental Methodology

We used the holdout technique to validate the classification algorithm, assessing how the results of a statistical analysis will generalize to an independent data set. The holdout technique consists of choosing a random subset of observations from the samples to build a training set, and the remaining observations are retained as the testing set. This allows training the model with enough data and then accurately validating it. Validation requires two steps: first, we create the model fitting it using the training set; then we use the model to predict the class (character) for each sample in the testing dataset. The results obtained for each model built are presented and analysed in the next section.

The model performance and the whole de-identification pipeline is measured by setting aside a random fraction of the labelled image patches not used for training.

Subsequently, the documents of this test set are classified with our prediction model and the observed estimates are compared with the true labels. Measures of classification success, such as precision and recall, are often used to make the performance analysis. Precision quantifies the fraction of predicted labels that are in fact correct, i.e., corresponding to the target class. Recall indicates which fraction of the class is correctly identified among all the samples belonging to the class.

$$Precision = \frac{TP}{\{TP\ \cap FP\}} \qquad\qquad Recall = \frac{TP}{\{TP\ \cap FN\}}$$

where, TP: true positives; FP: false positives; TN: true negatives; FN: false negatives

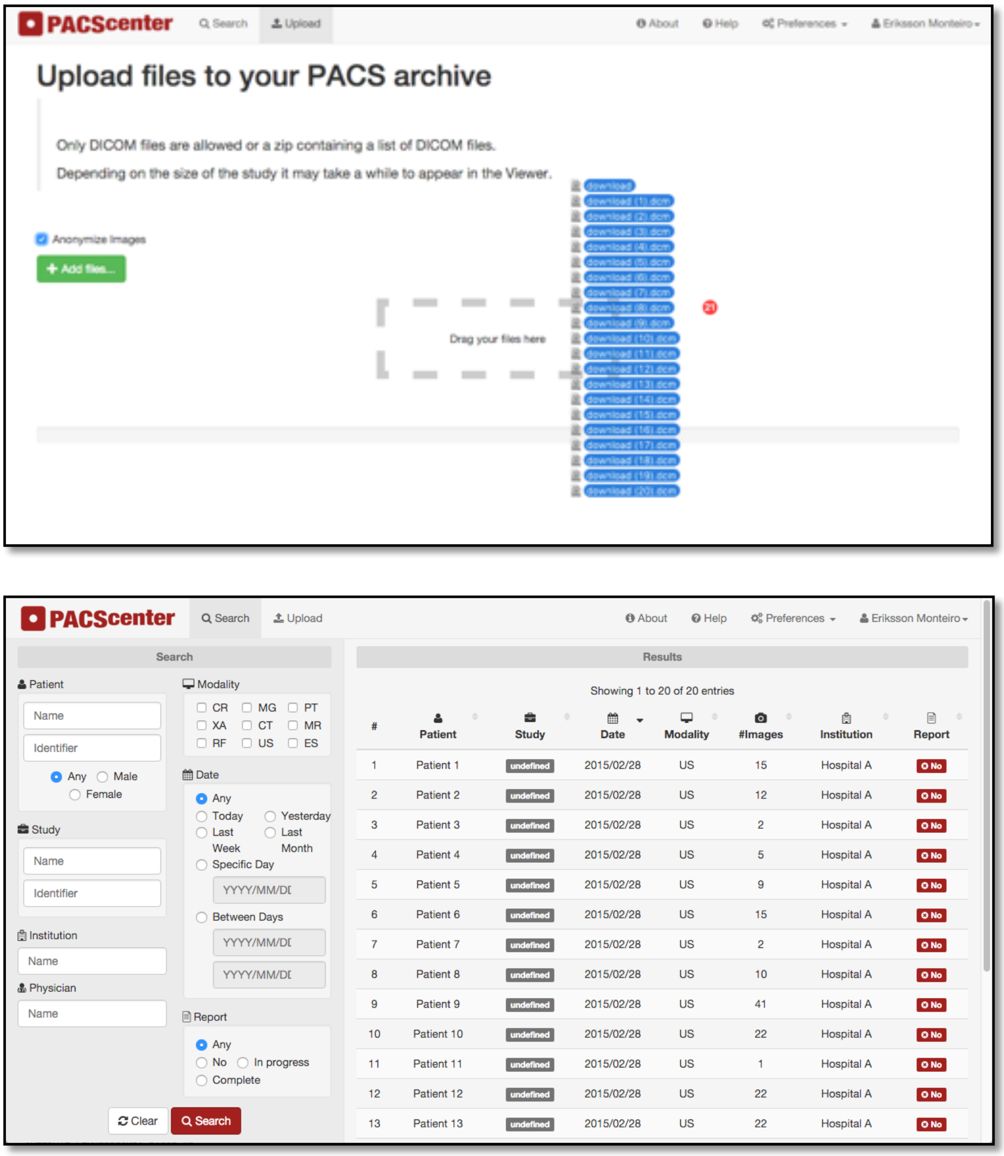

Figure 5.10 Web application for de-identification of medical imaging studies:
On top, we have the upload form; and on bottom, we have the search form.

There is a trade-off between precision and recall. Precision is high if only samples with a high “degree of membership” are assigned to the target class. However, many samples might have been overlooked, corresponding to a low recall. When on the other hand the model is more exhaustive, recall increases and precision goes down. The F1-score is a compromise of both for measuring the overall performance of classifiers.

$$F1 = \frac{2 * Precision * Recall}{Precision + Recall}$$

5.4.2 OCR Performance Evaluation

The validation of the proposed pipeline starts by identifying the best classification model for OCR in ultrasound images. Experimental trials were conducted over a validation dataset composed of 94488 samples (10% of our dataset). Performance measurements were recorded for each classification model and at the end, we observed that the CNN model stood out as having the best performance of the 4 classification models tested.

We present the results obtained in Table 5.2. These results allowed us to compare the performance of the classifiers, and to choose the best model to be used in the anonymization pipeline. The model based on the Random Forest algorithm was the worst. We obtained 89% of F1-score with this model. We believe that the worst performance of the RF algorithm is due to only using pixels’ intensity value and the inability to generalize. In image recognition tasks, using pixel intensity may not be sufficient to create an accurate model. A comparison of the results obtained using RF and those obtained using an ensemble of RBM and a linear model reveals that non-linear information extraction from the raw pixel data may increase the OCR performance. The differences between the model based on RF and the model based on an ensemble of RBM and logistic regression are highlighted in Table 5.2, where the results show that using the ensemble we increased performance (F1-score) from 89% to 91%. More evidence of the impact of non-linear feature extraction from raw input on image classification tasks is the fact that we got better results using an ensemble of RBM and RF classifiers than with the model based on RF.

Table 5.2 The performance of each classifier when recognizing a character.

Classifier	F1-Score
Random Forest	0.89
RBM and Logistic regression	0.91
RBM and Random Forest	0.94
Convolutional neural network	0.97

Moreover, we could also observe that the ensemble of RBM and RF improved the classification performance to 94% (F1-score). Therefore, the RF algorithm could use the information in the non-linear features provided by the RBM better than the use of a linear model such as logistic regression. Finally, the model that performed best in the test set was the CNN. After testing the CNN model, it reported 97% in the F1-score.

5.4.3 Anonymization Pipeline Evaluation

The results obtained in the previous section indicate the CNN model was the best. This section, therefore, moves on to evaluate the whole anonymization pipeline where we used the CNN model for object recognition. An automated process was implemented to anonymize a set of studies extracted from a real-world PACS archive. The overall performance of our medical imaging anonymizer was measured based on the accuracy obtained when removing all sensitive annotations from the images. Therefore, in the result assessment process, we had to verify whether all sensitive information was removed from the resulting images, marking them as correctly anonymized, or as anonymization errors if we left one or more pieces of sensitive information visible in the image.

The first performance results consisted of the analysis of 500 US studies with different patient names. These studies were anonymized using the pipeline, and at the end, we visually inspected the resulting images to evaluate performance (Figure 5.11). Thus, for each study we observed which one had all sensitive words removed (anonymized), which one failed to remove (not anonymized) and which one had some words / image region mistakenly removed (mistake). Accordingly, as can be observed in Figure 5.11 we obtained a 78.6% success rate (anonymized), 21.4% of not anonymized images, and 0.8 % of images with some regions mistakenly removed.

The first set of results were not as good as anticipated considering that we used a classification model reporting 97% precision, recall and F1-score in the test set (Table 5.3 - Dataset A). Therefore, we tried to find which step in the pipeline was harming the results. The pipeline was strongly affected by mistakes in the object detection step and in the object recognition step, and then, recognizing words in the images with some mistakes led to a Levenshtein distance greater than 1. Therefore, we decided to trace the origin of the errors, evaluating the performance of the object recognition model using a new test dataset built using samples identified in the object detection step. We extracted 5500 characters using the object detection step and these samples were manually curated. We extended the test set to 82500 samples using the same process described in Figure 5.4. The classifier performance for this new test dataset (Dataset B) is presented in Table 5.3. Overall, the object detection step affected the results for the measures, where we obtained 86% precision, 79% recall and 76% F1-score.

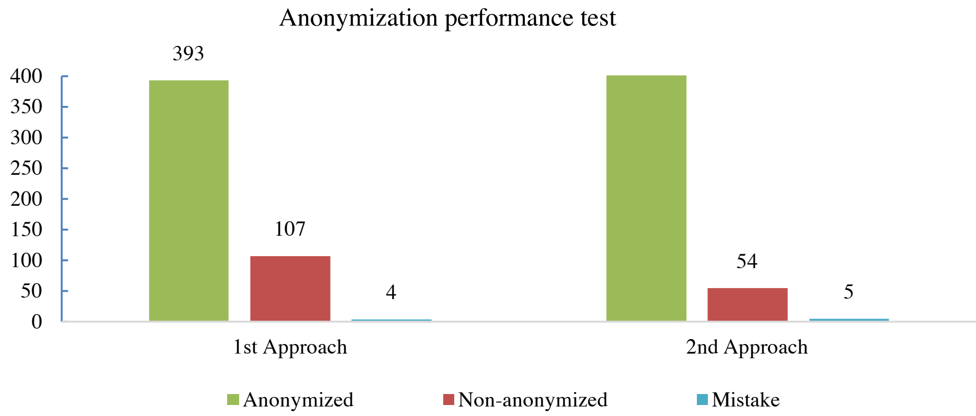

Figure 5.11 The overall anonymization service performance:
This figure shows the performance of the first implementation (1st approach) and the performance after improving the word recognition process (2nd approach).

Table 5.3 CNN-based classifier performance.

Dataset A			Dataset B		
precision	recall	f1-score	precision	recall	f1-score
0.97	0.97	0.97	0.86	0.79	0.76

Several issues were identified in the automatic character detection process, which is a challenging process that may not be so accurate when segmenting characters. Moreover, a possible explanation for this result may be that the overlay font size can be a problem due to the need to normalize patches, resizing them to 32x32, and in this process either throw away information when downscaling or introduce noise when upscaling. In our case, the samples extracted from the US images were very small (9x9 patches). Therefore, when resizing them to 32x32, we introduce noises to the sample. The lesser information available in the extracted samples had a significant impact, reducing the classification accuracy.

After analysing the precision, recall and F1-score of each character, we also observed that the model had problems distinguishing identical characters, such as *"l"* and *"1"*, *"u"* and *"v"* or *"o"* and *"0"*. Then we decided to introduce an extra layer to improve the word reconstruction step where we added context to the word being identified. Specifically, when comparing a word Wr with a sensitive word Ws which is part of the patient's name, if the classifier labels a character $Ci \in Wr$ as a number we replace it with the more probable letter according to the classifier model. On the other hand, we do the opposite when identifying patient ID, replacing letters with numbers. There was a significant improvement in the anonymization results when adding this layer to improve word reconstruction. By analyzing the results, we observed an evident impact of the improvement in the word reconstruction step, reporting 89.2% success rate, 10.8% of images not anonymized and 1.0 % of images with regions mistakenly removed.

Regarding the final results, we may state that it is possible to implement an automated process for pixel data de-identification with acceptable performance. Also, it is interesting to note that besides an acceptable success rate in identifying and removing sensitive information from the medical images, the results showed a very low percentage of images with regions mistakenly removed. Hence, the findings raise intriguing concerns regarding the degree of success of the system applied to any kind of medical imaging modalities due to the impact of font size / resolution on overall system performance.

5.5 Final Considerations

The purpose of the current study was to develop a method for automatic patient de-identification in medical images. Thus, we developed a machine learning-based system with a reliable anonymization success rate, and which, consequently, may have several applications, such as in improving current methods that only consider DICOM metadata.

Although the study has successfully demonstrated that we can automate de-identification in pixel data, it has also some limitations. This recognition depends on complex processes, such as image pre-processing, object detection and image resolution. While the results were very convincing for the US modality, we believe there is a need to create distinct classification models for other modalities to obtain similar results.

Summarily, our methodology presented promising results and it may represent an added value in automatic patient de-identification in medical imaging, offering an agile solution for use cases of medical image-sharing among institutions and users. Moreover, the system may be used in real world environments for supporting automated de-identification processes, since it identifies the cases where the anonymization is not fully achieved, through the inspection of sensitive tokens extracted from DICOM metadata.

6 Conclusion and Future Directions

" The important thing is not to stop questioning.
Curiosity has its own reason for existing."
Albert Einstein

6.1 Conclusion

The medical imaging area has been continuously creating new computational challenges related, for instance, to data acquisition, representation, processing, storing and searching. In radiology, the visualization of images is a key functionality, and, for a long time, this was exclusively performed on dedicated workstations. These workstations are usually located in the radiology departments, restricting the analysis and diagnostic activities to those physical spaces. This fact has been for a while a limitation to the radiology services, being difficult for the radiologists to remotely work. Nevertheless, the evolution of the Web technologies, have opened new possibilities for pure Web medical image viewers. At the beginning of this doctoral program, our main challenge was to prove that those technologies are already mature enough to build a solid alternative to traditional medical images workstations.

Regarding collaborative work in radiology, since the beginning of IT adoption by health organizations, we can find radiology systems which have the ambition to offer tools for collaboration. Likewise, these systems have been evolving along with current trends, using new technologies and computing paradigms to deliver better solutions for collaboration in radiology. Those solutions have also to incorporate robust models to preserve patients' data security and privacy. Considering that security and privacy concerns may hinder the collaboration by introducing time-consuming procedures and additional processes, it is important to develop solutions to reduce these processes costs and streamline the data sharing between collaborators.

During this research, we have addressed the challenges on ubiquitous medical viewing and diagnostic, collaborative work in radiology and fast data sharing. We proposed several software architectures to promote ubiquitous medical image visualization and diagnostic. We have also created a platform that facilitates the collaboration and the data sharing between radiologists.

6.2 Main Contributions

We achieved some important outcomes during this research process, aiming at advancing the current software solutions for radiology practice.

As first contribution, we created a software architecture for Web-based medical image visualization, which the main objective is to promote remote work. This platform is accessible from any modern Web browser, and can also be accessed using mobile devices. Therefore, with this application, we created a novel ubiquitous solution for medical image analysis, which usage is not tied up to specialized viewing workstations. The implemented architecture facilitates diagnostic of medical images from anywhere via an Internet connection. We propose this viewing solution as a service residing on Web technologies, to support medical images visualization. It allows a radiologist to connect to their radiology network and remotely perform medical diagnosis.

The second contribution was a Web-based collaborative platform for radiology which simplifies the establishment of teleradiology workgroups. The platform uses the kind of interactions that we can find in social network applications, to create a easy to use workspace, facilitating data sharing, collaborative medical image analysis, and communication between collaborators.

Moreover, we support the idea that efficient dataflow and availability of medical records are key for any teleradiology system. Therefore, we demonstrated the applicability of current trends, such as cloud computing, mobile computing and web application, in the future of radiology systems. Using these technologies, we purposed a flexible architecture capable of improving medical information flow, being used at different teleradiology scenarios including tele-reporting service and teaching of radiology. We achieved an interesting result using the collaborative platform in teaching of radiology, because we can customize it to work as an e-Learning platform where the radiology trainees have their individual user areas. The establishment of collaborative workflow between colleagues is very simple, allowing them to share resources and collaboratively discuss clinical cases. Moreover, with an embedded visualization tool in the platform, we support collaborative visualization of medical studies, allowing multiple users to interact simultaneously in the same view.

The amount of data generated and stored in radiology systems tends to grow fast. With the deployment of a collaborative system for radiology, we expected to store large amounts of information in the platform. Consequently, we designed an architecture for data exploration, implementing algorithms to create a semantic knowledge base from radiology textual data. This knowledge base can be used to generate relevant recommendations to the users in the platform. Furthermore, we proposed a modular architecture to build a clinical recommender system, combining features extracted from images and reports. This can be useful for radiologist when performing clinical diagnosis, giving them more confidence in the decision-making process and a rapid access to helpful information regarding their current context. We envisage that, soon, recommender systems will be reliable enough to support physicians in their daily activities.

It is expected to find special requirements concerning information protection in any health systems. These concerns should be even more carefully covered in collaborative systems, where private patients' data may be stored and transmitted between users of different organizations. In this sense, information security and privacy safeguard may create barriers to fast data sharing in such environments. Hence, we created a solution for automatically de-identification of medical images, with regards to annotations burned in the pixel data. This tool has great potential to accelerate data sharing when there is need to remove sensitive data from the image itself. In contrast to image metadata anonymization, where we can find several solutions to perform automatic anonymization, the users must do manual removal of areas containing sensitive information. In this connection, our methodology is an added value for automatic patient de-identification in medical imaging, being a solution to enable fast data sharing processes among institutions and users.

Throughout the conception and development of the software solutions presented in this document, we have always worked closely with some regional radiology organizations to validated the results, and always focusing on the impact that the proposed solution would have in real environments.

6.3 Future Work

This thesis introduced novel methods and architectures that can be deeply explored in different scenarios. Additionally, we can identify some research lines that can be further explored in the future.

A first challenge that can be addressed is related with the visualizations of high resolution images. It would be interesting to evaluate the applicability of Web GL and other Web technologies to improve the rendering performance of high resolution medical images. Moreover, beside traditional high resolution medical imaging modalities, we can find bigger medical imaging modalities, such as whole-slide imaging, and the rendering of these images can also be a challenging task.

Other future researches could be the exploration of different methods to enable reversible anonymization in a collaborative radiology system. Thus, the users can be granted the access to the original image or the anonymized image only.

7 References

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