

POLITECNICO DI MILANO

Scuola di Ingegneria Industriale e dell'Informazione
Corso di Laurea Magistrale in Ingegneria Informatica



POLITECNICO
MILANO 1863

Liquid Android: A Middleware for managing Android Intents in a Distributed Net over Wi-Fi

Relatore:

Prof. Luciano Baresi

Tesi di Laurea di:

Marco Molinaroli

Matricola:

837721

Anno accademico 2015–2016

Ringraziamenti

Ringraziamenti.

Milano, April 2017

Marco

Sommario

Parole chiave: PoliMi, Tesi, LaTeX, Scribd

Abstract

Text of the abstract in english...

Keywords: PoliMi, Master Thesis, LaTeX, Scribd

Contents

1	Introduction	1
1.1	Motivation	1
1.2	Outline	2
2	State of the Art	5
2.1	Android OS	5
2.1.1	Brief History	5
2.1.2	Structure	7
2.1.3	Application Framework	8
2.1.4	Security	10
2.1.5	Connectivity	12
2.2	Distributed System	12
2.2.1	Definition	12
2.2.2	Challenges	13
2.2.3	Comunication Model	15
2.2.4	Architectures	16
2.2.5	Naming	19
2.3	Technical Background	20
2.3.1	Liquid Computing	20
2.3.2	Java network programming	20
2.3.3	Zeroconf	23
3	Problem Analysis	27
3.1	Contextualization	27
3.2	Considered Devices	28
3.3	Definition	28
3.4	Probelm scenarios	30
3.4.1	Background working middleware	30
3.4.2	Development API	31
3.4.3	Data management	32
3.5	Constraints	33
4	Proposed Solution	37
4.1	Existing Solutions	37
4.1.1	Boincoid and HTC Power to Give	37
4.1.2	Plex for Android	38
4.1.3	Goolgle Home and Cast API	39

4.1.4	DroidMote and Remote control systems	39
4.2	General Idea	39
4.3	Theoretical solution, extending the Android OS	42
4.3.1	Network Architecture	43
4.3.2	Communication Model	46
4.3.3	Data management Model	57
4.4	Liquid Android API Library	58
4.4.1	General Structure	58
4.4.2	Controller Components	59
4.4.3	UI Components	62
4.4.4	Use Cases	63
5	Case Study	65
5.1	Design Choices	65
5.1.1	Application Description	65
5.1.2	Requirements	66
5.1.3	Used Technologies	67
5.2	Working Demo	68
5.2.1	Live Test Cases	68
6	Conclusions and Future Works	69
	Figures Copyright	71
	Bibliography	73

List of Figures

2.1	The T-Mobile G1 and the Android 1.0 menù	5
2.2	Android OS fragmentation chart	7
2.3	Android OS 4 layers	7
2.4	Intent resolution mechanism	10
2.5	Android 5.1- permission example	11
2.6	Android 6.0+ permission example	11
2.7	Android permission Examples	11
2.8	Distributed system structure	13
2.9	Distributed system challenges	14
2.10	RPC in detail	15
2.11	RMI in detail	16
2.12	Client server architecture	17
2.13	P2P architecture	17
2.14	Publish-subscribe architecture	18
2.15	TCP/IP sockets	21
2.16	Java RMI structure	24
3.1	Distributed intent resolution	29
3.2	Liquid Android working as stand alone middleware APK	31
3.3	Liquid Android API working example	32
3.4	Liquid Android API data management example	32
4.1	Plex Platform	38
4.2	Liquid Android working example	41
4.3	P2P Liquid Android network example	43
4.4	UML structure for an Intent	50
4.5	Files Over the Socket example	57
4.6	Cloud Group example	58
4.7	Liquid Android General UML	59

List of Tables

2.1	Android versions	6
2.2	Android OS versions fragmentation	7
2.3	Transparency levels	14
2.4	Comparison between communication models	16
4.1	Intent Structure	48
4.2	JSON-Intent fields	51
4.3	Category fields	51
4.4	JSON-Bundle Object fields	52
4.5	Possible data types	55

Listings

2.1	DateServer example	21
2.2	DateClient example	22
4.1	Zerconf registration example	45
4.2	Implicit Intent example	55
4.3	Conversion of the Intent in Listing 4.2 to JSON-Intent	56
4.4	Intent filter example	62

Chapter 1

Introduction

1.1 Motivation

Nowadays mobile devices have changed the way we approach to technologies, they are powerful enough to do most of the things we need in a fast and efficient way, without the need of use of a *regular computer* with a *standard desktop operating system*. Mobile operating systems (*mobile OSs*) combine features of a personal computer operating system with other features useful for mobile or handheld use; usually including, and most of the following considered essential in modern mobile systems; a touchscreen, cellular, Bluetooth, Wi-Fi Protected Access, Wi-Fi, Global Positioning System (GPS) mobile navigation, camera, video camera, speech recognition, voice recorder, music player, and so on. By the end of 2016, over 430 million smartphones were sold with 81.7 percent running Android, 17.9 percent running iOS, 0.3 percent running Windows Mobile and the other OSs cover 0.1 percent [26].

Many people have multiple mobile device for personal use, and for the reasons discussed above would be great if people can use this wide variety of mobile devices together equipping their operating systems with services to make them *distributed mobile OSs*

I stated that Android is the most common mobile operating system, it is open source and do not need special developer licenses to build applications. So in this work I will try to provide a solution to the problem of making mobile operating systems acting as distributed OSs, focusing my attention on Android devices. It is now clear which Android is not only a tiny operating system, but a full functional OS to be used for general purposes. One of the most peculiar characteristic of the Android OS is which it can be installed in a variety of devices such as "*handheld*", like smart-phones and tablets, "*wearable*", like smart-watches, but also in other kind of things like standard desktops and laptops, smart-tv and tv boxes, and so on.

The great variety of devices described above can run and benefit all the functions of the Android OS which is acknowledged for its ease of use, and the great abundance of applications, with which users can do almost everything.

However one of the greatest limits of Android is that the system was designed to run on the top of a virtual machine and each application which can be ex-

ecuted starts a Linux process which has its own virtual machine (VM), so an application's code runs in isolation from other apps. This technique is called "*app sandboxing*" and it is used to guarantee an high level of security, because different applications can not read write, or worse steal, data and sensible information from other applications. That is, each app, by default, has access only to the components that it requires to do its work and no more. This creates a very secure environment in which an app can not access parts of the system for which it is not given permission.

Under this limitations the Android OS provides a mechanism to make communicate the various component of the applications and the operating system itself : the so called "*intents*". An intent is an abstract description of an operation to be performed, it provides a facility for performing late runtime binding between the code in different applications. Its most significant use is in the launching of activities. However, even do the intents can be created and resolved within the same android running devices, there is not a mechanism that can send and resolve intents from a devices to another one.

In a world where computers are everywhere and can do almost everything and can communicate among them in different but efficient ways, the fact that android devices are not able to easily exchange intents is such a major limitation to the android users. As we know our world is fast moving to a world of "*ubiquitous computing*" where there is no more a single "*fat calculator*" but a variety of multipurpose and specialized devices. In this world of pervasive computation, Android devices are widespread, cheap and powerful enough to do most of the things that we can imagine and would be great if they can be used together in a smart way. The aim of this thesis work is to study enough the android framework to find a solution to this problem, and create a middleware to extend the Android OS, creating a distributed system in which intents can be generated from one device and resolved by others in a net connected in a LAN. This can help developers build distributed native Android application to exploit the power of any different device running the OS and let the users use their own devices such as they were one single big device.

Each sentence or technology, that may appear not clearly explained here for the reader, is further discussed and clarified in next chapters.

1.2 Outline

The thesis is organized as follows:

In the second chapter the state of art is described: a full overview on current technologies, ideas and issues is provided. The chapter starts presenting the Android operating system with a brief history of versions. Then a deep presentation of Android's framework component is give to the reader, including security model and connectivity functionalities. The chapter continue describing what is a distributed system, listing its main challenges, properties and its working mechanism such as the communication models, and architectural patterns. The final section explains the term *Liquid*

computing, presenting some existing technologies which can be useful to understand the problem and then the proposed solution and development.

In the third chapter I have defined the faced problem, its constraints and its boundaries. The chapter starts with a contextualization of the given problem, giving a brief recap of the state of the art. Then are provided some restriction, considering only devices in which the developed system could be installed. The chapter continues with the full description of the problem, the main idea and also a working scheme of the component to be developed. Are then presented problematic scenarios to be studied, including detailed description of what the middleware to be implemented should work in these situations. There is, finally, a list of constraints that the system must meet to be considered a good solution to the given problem.

In the fourth chapter

In the fifth chapter

In the sixth chapter

Chapter 2

State of the Art

2.1 Android OS

As already mentioned in 1.1, the Android operating system is an open source OS developed by Google based on Linux kernel, that can be installed on many different kind of devices.

In this section i want to give to the reader the basic knowledge of the Android framework to understand why and how the operating system works.

2.1.1 Brief History

The Android era officially began on October 22nd, 2008, when the *T-Mobile G1* launched in the United States [23].

At that moment the company of mountain view, Google, felt the need to create a new operating system which was able to be installed on most modern mobile phones of the time. To meet this need the Google engineers created an OS that was based on the Linux kernel, lightweight enough and ease to be used with simple hand gestures by touching the screen of the phone.



Figure 2.1: The T-Mobile G1 and the Android 1.0 menu

The main characteristic of the OS were and are also now:

- The pull-down notification window.
- Home screen widgets.
- The Android Market.
- Google services integration (eg. Gmail).
- Wireless connection technologies (eg Wi-Fi and Bluetooth)

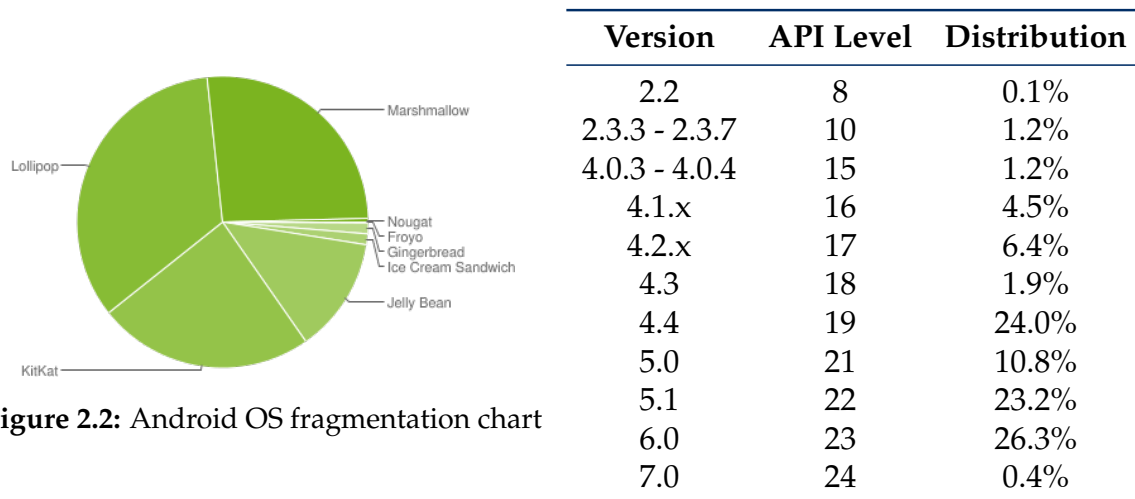
The success of the first version of the brand new mobile operating system and the open source philosophy guaranteed the fast spread of the Android devices all over the world. In few years Google improved and released many version of the OS and with the help of the market growth Android has become a complete os. In the table below there is a brief description of the various distribution of the Android OS at the time of writing of this document.

As we can see in Table 2.1 there are, currently, 25 level of the Android *API*

Table 2.1: Android versions

Name	Version	Release Date	API Level
Alpha	1.0	September 23, 2008	1
Beta	1.1	February 9, 2009	2
Cupcake	1.5	April 27, 2009	3
Donut	1.6	September 15, 2009	4
Eclair	2.0 – 2.1	October 26, 2009	5–7
Froyo	2.2 – 2.2.3	May 20, 2010	8
Gingerbread	2.3 – 2.3.7	December 6, 2010	9–10
Honeycomb	3.0 – 3.2.6	February 22, 2011	11–13
Ice Cream Sandwich	4.0 – 4.0.4	October 18, 2011	14–15
Jelly Bean	4.1 – 4.3.1	July 9, 2012	16–18
KitKat	4.4 – 4.4.4	October 31, 2013	19
Lollipop	5.0 – 5.1.1	November 12, 2014	21–22
Marshmallow	6.0 – 6.0.1	October 5, 2015	23
Nougat	7.0 – 7.1.1	August 22, 2016	24–25

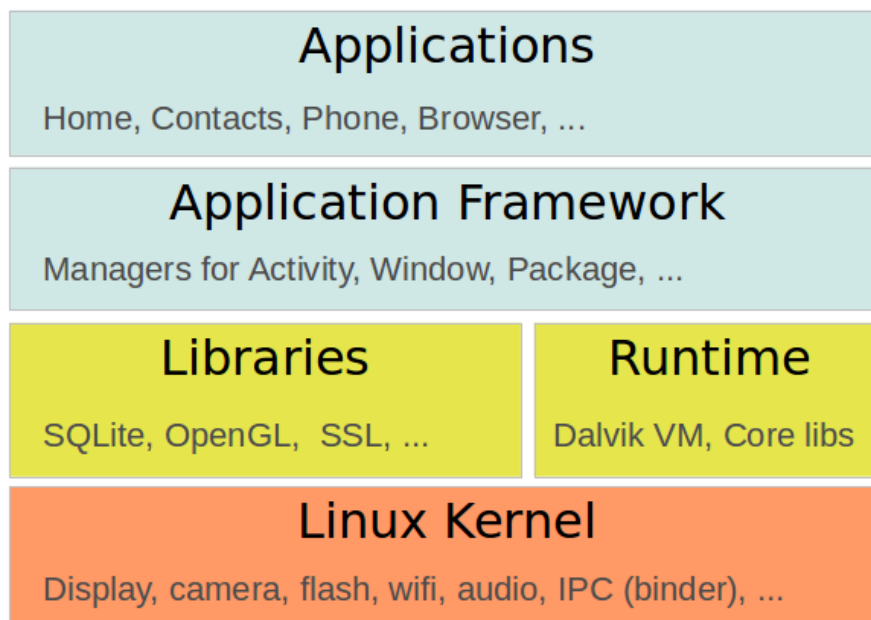
(Application programming interface) which developers can use to build Android applications. In particular various API levels introduce innovations in the OS but, applications developed using an higher *API level* can not be executed in a device running lower versions of the operating system. This is a second major limitations for the "*Android ecosystem*", moreover as mentioned before, the Android OS is released under an open source license, which is great for the developer, but which prevents Google to provide updates, in a centralized way, to all devices. For this reason there are currently many active devices running different versions of the mobile OS, as we can check in Table 2.2, which shows, in percentage, the fragmentations of active machines running Android OS.

Table 2.2: Android OS versions fragmentation**Figure 2.2:** Android OS fragmentation chart

Data in Table 2.2 were collected during a 7-day period ending on December 5, 2016, by Google. Any versions with less than 0.1% distribution are not shown [13].

2.1.2 Structure

Android is an operating system based on the Linux kernel. The project responsible for developing the Android system is called the *Android Open Source Project (AOSP)* and it lead by Google.

**Figure 2.3:** Android OS 4 layers

The OS can be divided into the four layers as depicted the Figure 2.3. An Android application developer typically works with the two layers on top to

create new Android applications [27].

Linux Kernel

The Linux Kernel is the most flexible operating system that has ever been created. It can be tuned for a wide range of different systems, running on everything from a radio-controlled model helicopter, to a cell phone, to the majority of the largest supercomputers in the world [20]. This is in practice the communication layer for the underlying hardware.

Runtime and Libraries

Runtime is the term used in computer science to designate the software that provides the services necessary for the execution of a program. There are two different "*runtime systems*" which can work with the Android OS:

- *Dalvik VM* is an optimized version for low memory devices of the *Java Virtual Machine (JVM)* used in Android 4.4 and earlier version. It is stack based and it works by converting using a *just-in-time (JIT)*, each time an application is executed, Android's *bytecode* into machine code.
- *ART (Android Runtime)* introduced with Android 4.4 KitKat. This runtime uses an *AOT (Ahead-of-Time)* approach, with which code is compiled during the installation of an application and then is ready to be executed.

Standard Android libraries are for many common framework functions, like, graphic rendering, data storage, web browsing. [27]. This layer contains also standard *java libraries*.

Application Framework

The application framework is the layer that contains the Android components for the application such as activities, fragments, services and so on.

Applications

Applications are pieces of software written in *java code* running on top the other layers.

2.1.3 Application Framework

In this section I want to give some details of the application composition and work flow to better understand the subsequent sections in which I will describe the given problem and the proposed solution.

As briefly described in 2.1.2 the Android application framework ("*AppFramework*") is the core of the Android *development API*. It contains useful and needed components to build native apps.

The main components with which each application is composed are:

Intents

Intents are objects that initiate actions from other app components, either within the same program (*explicit intents*) or through another piece of software on the device (*implicit intents*). According to the official Google's Android for developer documentation, an Intent is a sort of messaging object which can be used to request an action from another application component (eg. activities). There are three fundamental use cases:

- Starting an activity: we will see that activities represents a single screen in Android applications, intents allow to start activities by describing them and carrying any necessary data.
- Starting a service: I will explain later in deeper details that services are component which performs operations in background. As for the activities, services are initialized through intent and in the same way they describe the service to start and carries any necessary data.
- Delivering a broadcast: broadcast is a message that any app can receive. The system delivers various broadcasts for system events, such as when the system boots up or the device starts charging.

As already mentioned there are mainly two categories of intents:

- explicit intents, used when it is needed to start component within the same application. As the name implies explicit intents call components by using by name (the full *class object* name), for example, it is possible to start a new activity in response to a user action or start a service to download a file in the background.
- implicit intents do not name a specific component, but instead declare a general action to perform, which allows a component from another app to handle it. For example, if you want to show the user a location on a map, you can use an implicit intent to request that another capable app show a specified location on a map [11].

The Figure 2.4 explains well how an intent is resolved by the OS whether it is implicit or explicit. When an implicit intent needs to be resolved, the OS searches applications which can handle it by means of *intent filters*. A Intent filter specifies the types of intents that an activity, service, or broadcast receiver can respond to. The Android System searches all apps for an intent filter that matches the intent to be resolved. When a match is found, the system starts the matching component, or, if there are more than one, let the user select the preferred action to be performed.

Activities

Activities are one of the fundamental building blocks of apps on the Android platform. They serve as the entry point for a user's interaction with an app, and are also central to how a user navigates within an app. [12]. An activity is the

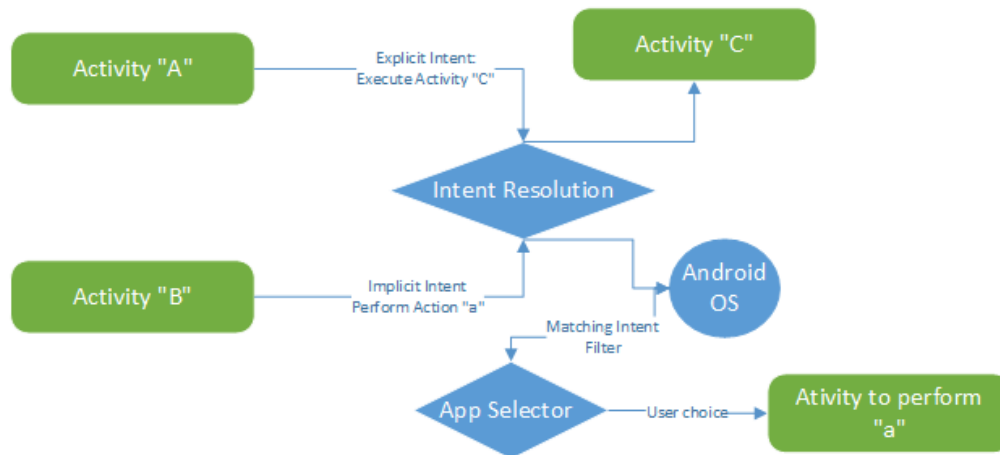


Figure 2.4: Intent resolution mechanism

entry point for interacting with the user. It represents a single screen with a user interface *GUI*: in this way activities are containers for other Android's GUI elements (eg. buttons, textviews,...).

Services

A service is a general-purpose entry point for keeping an app running in the background for all kinds of reasons. It is a component that runs in the background to perform long-running operations or to perform work for remote processes. A service does not provide a user interface [10].

Broadcast Receivers

Broadcast Receivers are components that enable the system to deliver events to the app outside of a regular user flow, allowing the app to respond to system-wide broadcast announcements. Because broadcast receivers are another well-defined entry into the app, the system can deliver broadcasts even to applications that aren't currently running [10].

2.1.4 Security

As described in 2.1.1 Android was born to be a good mobile OS and it is mainly for this reason that the system is designed to protect personal and sensible data from malicious guys.

Like the rest of the system, Android's security model also takes advantages of the security features offered by the Linux kernel. Linux is a *multiuser* OS and its kernel can isolate user data from one another: one user can not access another user's file unless explicitly granted permission. Android takes advantages of this user isolation, considering each application a different user provided with a dedicated *UID* (*User ID*) [17] Android in fact, is designed for smartphones that are personal devices and do not need, usually, a multi physical user support. The most important security techniques adopted by Android are:

Application Sandboxing

Android automatically assigns a unique *AppID* (Linux UID) when an application is installed and then executed that specific app in a dedicated process as that UID. This technique isolate all the applications at process level and additionally each app has permissions to read/write a specific and dedicated directory.

Permissions

Since application are sandboxed and do not have the rights to read/write data outside them, it is possible to grant additional rights to android applications by explicitly asking them. Those access rights are called *permission*. Applications can request permissions by listing them in a configuration file called *android manifest*. In Android 5.1 and earlier versions permission are inspected and granted at installation time, when the user is alerted with a dialog box in which are listed permissions the application to be installed needs to work properly and when granted cannot be revoked. Starting from android 6.0 permission are asked the first time that an application need them, and when are granted they can be revoked manually in the OS settings for that specific application.

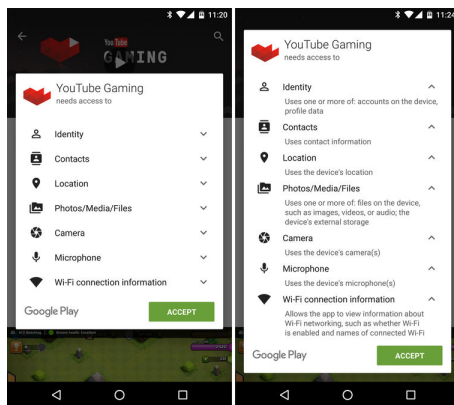


Figure 2.5: Android 5.1- permission example

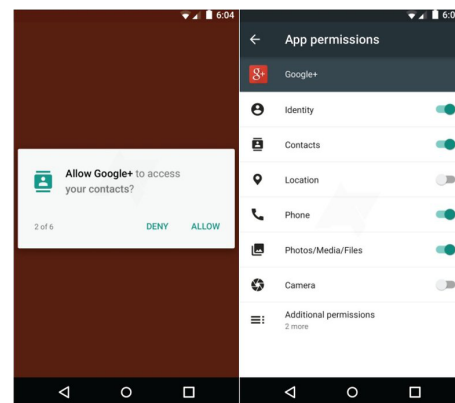


Figure 2.6: Android 6.0+ permission example

Figure 2.7: Android permission Examples

SELinux

Security Enhanced Linux, is a *mandatory access control (MAC)* system for the Linux operating system. With a MAC the operating system constrains the ability of a subject or initiator to access or generally perform some sort of operation on an object or target. Starting in Android 4.3, SELinux provides a mandatory access control (MAC) umbrella over traditional discretionary *access control (DAC)* environments. For instance, software must typically run as the root user account to write to raw block devices. In a traditional DAC-based Linux environment, if the root user becomes compromised that user can write to every raw block device. However, SELinux can be used to label these devices so the process assigned

the root privilege can write to only those specified in the associated policy. In this way, the process cannot overwrite data and system settings outside of the specific raw block device [2].

2.1.5 Connectivity

As already amply explained previously many Android design choices are due to the fact that it was thought for mobile devices which must have connectivity to intercommunicate among them.

With the evolution of various wireless communication technologies, Android devices, nowadays, are equipped with different kinds of modules, the most common are:

- Wi-Fi
- Bluetooth
- NFC
- Cellular Network

The Android OS provide a full library to operate with these technologies and it is possible to integrate in applications the possibility to communicate over these wireless modules. With the *Android connectivity API* data can be send and received in an efficient way.

I have only quickly listed some features and possible issues of my source, to have a complete idea it is possible to read all the official Android documentation in [10].

2.2 Distributed System

In this section I want to give to the reader some basics about distributed systems, including technical details and examples to make the proposed solution easier to understand.

2.2.1 Definition

A distributed system is a collection of independent computers that appears to its users as a single coherent system.

This definition has several important aspects. The first one is that a distributed system consists of components (i.e., computers) that are autonomous. A second aspect is that users (be they people or programs) think they are dealing with a single system. This means that one way or the other the autonomous components need to collaborate [24].

In Figure 2.8 it is possible to see how can be structured a distributed system: at the top we have the real distributed application, which is the final interface to be

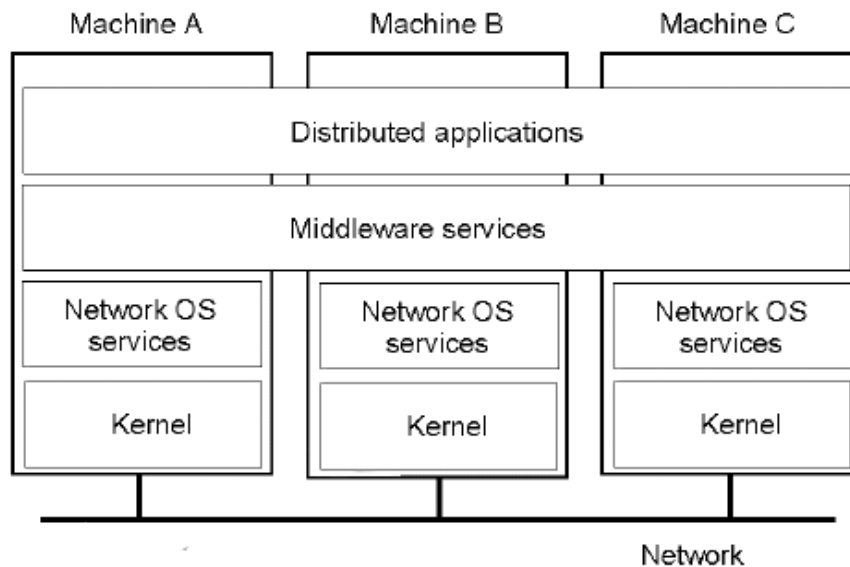


Figure 2.8: Distributed system structure

used, under which it is possible to have different combinations of services used to make communicate different machines that may use different operating systems. The real magic is done by the layer called *middleware service* in the picture. A middleware in computer science is a set of software which act as intermediaries between structures and computer programs, allowing them to communicate in spite of the diversity of protocols or running OSs.

2.2.2 Challenges

There are many challenges in distributed systems field: distributed applications are often really complex and easily exposed to physical and technical failures because of their nature. Major challenges and property to be considered when developing a system of this kind are:

- Heterogeneity, is a major challenge because there are many different component to be considered, distributed systems may be developed for example for different hardware, networks, operating systems and programming languages.
- Openness, determines whether a system can be extended and reimplemented in various ways, so distributed systems should use standards as much as possible. Developers should always choose the simplest ways during design and implementation phases.
- Security, is crucial in many areas of computer science and specially in distributed systems, where data are exchanged by a several number of machines.
- Scalability, is the ability to easily increase the size of the system in terms of users/resources and geographic span.

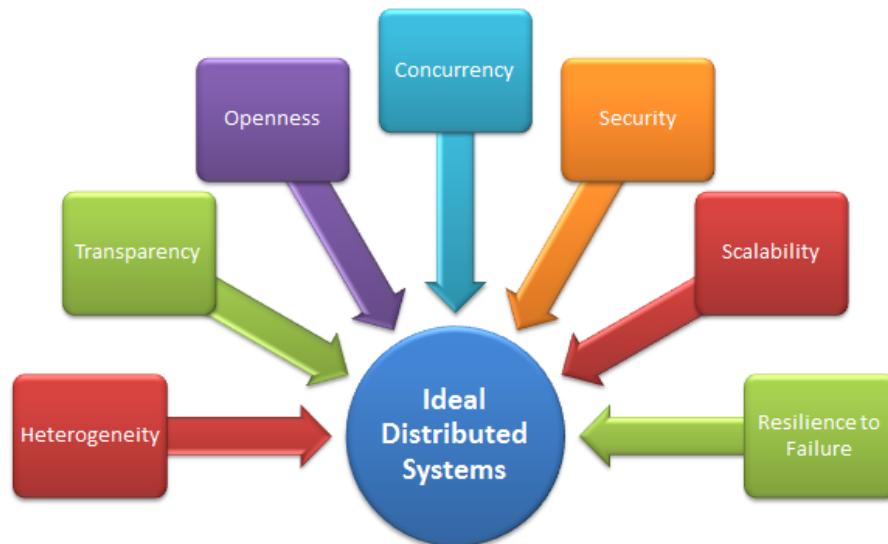


Figure 2.9: Distributed system challenges

- Failure handling, is important because having different components working together to a common goal means that distributed system can fail in many ways. This raises some issue: it would be nice if distributed systems can detect, mask and tolerate failures.
- Concurrency in distributed systems is a matter of fact, access to shared resources (information or services) must be carefully synchronized.
- Transparency level are listed in Table 2.3

Table 2.3: Transparency levels

Transparency	Description
Access	Hide differences in data representation and how a resource is accessed
Location	Hide where a resource is located
Migration	Hide that a resource may move to another location
Relocation	Hide that a resource may be moved to another location while in use
Replication	Hide that a resource may be shared by several competitive users
Concurrency	Hide that a resource may be shared by several competitive users
Failure	Hide the failure and recovery of a resource
Persistence	Hide whether a (software) resource is in memory or on disk

2.2.3 Communication Model

There are, in distributed system literature, some well known techniques to let communicate machines, programs and components. Each of the methods described later exploits the network protocols by acting as a middleware: they use and mask lower layer protocols to provide ready to use communication services.

Remote procedure call (RPC)

RPC is a paradigm in which a client process invokes a remotely located procedure (a server process), the remote procedure executes and sends the response back to the client [19]. As described in Figure 2.10 RPC provides the localization

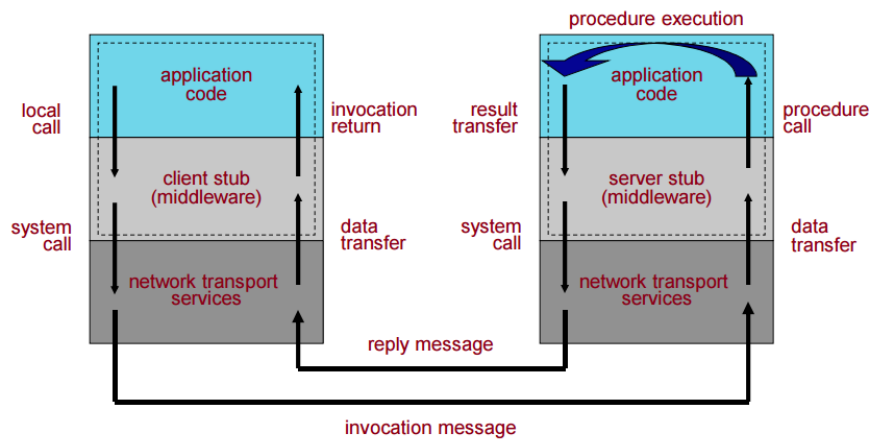


Figure 2.10: RPC in detail

of the code to be executed exploiting the network transport services, create a message which can be serialized and transferred over a standard network protocol and then provides methods to de-serialize the message and convert in into a standard local procedure call in the receiver machine. Very important in this mechanism is the concept of *ILD* (Interface definition language) which raises the level of abstraction of the service by separating the interface from its implementation: in this way RPC can be language independent by generating automatic translations from IDL to target language.

Remote method invocation (RMI)

RMI exploits the same idea of RPC but with different programming constructs: it is designed to let communicate object oriented (OO) programming languages. The Figure 2.11 shows in detail how RMI is supposed to work. Like RPC, RMI uses an IDL which is designed to support OO programming languages features such as inheritance and exception handling.

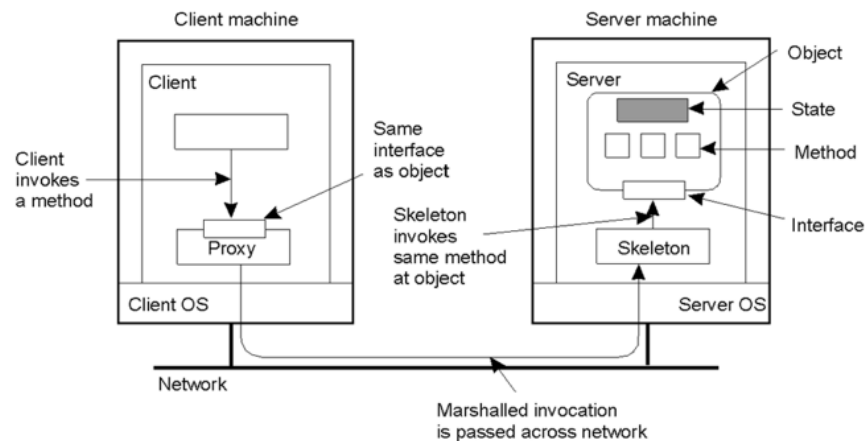


Figure 2.11: RMI in detail

Message oriented

Message oriented communication is a style based and centered on the notion of simple messages and events. The most straightforward example of it is *message passing*. Typically message passing is implemented directly on the network sublayers (eg. sockets). Message passing differs from conventional programming where a process, subroutine, or function is directly invoked by name. In Table 2.4

Table 2.4: Comparison between communication models

RPC/RMI	Message Oriented
<ul style="list-style-type: none"> • natural programming abstractions • point to point communication • designed for synchronous communication • high coupling between the caller and the callee 	<ul style="list-style-type: none"> • centered around the notion of message/event • multipoint support • usually asynchronous • high level of decoupling

are shown the most significant differences between RPC/RMI approach and message communication models. Moreover there are some implementation of message passing at middleware layer like *publish-subscribe* which is further explained in the following paragraph.

2.2.4 Architectures

There are actually many different kinds of distributed systems which can be classified by means of their architecture composition.

Client-Server

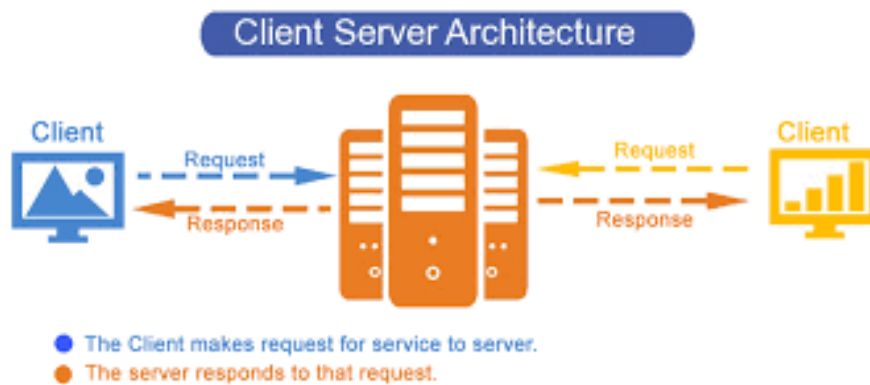


Figure 2.12: Client server architecture

Client-Server is the most common architecture in computer systems, there are many variants depending on the internal division of its components but it has a common separation of duties. Server side components are passive and wait for clients invocations. Client computers provide an interface to allow a computer user to request services of the server and to display the results it returns. Servers wait for requests to arrive from clients and then respond to them. Ideally, a server provides a standardized transparent interface to clients so that clients need not be aware of the specifics of the system (i.e., the hardware and software) that is providing the service. The communication adopted by these kind of systems is message oriented or through RPC.

Peer-to-Peer (P2P)

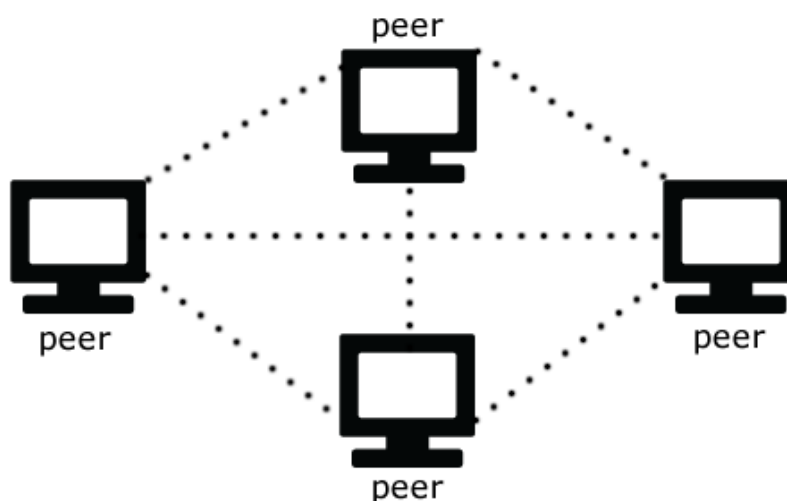


Figure 2.13: P2P architecture

P2P is a fully distributed architecture which in contrast to client-server has not a centralized service provider. Peers are both clients and servers themselves,

P2P promotes sharing of resources and services through direct exchange between peers. Compared to a centralized client-server architecture a P2P net scales better and typically does not have a single point of failure.

REST style

Representational State Transfer (REST) is a style of architecture based on a set of principles that describe how networked resources are defined and addressed. An application or architecture considered RESTful or REST-style is characterized by:

- state and functionality are divided into distributed resources,
- every resource is uniquely addressable using a uniform and minimal set of commands (typically using HTTP commands of GET, POST, PUT, or DELETE over the Internet),
- the protocol is client/server, stateless, layered, and supports caching.

Event based

Event based is an architecture in which components collaborate by exchanging information about occurring events. In particular components in the net can *publish* notifications about the events they observe or [subscribe] to events they are interested to be notified about. This architecture can be fully distributed with all the same nodes or can have some semi-centralized nodes which are specialized in computing events or routing messages. Communication is, in this case, purely message based asynchronous and multicast.

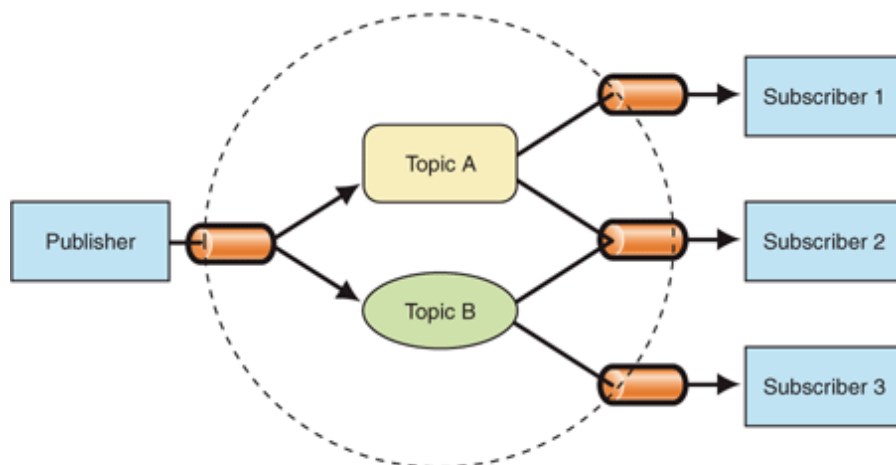


Figure 2.14: Publish-subscribe architecture

2.2.5 Naming

Naming is one of the major issues when building distributed systems, in fact, it is often impossible to know a priori, exactly the addresses and port services of all the components in a distributed network, especially when the system allows dynamic connections and disconnections. It is important therefore, to adopt a naming model or service, to automatize components discovery and connections, when running a distributed system. To understand how naming models e solvers work it is important to introduce some naming concepts in the distributed systems paradigm.

In distributed systems names are used to identify a wide variety of resources such as computers, hosts, files, services as well as users. Names are usually accessed by an *access point* which is a special entity characterized by an *address*. Addresses are just special names which can be used by communications protocol to connect different machines. For this reason it is important to know access point addresses because otherwise it would be impossible to connect components. Dynamic systems let components change access points frequently, so having *location-independent* names is much more convenient than known static addresses which can change during system execution. *Identifiers* such that they never change during the lifetime of an entity, are unique, and can not be exchanged between different entities. In this way, using identifiers, it is possible to split the naming problem in two: mapping a name to the entity and then locating the entity itself. Naming schemes are the solution to the first problem, and the most used ones are:

- *Flat naming*, or unstructured, are simple identifiers represented by random strings of bits. An important property of such a name is that it does not contain any information whatsoever on how to locate the access point of its associated entity [24].
- *Structured naming* are composed from simple, human-readable names, not only file naming, but also host naming on the Internet follow this approach, in fact, flat names are good for machines, but are generally not very convenient for humans to use [24].
- *Attribute based naming* is a way to describe an entity in terms of (*attribute, value*) pairs. Flat and structured names generally provide a unique and location-independent way of referring to entities. Moreover, structured names have been partly designed to provide a human-friendly way to name entities so that they can be conveniently accessed. In most cases, it is assumed that the name refers to only a single entity. However, location independence and human friendliness are not the only criterion for naming entities [24]. Using attribute based naming is possible to give more information about entities or services to be found.

The solution to the second problem is called *name resolution*. Name resolution in the process of obtaining the address of a valid access point of an entity having its name. Name resolution services highly depends of the naming model adopted by a system.

For sake of brevity here are not reported any detail of name resolution systems, but only basic naming notions to understand author's design choices in solving the thesis problem.

2.3 Technical Background

This section has the aim to give to readers a useful technical background to understand the implemented and proposed solution in the following chapters.

2.3.1 Liquid Computing

The term was coined for Apple's liquid computing feature and refers to a style of work-flow interaction of applications and computing services across multiple devices, such as computers, smartphones, and tablets.

In a liquid computing approach, a person might work on a task on one device, then go to another device that detects the task in progress at the first device and offer to take over that task. In other terms liquid computation is a sort of what is called *ubiquitous computing* which is a model of man-machine interaction in which information elaboration is integrated in everyday objects.

Examples

There are some implementation of this concept in mobile computer science, the most significant are:

- Apple continuity, is a system, developed by Apple, with which a user can initiate a task on one device and end the task on another. For example it is possible to answer a call with a computer without using the phone.
- Google chrome and Gmail, developed by Google, allow users to surf the web and to write email on every available device as if they were using a single device. By registering a Google account chrome can save the navigation history of the user and show it on any logged device. In the same way Gmail saves automatically emails and for example is possible to start writing an email on a desktop pc and then completing and sending that email on a smartphone.
- Microsoft One Drive sync is a system, developed by microsoft to allow users to synchronize file and settings among their devices like desktops, notebooks smartphones and so on.

2.3.2 Java network programming

Since the entire Android development API is written in Java, the whole implemented solution will be in Java code.

Java is a known general-purpose computer programming language that is concurrent, class-based, object-oriented [25], and specifically designed to have as

few implementation dependencies as possible. It is intended to let application developers "write once, run anywhere" (WORA) [29], meaning that compiled Java code can run on all platforms that support Java without the need for recompilation.

The *Java Development Kit (JDK)* includes many utility libraries, useful to develop any kind of application, I want to focus attention on network programming libraries to be used when developing distributed system using Java code. There are, currently many different possibilities among which to choose to let Java software components communicate on the network, the most simple and common are *Sockets* and *Java RMI*.

Sockets

Sockets are abstractions through which an application may send and receive data, in much the same way as an open file handle allows an application to read and write data to stable storage. A socket allows an application to plug in to the network and communicate with other applications that are plugged in to the same network. Information written to the socket by an application on one machine can be read by an application on a different machine and vice versa [6]. Different types of sockets correspond to different underlying protocol suites and different stacks of protocols within a suite. In Figure 2.15 it is shown the

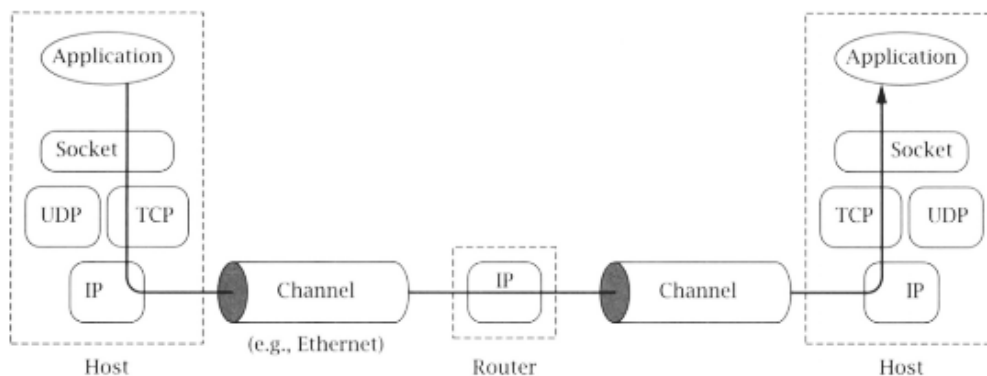


Figure 2.15: TCP/IP sockets

working mechanism of a *TCP/IP socket*: the application exploiting the socket communicate using the TCP transport layer and the IP networking layer. In this way it is possible to read/write packets knowing four variables: socket TCP port number and IP address for the sender and the receiver.

Java provide a network library with which is very easy to implement a client/server simple application using TCP/IP sockets. The following snippet of code are provided to give a concrete Java client/server application using sockets.

Listing 2.1: DateServer example

```
1 package ex.networking;
2
3 import java.io.IOException;
4 import java.io.PrintWriter;
```

```
5 import java.net.ServerSocket;
6 import java.net.Socket;
7 import java.util.Date;
8
9 /**
10  * A TCP server that runs on port 9090. When a client
11  * connects, it
12  * sends the client the current date and time, then
13  * closes the
14  * connection with that client.
15  */
16 public class DateServer {
17     public static void main(String[] args) throws
18         IOException {
19         ServerSocket listener = new ServerSocket(9090);
20         try {
21             while (true) {
22                 Socket socket = listener.accept();
23                 try {
24                     PrintWriter out =
25                         new PrintWriter(socket.
26                             getOutputStream(), true);
27                     out.println(new Date().toString());
28                 } finally {
29                     socket.close();
30                 }
31             }
32         } finally {
33             listener.close();
34         }
35     }
36 }
```

Listing 2.2: DateClient example

```
1 package ex.networking;
2
3 import java.io.BufferedReader;
4 import java.io.IOException;
5 import java.io.InputStreamReader;
6 import java.net.Socket;
7
8 import javax.swing.JOptionPane;
9
10 public class DateClient {
```

```

11
12     /**
13      * Runs the client as an application. First it
14      * displays a dialog
15      * box asking for the IP address or hostname of a
16      * host running
17      * the date server, then connects to it and displays
18      * the date that
19      * it serves.
20      */
21     public static void main(String[] args) throws
22         IOException {
23         String serverAddress = JOptionPane.
24             showInputDialog(
25                 "Enter IP Address of a machine that is\n" +
26                 "running the date service on port 9090:");
27         Socket s = new Socket(serverAddress, 9090);
28         BufferedReader input =
29             new BufferedReader(new InputStreamReader(s.
30                 getInputStream()));
31         String answer = input.readLine();
32         JOptionPane.showMessageDialog(null, answer);
33         System.exit(0);
34     }
35 }

```

Comments in the example gives the full explanation of how simple client/server Java application using TCP sockets works.

Java RMI

Java RMI it is an implementation of *Remote Method Invocation* previously discussed in 2.2.3. It represent the best alternative to sockets when building network applications. Java RMI is a complete middleware itself, in fact, it raises the level of abstraction of the network communication environment.

Remote method invocation allows applications to call object methods located remotely, sharing resources and processing load across systems. Unlike other systems for remote execution which require that only simple data types or defined structures be passed to and from methods, RMI allows any Java object type to be used - even if the client or server has never encountered it before. RMI allows both client and server to dynamically load new object types as required.

2.3.3 Zeroconf

Zero-configuration networking or *Zerconf* is a set of technologies that automatically creates a usable computer network based on the TCP/IP Internet paradigm, when computers or network peripherals are interconnected.

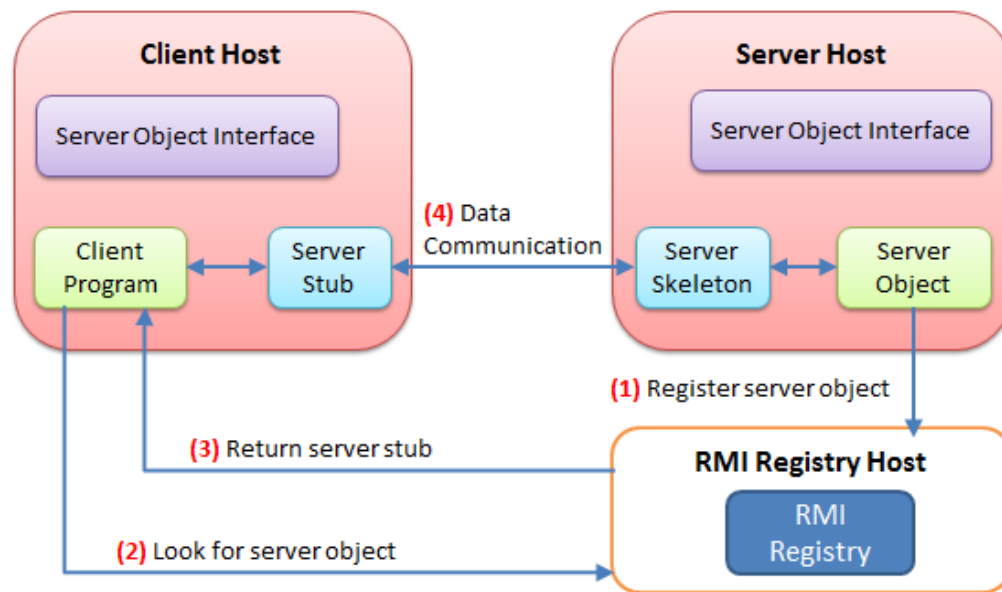


Figure 2.16: Java RMI structure

The aim of this technology is to let users easily connects to various local network services, without the need of configurations. The architecture of Zeroconf is built around simplicity. It should be as easy for an end users to connect a printer or locate streamed music as it is for him to turn on light bulb [8].

It is built on three core technologies: automatic assignment of numeric network addresses for networked devices, automatic distribution and resolution of computer hostnames, and automatic location of network services.

Service Discovery and Name Resolution

To the end user, the most important facet of Zeroconf is the ability to easily browse for available services in the network. With Zeroconf you browse for services, not for hardware [8]. Internet protocols use IP addresses for communications, but these are not really human-readable; IPv6 in particular uses very long strings of digits that are not easily entered manually. To address this issue, the internet has long used the Domain Name System (DNS), which allows human-readable names to be associated with IP addresses, and includes code for looking up these names from a hierarchical database system. Users type in common names, like wikipedia.org, which the computer's DNS software looks up in the remote DNS databases, translates to the proper IP address, and then hands off that address to the networking software for further communications [5]. Zeroconf deals with record, find and resolve network services like DNS systems do. It associates the service itself, providing its name and description when registering it, with the machine that provides it, knowing the IP and the used port. When there is the need of a connection the device that want to use the service, automatically, by finding it with Zerconf, knows connection variables , resolved by the protocol.

Implementations

Zeroconf is paradigm and its component can be implemented in many ways and using different technologies, therefore there are many different names to indicate services which provide Zeroconf functionalities.

Apple Bonjour is one of the first implementations of the Zeroconf technology, it is an Apple trademark and its registered name is Rendezvous. Bonjour, also known as zero-configuration networking, enables automatic discovery of devices and services on a local network using industry standard IP protocols. Bonjour makes it easy to discover, publish, and resolve network services with a sophisticated, yet easy-to-use, programming interface that is accessible from Cocoa, Ruby, Python, and other languages [16].

jmDNS is a Java implementation of multi-cast DNS and can be used for service registration and discovery in local area networks. JmDNS library is fully compatible with Apple's Bonjour. Java as a language is not appropriate for low-level network configuration, but it is very useful for service registration and discovery. JmDNS provides easy-to-use pure-Java mDNS implementation that runs on most JDK1.6 compatible VMs [22].

Android NSD implements the DNS-based Service Discovery (DNS-SD) mechanism, which allows your applications to request services by specifying a type of service and the name of a device instance that provides the desired type of service. DNS-SD is supported both on Android and on other mobile platforms. Adding NSD to your Android applications allows users to identify other devices on the local network that support the services the app requests. This is useful for a variety of peer-to-peer applications such as file sharing or multi-player gaming. Android's NSD APIs simplify the effort required for the implementation of such features [15].

Chapter 3

Problem Analysis

In this chapter the specific problems of this work will be detailed and analyzed, explaining what are the limits and the constraints the challenge has. The chapter starts with a brief recap, followed by the proper definition of what I faced, while in the last part there is a list of constraints my architecture will have fulfilled in order to have a universal and functional solution.

3.1 Contextualization

As already explained introducing this thesis work in [1.1](#), I studied in deep the Android operating system to find, and later implement a concrete solution, to the problem I will define and describe in dept in this section. All the work done by me is focused on Android because every mobile operating system is different to each other and has proprietary working mechanism which have to be studied separately. Since there are many more Android devices than any other mobile OS, and Android is an open source software and there is no need to buy development licenses or proprietary hardware or software like using for example Apple systems, I decided to work with it, even if by studying another mobile OS and implementing the same concepts of my solution it is certainly possible to achieve the same result i got by working only with Android. In the previous chapter, number [2](#), I have defined Android OS working mechanism and components, pointing out the main focus on intent generation and resolution mechanism. I have then defined in deep what a distributed system is and should be, explaining connection mechanism architectures and properties.

The Android OS is a centralized operating system designed for a single physical user, to be used on personal mobile devices such as smartphones and tablets. The result of this Google's ideas is that in contemporary society there is a wide spread of Android devices, which now have computing capacity comparable to normal desktops and notebooks. Many people have multiple devices which they use separately: typically they use smartphones for calls and work emails and maybe tablets to easily surf the Internet and play games, but what they can not do is use them together to perform a common task easily. Android, in fact, has not been thought to build a real distributed system, the networking functionalities are designed to exchange messages, and to replace standard personal computers

in some task as indeed sending emails. The result is a non collaborative confused cloud of devices, which are connected to the net, but are not really connected themselves to cooperate. Solutions are often partial or proprietary and closed, even if some useful solutions exist.

The idea is let android devices collaborate and cooperate in a *Liquid environment* like the one presented in section 2.3.1. The fundamental requirement is the implementation of an android service, able to build and maintain a distributed net of android devices over a Wi-Fi LAN (Local Area Network), and then let one, or more devices in that net generate Android intents and distribute them one, or more, of the other devices involved. Thus in this chapter I am considering only Android devices that can be connected in a WiFi LAN.

After this brief recap of what has been said about the Android OS and distributed systems in the state of the art chapter, here I am trying to define with more precision the problem I am going to face: which its constraints and its possible goals are.

3.2 Considered Devices

As anticipated above, I am going to take into account only devices that can be somehow connected to a LAN, but as described in 2.1.5 Android devices are built to be connected to the Internet and most of them comes with a WiFi chip integrated. Another *"little relaxation"* I want to do is linked to the variety of Android OS versions. I want to take into account only devices updated to at least version 4.4 (API level 19). This is due to the fact that starting from Android KitKat (4.4 version) Google brought some important improvements to the libraries of the framework and in addition, according to the Table 2.2, with this choice it is possible to cover the 84% of the active Android devices.

Having done these clarifications, now I am defining the problem.

3.3 Definition

How can we transform a standard mobile OS into a distributed version of it? This is the general question I want to give an answer in this work. As already said the Android OS is a pretty closed system itself, the intent resolution mechanism shows how it is difficult to let communicate various components inside a single device. On the other hand it is equally true that Android devices are real powerful modern computers and would be great if somehow it could be possible to have a device able to detect other devices in a LAN send data and task to perform in a transparent way and then get back, if necessary, result or data. Let me be more concrete, often in a home environment there are several android devices, with a distributed intent resolution mechanism it would be possible for example to take a photo from one device with the camera of another one, to generate an intent to open a file on a group of devices simultaneously, to play a video remotely and so on, only by generating intents and then send them to the distributed net. *How can we let multiple android devices act as a single big distributed system?* This is the

question that my thesis is trying to answer. My work is a concrete solution, it is about defining and creating a method to distribute android intents from one device to other in a LAN and then let the OS act as usual to manage and resolve them.

So I am trying to let different android devices talk by means of distributing intents using well known architecture: a master component, let me call it *distributed intent generator* acting as client, and a slave component *distributed intent solver* acting as a server. The two components i will realize will be common Android background services registered on the WiFi LAN. Both of these components will result in android applications so that a single device could be used to control others or to be controlled.

In Figure 3.1 is presented how such a system should work once the net is up. The distributed system in figure is a simplification of what the middleware for distributing intents will do. The architecture will communicate using standard android networking messages that are build on top standard protocols of the ISO/OSI stack.

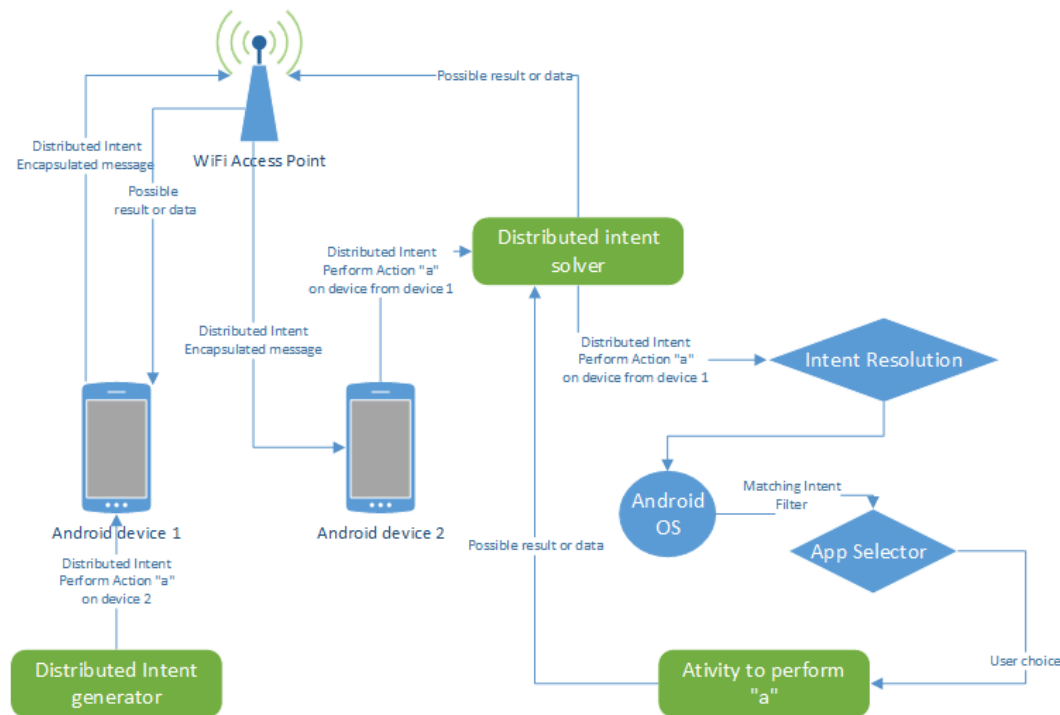


Figure 3.1: Distributed intent resolution

The important point is having a message with a well defined content: it is what the two parts must write and read, so it has to be clear for machines, must be compliant with all the requests of *M2M (Machine-to-Machine) communication*. This type of communications is a constraint of my work and are explained in the next section 3.5. Another important point is let the Android OS work as it is designed for, the main aim of this thesis work is to build a middleware to let distribute native Android intents over the network. This is a new approach to this problem in fact, there are yet some android applications which let the user send stream or data to other devices in a LAN but, with specialized and ad hoc

built messages within the same application context, using a mechanism really close to explicit intent resolution. My middleware is supposed to address the problem using a more general approach and a mechanism equal to implicit intent resolution. What I'm doing is create a system to spread any kind of implicit intent and let the OS react as usual to perform the required action. It is not even marginal the choice of the type of network to be used in such a system. Android devices are in fact, usually, mobile devices, and for this reason they can be easily moved from one place to another, so the network must take into account this property dynamically react to continuous changes.

Next sections will properly define all the constraints of the given problem and propose a solution that fulfills them all.

3.4 Problem scenarios

As already anticipated with the definition of the problem, the aim of this thesis is to give the feeling, to users, that they are working with multiple Android devices as if they were one single distributed operating system. I want to analyze some problematic scenarios and then in the next chapter of the thesis provide, if possible a solution to each specific case.

3.4.1 Background working middleware

In the best case, the result to be achieved would be a single Android APK, to be installed on devices as background bunch of services acting as a middleware. Liquid Android services which providing a communication interface can listen distributed events invocations and react to them automatically. The middleware may intercept local intents, find online devices in the distributed network, let the user select on which of them execute the task and send the intent to the selected remote Android device.

The Figure 3.2 shows a possible UML component diagram of the Liquid Android middleware, the scheme points out the interactions between the Liquid Android application (APK) and other possible applications installed on the device. The group of services intercepts the local intent, created by a different application in the same device, let the user of the system select on which available device execute the task, build and spread the the distributed intent message on the LAN, and when the message arrives at the other device the middleware transform the received message in a local intent to be resolved as usual by the operating system.

I want to provide a simple but concrete example to be more precise, every Android OS version comes with a web browser installed as an APK. When an application needs to open a URL with a browser generate an intent to perform such an action, with a middleware as described above it would be possible to click on the URL on a first device and to open the link in a second device having only installed the Liquid Android APK on both devices.

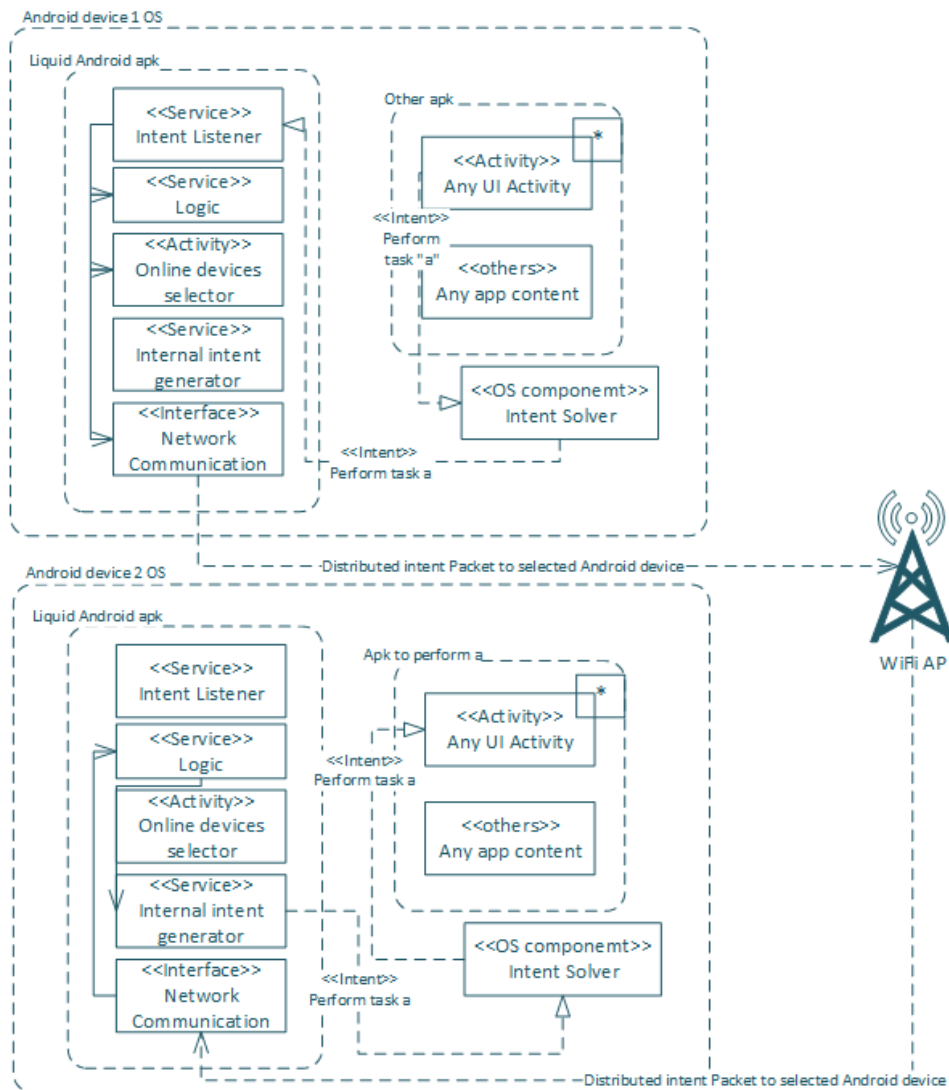


Figure 3.2: Liquid Android working as stand alone middleware APK

3.4.2 Development API

A second interesting scenario is one in which the Liquid Android middleware could become a ready to use *application programming interface (API)*. By abstracting the underlying implementation and only exposing objects or actions the developer needs, an API reduces the cognitive load on a programmer. By developing the middleware as an API is it possible to give to Android programmers a library to implement easily and faster, native Android distributed applications. The API implemented could be integrated during the development of such applications like other Android libraries to generate one single APK containing also Liquid Android components. For these purposes it is necessary to produce accurate documentation for developer who could use the Liquid Android API. As already done for the previous case, let me make an example. In Figure 3.3 there is a scheme showing how the middleware could be used to build two different applications with two different packages (apk) including both the Liquid

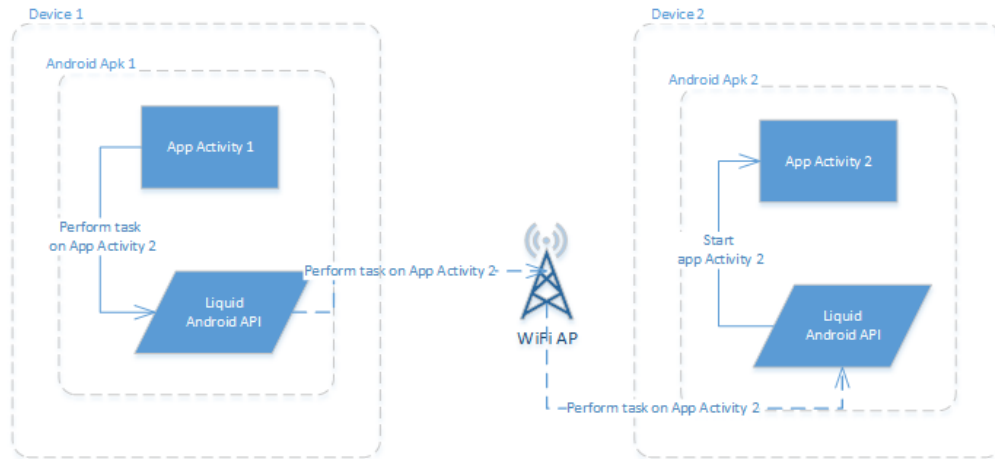


Figure 3.3: Liquid Android API working example

Android API which let them communicate by sending Android intent generated by *Android Apk 1* and then received by *Android Apk 2* installed respectively on two different devices.

3.4.3 Data management

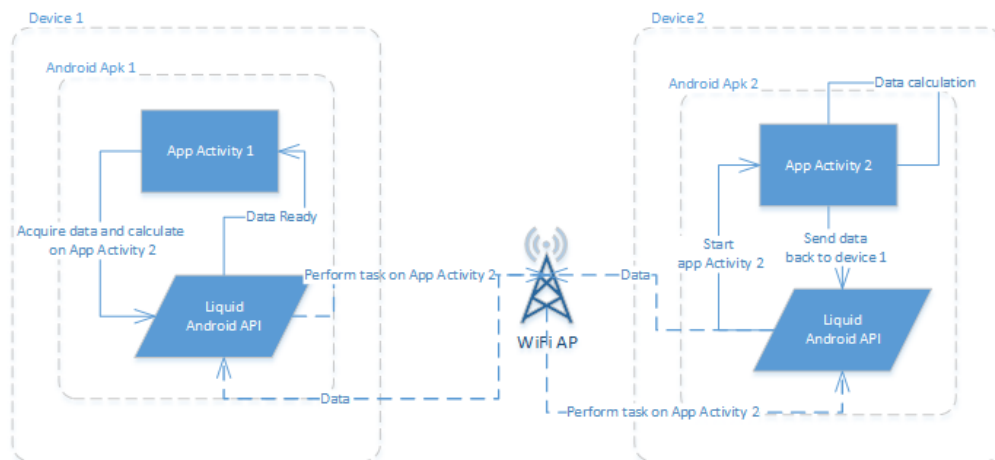


Figure 3.4: Liquid Android API data management example

Last interesting scenario to study is the data management problem in using such a system. This is a different type of scenario because it involves both previous scenarios. Having a distributed system always raises the problem of distributed data and data consistency. The middleware to be implemented must consider also the possibility to be used to build distributed Android applications in which data are generated somewhere by one device and then they need to be processed for a result by another one. A simple, but not trivial, example could be the case of a distributed calculator. A device acquires data and sends them to another one to be processed and then ask to that device the results. In the Android environment there is not the concept of distributed file system, so data

involved in such an application must be considered and efficiently exchanged between devices.

3.5 Constraints

In this section I would like to list a set of constraints for the defined problem, that become requirements that the solution must meet. The section should be divided into two parts, the first for the requirements of the network, the second for the ones of the Android distributed intent generator and solver. The two sections are actually closely related so here I preferred to keep the two parts together, analyzing the entire middleware structure.

Here is the list:

- *M2M communication*: M2M communication is defined as a communication in which the two interlocutors are not humans. It is a communication completely handled by machines and computers [7]. It can be considered one of the fundamental enabling technologies of this thesis work, it permits object to communicate without humans being involved. In This type of communication the reader of the content is a computer, in this case are Android devices. The content of the messages must be well formed, the middleware must react properly to the event of receiving a distributed intent. So a clear, defined syntax with a well fixed structure must be set in order to make everything understandable to a computer.
- *Transparent*: As already widely discussed a middleware is those which do the *magic*. The proposed solution is intended to be transparent to the Android OS and let it work as usual in resolving implicit intents whether they are distributed or not. Moreover as discussed in the chapter 2, to be more precise in Table 2.3, a distributed system must be transparent at many level, in this case the middleware must act as resources manager and efficiently mask resources access and location.
- *Lightweight*: Another constraint to my system is the fact that whatever system I choose to be the solution it must be lightweight. This is needed because my system will work on a WiFi LAN. Messages must be encapsulated, serialized from one device and transferred in another one to be deserialized and analyzed to be executed. Messages must be as easy as they can because they are very frequent in such a system.
- *Modular*: The implementation of the solution must be modular, this is due to the fact that this middleware is intended to be used as is but also to implement easily other kind of native Android distributed system application. Having a modular structure facilitates the specialization of its component and make all the middleware more readable and easy to use. In this way Liquid Android can be the substructure of other works.
- *Extensible*: the implemented solution must meet canonical programming principles Extendability is one of the most important properties to take into

account when building a computer system, especially when developing a middleware. Liquid Android modules have to be extensible to be improved or adapted to different purposes.

- *Secure*: Liquid Android middleware must meet standard Android security design principles as described in 2.1.4. The implementation must not exceed the limits imposed by the OS, I do not want to break the Android permission scheme and authorization model by *rooting* the operating system, a process with which is possible to perform action as the administrator in Android environment. Rooting Android devices let application overcome the boundaries of standard applications, by letting them read and write data from all the OS. Moreover the middleware operates on mobile devices which usually contains and can manage many sensible and personal data, communications between these devices must be as secure as possible to limit security threats.
- *Consistent*: Data and accessed resources involved in the system must meet consistency requirements. When developing distributed systems consistency is one of the main issue. The implemented solution must take into account data produced during the use of the system and make them consistent according to a chosen consistency model.
- *Scalable*: the system to be implemented has not a fixed number of devices involved in. The chosen network architecture must be able to react according to the changes. Android devices are free to join or leave the network any time, and the system should be able to detect and maintain a dynamic network. Scalability is, in fact, the capability of a system, network, or process to handle a growing amount of work, or its potential to be enlarged in order to accommodate that growth [4].
- *Concurrent*: another important aspect of distributed systems is concurrency. Concurrency is the decomposability property of a program, algorithm, or problem into order-independent or partially-ordered components or units [21]. The implementation of the services must ensure this property to the system. The middleware has to have the capability to handle different requests at the same time and execute task in more than one device simultaneously.

The listed requirements, as already told in some of them, are, sometimes, general, in the sense that they have to be respected for the final product: a global and complete structure that starts from the construction of the network architecture arrives to the user's interaction activities on Android devices. This is because the problem I am facing is very big and complex, and it is transversal to the existing technologies, so the whole system must work properly. Keeping in mind what I have just stated, some of these constraints become fundamental requirements that my system must meet. My work has to be clear for developers to be used for further implementations of native Android distributed systems, but even if it can be less clear to an average user it must be usable to those wishing to try distributed intents with their own devices in a home LAN.

In the next chapter I am presenting my idea, the *Liquid Android* middleware, the so called solution to the given problem, explaining what I have done, my considerations about the situation here faced.

Chapter 4

Proposed Solution

In this chapter the development of the solution will be reported step by step, with a full use case. The chapter starts with a list of similar solutions already developed, highlighting the differences between them and my thesis work. The remaining part is composed of three main sections: the first explains the choice of the network, the architecture, the naming service, etc. It lays the foundations for the second part: the definition of the Liquid Android middleware, or better the structure of what will do the magic: intercept, encapsulate, spread, and generate distributed intents in the network so made. The two parts are closely related, therefore their relation was taken into account when I made my choice. The real implementation of the valid solution is left for the next chapter.

4.1 Existing Solutions

Android distributed systems already exist as specific purpose applications to be installed on multiple devices, what is different to the aim of this thesis work is that these applications are closed source projects that can not be reused to build other purpose systems and there is not a coherent framework, library or API to be used to easily build such systems. I want to give some examples pointing out the nice features have these native distributed Android systems.

4.1.1 Boincoid and HTC Power to Give

Boincoid and HTC Power to Give are Android applications which aim is to exploit Android devices computation power to contribute to scientific discoveries by doing some task. The common idea is to have an Android distributed supercomputer which can handle heavy tasks and compute tons of data for larger purposes.

BOINC is an open-source software platform for computing using volunteered resources [3]. It is a program that lets you donate your idle computer time to science projects. Boincoid is a port of the BOINC platform to the Android operating system. The result is an Android BOINC client that behaves exactly like the original one.

HTC Power to give is very similar to Boincoid, it is a *CSR (Corporate Social Responsibility)* initiative from HTC that has been jointly developed with Dr. David Anderson at University of California, Berkeley. Using the HTC Power To Give, owners of Android OS smartphones can choose to 'give back' by supporting key research projects around the world. Scientific research often requires a vast amount of processing power for data modeling and analysis. HTC Power To Give, supported by the world's largest single distributed volunteer computing platform BOINC, lets users donate their unused smartphone computing power to science programmes across diverse fields as astronomy, environment, medicine and physics [18].

4.1.2 Plex for Android

Plex platform is a great, maybe the best, media content streaming distributed system platform. It is mainly composed of two components, the media server, and a client with which enjoy the contents. The Plex Media Server either running

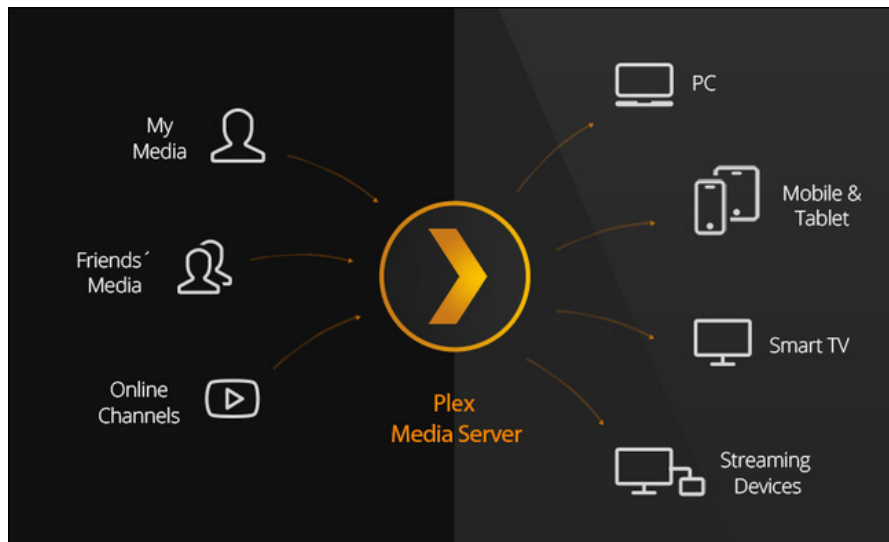


Figure 4.1: Plex Platform

on Windows, macOS, Linux, FreeBSD or a NAS which organizes audio (music) and visual (photos and videos) content from personal media libraries and streams it to their player counterparts. The players can either be the Plex Apps available for mobile devices, smart TVs, and streaming boxes, or the web UI of the Plex Media Server called Plex Web App, or the old Plex player called Plex Home Theater.

In particular Plex for Android application can connect to the media server to play its content and in addition it can search for Plex players in a LAN and send streamed content such as videos, movies or photo, to another player that can be also an Android device. In this way the Android Plex application client can behave like the Liquid Android system i want to develop. It can send a sort of *Android intent*, to reproduce a media, from one device to another, and then it can send commands such as pause, rewind, forward and so on. The limits of such a

system are that it is possible to send, and play, only multimedia contents, and only to devices which have the Plex app activity in foreground on the device.

4.1.3 Google Home and Cast API

Google itself provides an application to control and send contents from an Android device, to some special devices in home network. *Google Home* is an Android application which can find, setup, manage and control, Google's home devices like the *Google Chromecast*. In this way is easy to setup and control and Android distributed system in which user can send multimedia contents and command to the Google Home devices in the LAN. For these reason Google provides a development library, included in the Android framework, called *Cast API* with which it is easy, for a developer, to build applications that can send multimedia streams to other Google devices specifically built for these purposes. Also in this case the limitation is the kind of content, only multimedia, and also the type of devices involved which are limited number of special purposes devices.

4.1.4 DroidMote and Remote control systems

If we consider the possibility to control remote devices in a LAN, there are actually many different kind of applications that can do that also in an Android environment. DroidMote is probably the most complete application to control remotely an Android device from another one. It is composed by two parts, the server, to be installed in the device to be controlled, and the client, to be installed in the one which controls. With this application is possible to control entirely the device running the server component: is it possible to open applications, perform tasks, open system settings and so on.

These kind of systems are capable to generate local intents in remote devices over a LAN but in a completely different way from I want to develop the solution to the given problem. In this case the *controller* is explicitly controlling the remote device as it is using only the *controlled* one. These systems are solution only to the problem of remote control, they can not exploit distributed Android devices computation power, in fact in an environment like this Android devices are not cooperating to perform task but one of them is only controlling another one.

4.2 General Idea

To better explain what I consider solution for my work it is important to understand the playground to my work. As said in the previous chapter, [3](#), I am trying to extend the Android operating system by adding some functionalities to make it similar to a distributed OS, without the need of rooting it or change its standard working mechanism and components, staying in the 7th layer of the ISO/OSI stack, the application layer. Using already developed and operating tools, and respecting all the above listed constraints I am going to make mobile devices in a LAN network communicate and cooperate like they were using a

single coherent distributed operating system. In order to understand what is needed and how it is possible to solve the problem it is fundamental to understand the type of stack and the network structure we have to face, and standard Android working principle, in particular the intent resolution mechanism already described in Figure 2.4.

Only having clear in mind the problem and its structure it is possible to find the best possible solution. In particular it is possible to decompose the main problem in some sub-problems, which can be understood as general steps in doing similar works of extending a mobile OS to become a distributed OS:

- Network architecture, that is the structure and the classification of the nodes involved in the distributed system. As previously said it has to be as reliable as possible and allow dynamic connection due to the fact that nodes are mobile devices and can be easily moved in and out the network range.
- Communication model, that is the way in which involved actors perform the communication. It has to be compliant to M2M, and possibly to H2M communication, and as lightweight as possible to allow fast exchange of messages and data between the network nodes.
- Data model, as discussed before in the chapter 2, when building distributed systems it is also important to guarantee that data are managed correctly by adopting a consistency policy.

It is also necessary to identify the main actor involved in the problem, they are mainly two:

- Server application, it is the main actor of this thesis work, it must be an Android application which once installed on a compatible Android device can receive resolve and forward Android intents. It contains the logic and the controllers needed to handle the network structure, find other devices in the network, send and receive messages. It is responsible of resolving all the three sub-problems described above. The server application has also the double function of receiving a message from the network and translate it in a local intent to be resolved by the Android operating system, but also it can act as a client by forwarding a received intent from a third party client application to another server in the net, by encapsulating the intent in a network message.
- Clients, can be applications developed in several ways, they are those which are asking to the so called servers to complete task for them. In this case clients could be any kind of third party Android application installed in the device, also running the server component, generating implicit Android intents that need to be resolved by the OS.

Once defined the main actors of the problem I am facing, the next step is to understand how they can interact and communicate. As previously described defining the problematic scenarios in the chapter 3, the Liquid Android middleware in the



Figure 4.2: Liquid Android working example

best case would be a system service which users can control to distribute intents in the local network by using the WiFi chip of the devices. The Figure 4.2 shows exactly how the middleware is supposed to work. In the figure the two devices are both supposed to be connected to the same local network (*they are under the same WiFi access point*) and they are executing any standard Android OS version starting from 4.4 KitKat (*API level 19*). The so called, in the picture, *Device 1* is executing a third party application activity (*a client*) which contains a valid clickable URL link. By clicking a link, typically, Android applications generate an implicit intent asking to the OS to open and show the page linked by the URL. Usually, in the absence of other applications capable of solving this kind of implicit intent, the process ends with the opening of a browser in the same device, which opens the URL in one of its activities. In this case the Liquid Android application server, installed on both devices, should to tell the OS that it can handle that implicit intent, find the other devices in the net, in this case the so called *Device 2*, let the user choose with which device complete the task, convert the intent in a network message and send it to that device. Once the message arrived to the *Device 2* the Liquid Android middleware server application is responsible to translate again the received message into the starting implicit intent sent by the *Device 1* and to start the very same resolution mechanism for that intent by its own Android operating system, which should end by the opening of a browser activity to view the page.

It is clear that a solution for this scenario would be also, once implemented, a solution for the second problematic scenario proposed in 3.4.2. In fact we can consider the development of an API to build native Android distributed systems as a sub problem of the first one, already described above and in 3.4.1. The implemented version of the general solution could be also used as a library to implement special purposes similar systems by simply extending my framework and including its implemented Java classes in other Android applications projects. For these reasons in developing the solution I will try to make it as

clear as possible, and to parametrize as far as possible the settings variable of my framework to make it easily extensible and ready to use by other Android developers.

I would like now to list the goals that my work has to match, in order to be a valid proposal for solving the given problem. These goals are not to be intended as set in stone, they are the general motivation that leads to construct a prototype of the proposed software architecture. According to my thoughts during the development, it is possible to identify the following goals:

- The middleware must work without any proprietary application: it has to interface itself to the upper layer without installing any other application of any vendor in the owned device. It must be completely neutral to the market, it must work with any version of the Android operating system starting from the API level 19, also with Android customized versions developed by device maker like Samsung, LG, Huawei and any other brand. It is the fundamental requirement to create heterogeneous applications and to separate the various closed solutions of today and an open solution for everyone in the future.
- The middleware has to simplify the life of the developer, he should not have to worry too much about the substrates, he should be able to fast prototype. The developer should see my framework as help for his work. The idea is to provide a ready to use service, with which it is possible create new application by exploiting it.
- The middleware should offer the user the possibility to access directly to other devices in the network without the need of configure anything. Users, once installed the middleware should use its functionalities of receiving/forwarding intents in a transparent way, in the same way they use other applications and with the same mechanism they learned by using the standard Android operating system.

The next sections contain all the steps necessary to have a full working system. Firstly I would solve the, let me call it *general theoretical problem* by dividing it as discussed above and providing the solution for each of them, taking into account also the data management scenario. Then I would like to present the structure of the development API, while the actual implementation of the working Liquid Android application is left for the next chapter with some working tests and a deep component analysis.

4.3 Theoretical solution, extending the Android OS

In this section i will perform an in depth analysis of the possible solution to the given problem: how I can extend the Android OS providing it distributed functionalities.

4.3.1 Network Architecture

The first step while creating a distributed system is to define the networking architecture, in particular I must define the kind of nodes involved in the system and the way in which they interact, what they can do, which operation they can perform and in which way. As mentioned earlier the network architecture of the system must fulfill the following requirements:

- *dynamicity*, it must allow any device to perform the dynamic connection, and also disconnection, to the distributed system at any time, since the nodes of the network are mainly mobile devices and they can be moved easily. Nodes can *JOIN* and *LEAVE* every time, and the network must accommodate them automatically.
- *simplicity*, the network must be as simple as possible, it should not need any particular configuration on the nodes to *JOIN*. Any node should perform other nodes *DISCOVERY* in the network in a easy way without the need to know them a priori.
- *reliability and security*, are important non functional requirements in such a system. I want to make the network reliable and secure as much as possible by the adoption of standard software engineering techniques.

The network architecture that fits better all the requirements listed above is certainly a P2P network. As seen in 2.2.4, in peer-to-peer networks there is not a clear distinction between clients and servers, in fact a peer-to-peer network is designed around the notion of equal peer nodes simultaneously functioning as both "clients" and "servers" to the other nodes on the network.

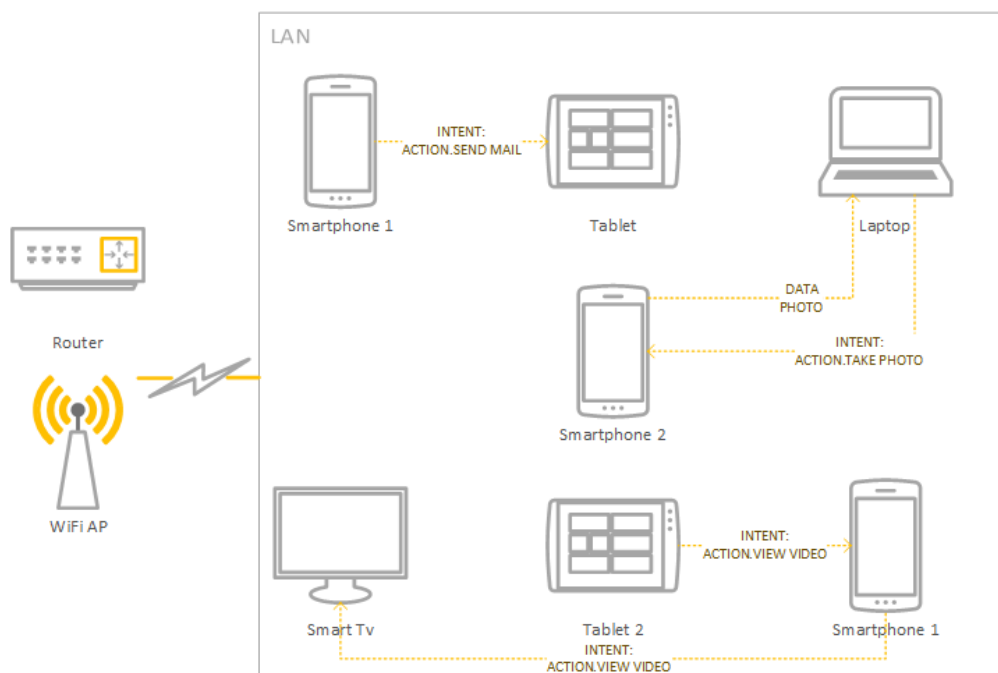


Figure 4.3: P2P Liquid Android network example

I think that an *unstructured P2P architecture* is the best choice for my system due to the fact that it does not impose a particular structure on the overlay network by design and data is still exchanged directly over the underlying TCP/IP network, so at the application layer peers are able to communicate with each other directly, via the logical overlay links. In Figure 4.3 there is an example of my architecture in which different devices are in range under the same local network and they can communicate sending intents and data.

To obtain this kind of structure, and let it change dynamically depending on the devices in range, I need to equip the devices with a *network service*. In computer networking, a network service is an application running at the network application layer and above, that provides data storage, manipulation, presentation, communication or other capability which, in this case will be used in combination with a peer-to-peer architecture based on the application layer network protocols. Different services use different packet transmission techniques. In general, packets that must get through in the correct order, without loss, use TCP, whereas real time services where later packets are more important than older packets use UDP. For example, file transfer requires complete accuracy and so is normally done using TCP, and audio conferencing is frequently done via UDP, where momentary glitches may not be noticed. In this case I will adopt the TCP transport layer because I need to transfer packets in a reliable way, as much as possible, and also avoid network congestions, the UDP protocol in fact lacks built-in network congestion avoidance while TCP has it.

To fulfill the above listed requirements of dynamicity and simplicity the right approach should be the Zeroconf one, already discussed in 2.3.3. Using a Zeroconf implementation to register and discover the service in the LAN will let the node to connect dynamically and in an easy way to the distributed system. The three main operations a node can perform are:

- *JOIN*, to join the system a node must activate the network service, it must provide an internal endpoint for sending or receiving data in the computer network. The best abstraction to do that is to open a socket, as seen in 2.3.2. In particular, a TCP socket is characterized by two main parameters: the *IP* and the service *PORT*. In my system the TCP socket is a great choice because, as already stated, it is a network abstraction and it can be used to let heterogeneous devices communicate and can be implemented in several different ways using basically any development language. By knowing the couple of variables of the network service another device can send messages, streams and so on, to it through the TCP socket. Since mobile devices change frequently their connections variables, because of their nature to be easily moved from one place to another, we need a system that can identify them dynamically. The name of the service and the chosen transport layer can be established once for all and they can never change. In this environment Zeroconf provides service registration and discovery. By registering the service name, port, and transport layer the node can be found in the LAN by other nodes looking for that kind of service. In this way nodes do not need to know, a priori, the two variables, IP and PORT of any node in the network, to communicate with each other, they, indeed,

need only to know the service name and the chosen transport layer to find other nodes in the network.

Listing 4.1: Zerconf registration example

```
1 public void registerService(int port) {  
2     // Create the NsdServiceInfo object, and  
3     // populate it.  
4     NsdServiceInfo serviceInfo = new NsdServiceInfo  
5     ();  
6     // The name is subject to change based on  
7     // conflicts  
8     // with other services advertised on the same  
9     // network.  
10    serviceInfo.setServiceName("LiquidAndroid");  
11    serviceInfo.setServiceType("liquid._tcp");  
12    serviceInfo.setPort(port);  
13    ....  
14 }
```

The snippet of code 4.1 is an example of how in Android it is possible to register a service using the Zeroconf approach. Once registered the service Zeroconf provides name resolution functionalities to discover other nodes and then connect to them to start the communication.

- *LEAVE*, I want that a node can decide whether join or leave the network at any time. To leave the network a node should only unregister the service registered using Zeroconf and then close the socket to avoid accidental or malicious connections.
- *SEARCH*, since the network is dynamic, it is necessary to determine how the nodes, once the service has registered, can search for and find other nodes. As already mentioned describing the *JOIN* operation Zeroconf also provide the network service discovery and the naming resolution mechanism. In this case Zeroconf uses a *Domain Name System (DNS) based Service Discovery*, the so called *DNS-DS*. DNS-SD allows clients to discover a named list of service instances, given a service type, and to resolve those services to *hostnames* using standard DNS queries. The specification is compatible with existing *unicast DNS* server and client software, but works equally well with *multicast DNS (mDNS)* in a zero-configuration environment. Each service instance is described using a *DNS SRV* and *DNS TXT* record. A client discovers the list of available instances for a given service type by querying the *DNS PTR* record of that service type's name; the server returns zero or more names of the form "<Service>.<Domain>", each corresponding to a SRV/TXT record pair. The SRV record resolves to the domain name providing the instance, while the TXT can contain service-specific configuration parameter. Once completed the resolution process the node which started it to find other nodes in the network, knows

any couple of IP/PORT of their open sockets and can connect to them to exchange messages or transfer data.

Given the network structure security is obviously a non functional requirement in building my system, but since my entire middleware, once connected, will allow to send and execute any kind of task, in the form of implicit intents, to each device involved I need to make some considerations about the security of such a system. The security of my system is highly influenced by the underlying physical network, if the LAN access is secured and protected my system will be, indeed, enough secure. The network should be protected using a firewall and the service ports used by the device involved in the system should not be accessible from the outside of the LAN. Moreover the WiFi should be protected using a strong password and a secure and updated access protocol like the WPA2. Furthermore, I want that users of my system are aware of the fact that it is running, so once the service is activated users will be alerted by a notification in the appropriate Android notification area.

4.3.2 Communication Model

Once the network is up the second step is let the device communicate to cooperate giving, to the final users, the feeling that they are working with a single big distributed operating system. To achieve this goal, as already explained several times, my system is supposed to intercept implicit intents, let the user select a target device, or a group of them, to perform the task, send it and once arrived perform it in the selected device or group devices. With TCP sockets it is very easy to exchange messages between networked devices, so it is equally easy to understand why I have chosen a message oriented structure as the communication model, briefly presented in 2.2.3, for my system. Furthermore, as already stated with the Table 2.4 such a model gives me more freedom of choice regarding certain characteristics that the system must have, I want the communication is:

- *concurrent*, in the original Android OS when an intent resolution mechanism is started by any other component of the system, for example an application activity, the OS stops its execution to perform, in foreground, the task the intent contains. I want to leave unchanged this kind of mechanism in my system, so when a, let me call it, *distributed intent* arrives from the socket, the operating system must treat it exactly as if it were a *local intent* and execute it in the same way it does with other intents. The arrival of a new distributed intent from another device is the event which triggers the standard OS resolution technique by suspending any other operation. I want the network listen and accepts messages with distributed intents to solve at any moment, in a fully concurrent way, so the last intent is triggered the first it is resolved and executed in a *LIFO*, last in first out, way like in a stack structure.
- *asynchronous*, the standard intent resolution mechanism, like many other in the Android operating system, is mainly asynchronous. When an implicit

intent is triggered it will be performed without knowing, a priori, what application will execute the task and how. To be more clear, for example when an application ask the OS to open a map of a place, the application which started the process do no need to know if the system completed the task and with which results. I want that my system do not need to change this behavior, if an operation need to be performed the intent is triggered and the OS reacts as usual without the need to send back acknowledgment messages ACKs. When it is necessary to synchronize the communication among the various components involved when an implicit intent is triggered Android provides a mechanism, using the system function *startActivityForResult(intent)*, to send the result back to the caller. I intend to keep the same mechanism also when dealing with distributed intents, but I want to maintain an asynchronous approach also in this case, the caller could continue its execution without waiting for the results and then, once done, receive back the response, in the form of another distributed intent, from the called. I will give further details of this case when presenting the kind of messages can be sent using my system and the data model solution part.

Now the difficult part is establish how intents can be sent through the sockets and which kind of messages my system can send and then handle to perform various kind of tasks.

The next step, hence, is to find a way to send the intents from a device to another without loosing information and once they are arrived to be executed like they were local intents. To do this job it is necessary to analyze in dept what an intent is in Android and what it can contain.

As showed in the chapter 2 in 2.1.3 intents are the way in which standard Android framework's components communicate among each other, and they also represent the abstraction of actions to be performed by Android applications. In the Android developer framework an intent is implemented as a Java Class containing the information and data to perform the task. An intent is an abstract description of an operation to be performed. It can be used in various ways: with *startActivity* to launch an Activity, with *broadcastIntent* to send it to any interested *BroadcastReceiver* components, and with *startService(Intent)* or *bindService(Intent, ServiceConnection, int)* to communicate with a background Service. However its most significant use is in the launching of activities, where it can be thought of as the glue between activities. It is basically a passive data structure holding an abstract description of an action to be performed [1].

Every implicit intent is characterized, mainly, by an *ACTION*, *DATA* and a bundle of *EXTRAS*. The Table 4.1 explains in depth what an intent could contain, of course there are many types of action, data, categories and extra that are not reported here for reasons of brevity but that can be found in [1]. The real problem, for the purposes of my system, is that the Android intent Java Class can no be serialized, automatically and send through the socket as it is. In computer science serialization is the process of translating data structures or object state into a format that can be stored, or transmitted across a network connection link, and reconstructed later in the same or another computer environment.

Table 4.1: Intent Structure

Attribute	Description	Examples
<i>ACTION</i>	The general action to be performed.	ACTION_VIEW ACTION_EDIT
<i>DATA</i>	The data to operate on, expressed as a Uri.	content://contacts/people/1 tel:123
<i>CATEGORY</i>	Gives additional information about the action to execute.	CATEGORY_LAUNCHER CATEGORY_ALTERNATIVE
<i>TYPE</i>	Specifies an explicit type (a MIME type) of the intent data. Normally the type is inferred from the data itself.	type */*
<i>EXTRAS</i>	This is a Bundle of any additional information. This can be used to provide extended information to the component.	EXTRA_TEXT EXTRA_TITLE

When the resulting series of bits is reread according to the serialization format, it can be used to create a semantically identical clone of the original object [9]. In a Java environment, like the Android one, Java Classes that implements the *Serializable interface* can be automatically serialized, by the environment itself, and sent through a socket and then automatically deserialized to reconstruct the original sent object by the receiver, but as already told the intent Class does not implement this functionality. I need therefore to find a way to do this process in a fully functional and also efficient way. There are, actually, many alternatives to accomplish this objective. For example I could generate a new Java Object, containing all the intent attributes, that implements the Java Serializable interface, convert intents to this new Object and then let Java perform its automatic serialization/serialization. As an alternative I could generate some kind of semi-structured data, using a well know, let me call it *container language*, such as JSON or XML, which can be easily sent, as a string, over the socket and then parsed to rebuild the original Java Object.

Since the effort required to develop one of the two solution, presented above as examples, is practically the same, I decided to opt for the second alternative, using a JSON structure, because it has substantial advantages.

JSON (JavaScript Object Notation) is a lightweight data-interchange format. It is easy for humans to read and write. It is easy for machines to parse and generate. It is based on a subset of the JavaScript Programming Language, it is completely language independent. These properties make JSON an ideal data-interchange

language [28].

It is based mainly on two types of structures:

- Key/Value pair set: it can be considered an object of an Object Oriented programming language,
- Collection of elements: it can be considered an array of Objects.

By converting any possible implicit intent in a *JSON-intent* the system complies with the following properties:

- *M2M communication*, and also *M2H communication*, as already stated JSON are really easy to read and understand by human and also by machines,
- *lightweight messages* and also *small overhead*, it is well known that Serialization in Java produce a big overhead and serialization/deserialization to be more general lacks efficiency. JSON are merely *well formatted Strings* which can be sent unaltered on the socket without the need be further converted. The sender send the JSON as a string and the receiver gets exactly that string.
- *freedom*, JSON is optimized to be used with a great variety of programming languages, the creation of a *JSON-intent* opens up various possibilities for further development: using the correct syntax, any device, even non-Android, could be a client of my system. In this way it would be possible to send original Android intents to any Android device, with my service installed and active, from a Client running in different OS and using different programming languages. It is possible, in fact, to use Zeroconf to find the service in many other environment and to connect to the socket to send JSON-intents to the connected Android devices.

To obtain a general solution to convert any possible Android intent in to a JSON-intent, and viceversa, i need to define the syntax of new object which must fit as much as possible to the structure of the Android intent Class. In fact it would be very easy to convert the major fields that characterize a given intent that are mostly correctly formatted strings, if it were not for the fact that the bundle of extras can contain different types of structured data.

JSON-Intent syntax

In this subsection I am going to define step by step the syntax of my solution, explaining with listings and images all the elements. An important and remarkable reflection is needed here: unfortunately it is not possible for me alone to consider every kind of intents and to convert properly any kind of data, but my system will work with great majority of them. It is in fact unlikely that implicit intents will contain strange structured data types or *Parcelable* and *Serializable* data which are usually used with implicit intents, which, for construction of the operating system, my system can not handle. For these reason I am not going to support, with this solution, that kind of data, since it would be very difficult, and

highly inefficient, send and reconstruct Parcelable and Serializable data types over my system. That said, I want to proceed with the definition of the syntax of the JSON-Intents.

In Figure 4.4 it is shown the complete structure of an intent including the de-

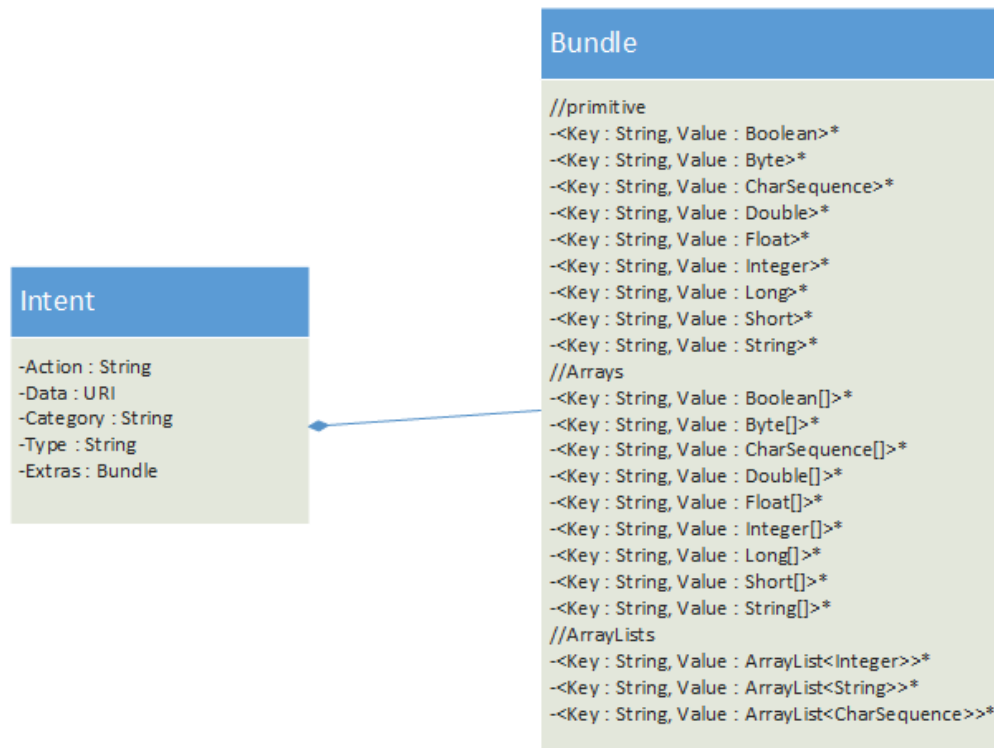


Figure 4.4: UML structure for an Intent

tailed description, using an UML model, of the bundle that is responsible of holding the Extras. The bundle is a sort of container of a non predetermined number of couples *<Key,Value>* in which the Key is always an arbitrary String, while the Value can be any of the structured data types listed in the schema. The *"*"* notation at the end of any attribute in the bundle, means precisely that the number of *<Key,Value>* is variable, and optional, for any kind of structured Value data type.

I have already analyzed the structure of an Android intent object in the Table 4.1, now I am reproducing the same structure to convert it in a JSON-intent. Using some tables i would explain all the syntax i have created. In the Table 4.2 it is shown the general structure for the JSON-Intent, precisely in the first column, *Name*, there is in bold the String keyword used in JSON to identify the field. In the second column, *Type*, it is explained which kind of data type the field, identified by the keyword in the first column, contains. Since JSON allows to store only *String*, *Boolean*, *JSON Array*, *Number* and *JSON Object* data types in the third column, *description*, there is a short explanation of how the conversion is performed.

Table 4.2: JSON-Intent fields

Name	Type	Description
action	String	It was a String also in the original Intent Object and do not need to be further converted. It is used also to identify, by using intent filters, which applications can execute the intent once arrived to the receiver.
[data]¹	String	It was a URI type in the Intent Object which can be easily stored as a string by using the <code>URI.toString()</code> method in Java.
[categories]	Array <Category> ²	It was a Set of Strings in the Intent Object so it can be converted in an array of Category JSON Objects (<i>JSON Array</i>) containing all the category of the intent.
[type]¹	String	It was a String also in the original Intent Object and do not need to be further converted.
[extras]¹	Array <Bundle Object> ²	It is a collection of all possible extras, it has to be converted in complex JSON Object which I will describe in the next tables.

Since *categories* and, as anticipated, *extras* are complex fields, containing array data types, introduced by me, I need to give further explanations of my choices in translating this objects form Java to JSON.

Table 4.3: Category fields

Name	Type	Description
category	String	It was a String also in the original Intent Object and do not need to be further converted.

In the Table 4.3, using the same notation of the previous table, it is shown how the *Category JSON object* is structured. It is, merely, a simple object containing a single field using the keyword *category* with a String value which is any possible Android intent's category.

¹The notation [Field] means that the field is optional

²The notation Array<Type> means that the Array contains Objects of that type

Table 4.4: JSON-Bundle Object fields

Name	Type	Description
[key] ¹	String	It contains the keyword, an arbitrary string, used to store the specific extra in the original Java intent object.
type	String	It is a string which describes the type of structured Java data type, it is used to correctly reconstruct the original Intent Object.
data	Variable	This field is the one which contains the actual data, it can be a primitive data type such as a boolean a double and so on, or a supported array. The full description of this field is given in Table 4.5.

In the same way the Table 4.4 shows the structure of the JSON-Bundle object. Every single JSON-Bundle object represents a possible *extra* of the original Java intent. The field *key* contains the string keyword used to identify the extra. The *type* field contains one of the keywords, in bold, defined in the next table, which is a String used to identify the structured Java data type, used to perform the so called *deserialization*, by reconvertng the JSON-Intent in a Android Java intent object. Depending on the type of data that it is necessary to store the *data* field can contain the actual data, if the original Java type was a primitive data type, or an array of JSON-Bundle objects without the field *key*, if the original data type was an Array or an ArrayList.

Java Object	JSON Object		
name	type content	data type	description
Primitive Data Types			
boolean	boolean	Boolean	The data field contains the actual boolean value.
byte	byte	Number	The data field contains the actual byte value.
CharSequence	charsequence	String	The data field contains the actual CharSequence value converted in String.

double	double	Number	The data filed contains the actual double value.
float	float	Number	The data filed contains the actual float value.
int	integer	Number	The data filed contains the actual int value.
long	long	Number	The data filed contains the actual long value.
short	short	Number	The data filed contains the actual short value.
String	string	String	The data filed contains the actual String value.
Array Data Types			
boolean[]	aboollean	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field <i>"boolean"</i> and in the data filed the actual boolean value.
byte[]	abyte	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field <i>"byte"</i> and in the data filed the actual byte value.
CharSequence[]	acharsequence	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field <i>"charsequence"</i> and in the data filed the actual charsequence value.
double[]	adouble	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field <i>"double"</i> and in the data filed the actual double value.

float[]	afloat	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field " <i>float</i> " and in the data filed the actual float value.
int[]	ainteger	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field " <i>integer</i> " and in the data filed the actual int value.
long[]	along	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field " <i>long</i> " and in the data filed the actual long value.
short[]	ashort	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field " <i>short</i> " and in the data filed the actual short value.
String[]	astring	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field " <i>string</i> " and in the data filed the actual string value.
ArrayList Data Types			
ArrayList <CharSequence>	alcharsequence	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field " <i>charsequence</i> " and in the data filed the actual charsequence value.
ArrayList <Integer>	alinteger	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Objects having in the type field " <i>integer</i> " and in the data filed the actual integer value.

ArrayList <String>	alstring	Array <Bundle Object> ²	The data filed contains an JSON Array of Bundle Ob- jects having in the type field "string" and in the data filed the actual string value.
-----------------------	-----------------	--	--

Table 4.5: Possible data types

In the Table 4.5 there is the definition for any Java types of data my translation supports: for every Java type, listed in the first column of the table, is provided the corresponding translation, using the last three columns.

In this way I completed the translation of any generic Android implicit intent, which can, easily, be converted in a JSON-Intent by generating a JSON complying with the syntax defined above. The conversion process can be automatized developing an *Intent Converter*, which I will include in the *Liquid Android API*, which i will describe in the following sections.

JSON-Intent example

In this small subsection I would like to provide a full example of a JSON-Intent document which represents a theoretical proof of concept. Notice that I did not use all the fields, and obviously all the data types, I have defined in the previous pages: not all of them are mandatory to have a working system and maybe they can result redundant, and and make the example more difficult to understand.

The use case describes a working implicit intent used to ask the Android OS to send an email.

In the Listing 4.2 there is, in Java code, an example of a method which creates an Android implicit Intent to send an email and then asks the OS to resolve that Intent by using an Activity. In the Listing 4.3 there is exactly the same Intent converted using the syntax proposed above by me. The JSON-Intent thus created can be easily sent through the socket and then reconverted back to the original Java Intent object.

Listing 4.2: Implicit Intent example

```

1 public void composeEmail(String[] addresses , String
   subject) {
2     Intent intent = new Intent(Intent.ACTION_SEND);
3     intent.setType("*/*");
4     intent.putExtra(Intent.EXTRA_EMAIL , addresses);
5     intent.putExtra(Intent.EXTRA_SUBJECT , subject);
6     if (intent.resolveActivity(getPackageManager()) !=
       null) {
7         startActivity(intent);
8     }
9 }

```

Listing 4.3: Conversion of the Intent in Listing 4.2 to JSON-Intent

```
1 {
2   "action": "android.intent.action.SEND",
3   "itype": "*\/*",
4   "categories": [{
5     "category": "android.intent.category.DEFAULT"
6   }],
7   "extras": [{
8     "type": "string",
9     "data": "example",
10    "key": "android.intent.extra.SUBJECT"
11  }],
12  {
13    "type": "string",
14    "data": "example@example.com",
15    "key": "android.intent.extra.EMAIL"
16  }]
17 }
```

Possible Messages

Having thus defined the communication model and language, i need now to define the possible kind of messages the system can handle: as mentioned earlier Android intents can be used with different methods to start different kinds of Android components, the are mainly 4 :

- *startActivity(Intent intent)*, ask the system to start an Activity to perform the operation contained in the intent passed as parameter.
- *startActivityForResult(Intent intent)*, it performs exactly the same operations of the previous method, farther, it is used to receive a result from the activity when it finishes. The caller activity receives the result as a separate Intent object in the activity's *onActivityResult()* callback.
- *startService(Intent intent)* ask the system to start a Service to perform the operation contained in the intent passed as parameter.
- *sendBroadcast(Intent intent)* ask the system to send a broadcast message that any app can receive.

Since my system is supposed to work, mainly, by using implicit intents, the most common method it will use will be the first. I want, also, to support the use of the other three methods, so since it is impossible to understand what kind of method it is needed only by analyzing any intent filed, i need to define standard attributes to let my system choose the right Android method to start the received intent. For these reasons my system will threat received intents with the first method unless unless otherwise specified. By including in the JSON-intent a standard extra field it is possible to support any method described above. Including

in the extras array the extra with **key:** *"andorid.intent.extra.LIQUIDMETHOD"*, **type:** *"string"*, **data:** *"RESULT"* or *"SERVICE"* or *"BROADCAST"* my system will start the received intent with the appropriate method. Furthermore during the development of my system I will analyze special cases of well known intents which need a result back, for example intents asking the OS to take a photo are supposed to receive back the taken picture.

4.3.3 Data management Model

The last step is to establish how the system has to manage data created, or manipulated, by sending/resolving distributed intents. I found, basically, two main good solutions which I want to present to the readers of my work. They are both good solutions for such a problem in building my system, having different advantages and disadvantages.

Files over the socket

Since the system exploits the LAN and creates a working P2P network, it is possible to send the generated data directly using it by sending result intent or files over the socket. To continue with the previous example, in which one device of the network ask another one to take a photo, the device which perform the operation and holds the original picture can put it on the socket and send its file or the result intent, properly converted in a JSON-Intent, to the device that sent the request. In this way basically it is possible to realize any type of data management operation only by exploiting the underlying network. This first solution has the advantage of not having to use external services to the local network, indeed it do not need to use the Internet connection. There is however the drawback of having to serialize/deserialize any data to be sent over the socket.

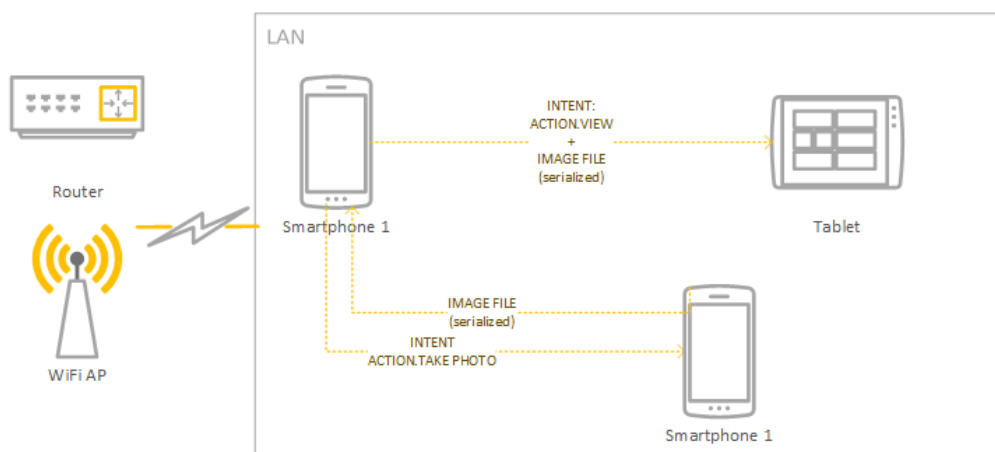


Figure 4.5: Files Over the Socket example

Cloud Group

It would be possible to easily implement a cloud group, with one of the well known cloud services supported by Android, such as *Google drive*, where devices, while my system is running, can store and download data needed by the distributed intent and generated by executing them. This second solution has the advantage that can be easily implement using existing cloud systems, but has as drawback the fact of it needs an Internet connection and some security issues because data in that way can be accessed also outside my system.

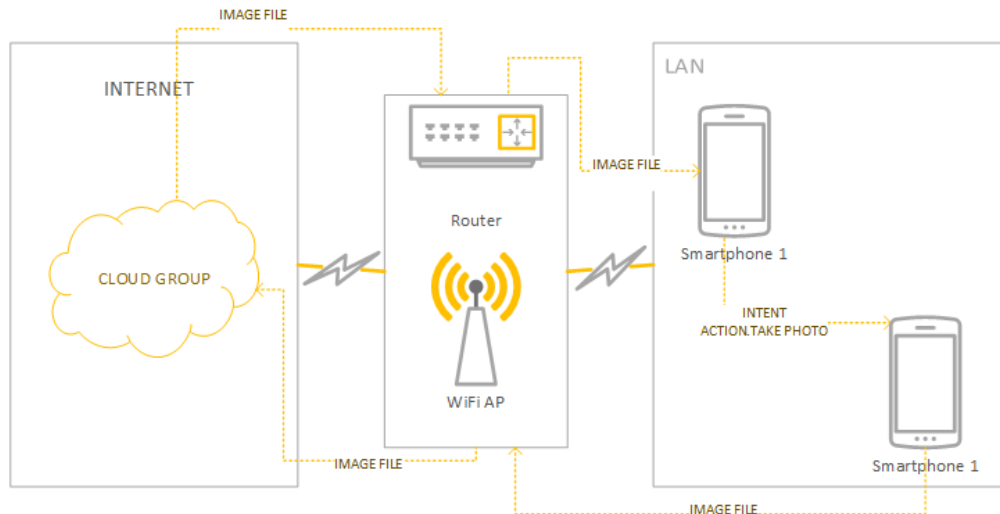


Figure 4.6: Cloud Group example

4.4 Liquid Android API Library

Once found, and described the so called theoretical solution, which mainly solves the 3.4.1 scenario, I started the concrete development of the system, trying to solve the problem and also, to create a system which can be easily extended and used to build other purposes systems.

In this section I will describe the *Liquid Android Framework* as a development API, solving the second scenario, 3.4.2, pointing out the main components, methods and configuration variables.

4.4.1 General Structure

I want to start giving an overview of the general structure of my system. I want to have few, but fully functional, components, and to accomplish the standard design pattern *Model View Controller (MVC)*.

In my API the model is represented by the JSON-Intent structure described in the previous sections: intents are the way in which my system communicates, so they are the main kind of data to deal with. Then there are the controller components, which are responsible to manage the data, and to build and maintain the network.

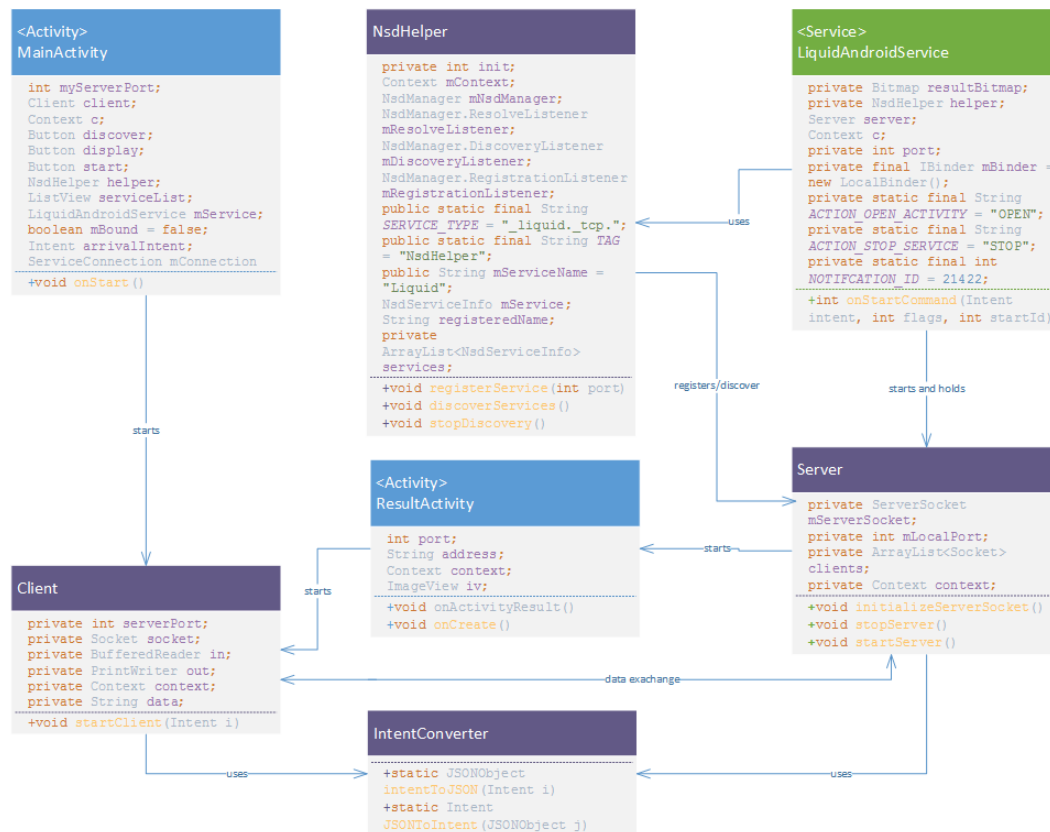


Figure 4.7: Liquid Android General UML

■ Android Service ■ Android Activity ■ Standard Java Class

Finally there are, also, *User Interface (UI)* components, which are responsible for the interaction with the final user of the system.

In Figure 4.7 there is the complete structure, by using an *UML Class Diagram* of the framework, in which it is possible to identify the various components by looking at the legend under the picture: components in light-blue are Android activity used to interact with the user, so the are, indeed UI components, while all the other classes are identifiable as controller components. The arrows in figure explain the existing relations among the class components, pointing out the way in which they interact in the system.

4.4.2 Controller Components

First of all, I want to analyze the way in which the controller components build and maintain the network and then how they send/receive JSON-Intent objects and execute them.

NsdHelper

It is a standard Java Class component, which we can see as a *Helper Class*. It contains all the methods used to register the network service and to search and

resolve other devices which are using the system, by finding other services in the LAN which are using the same name and the same transport layer. This class is an implementation of the *NSD Android API* already described in 2.3.3. Its main configuration parameters are:

- *SERVICE_TYPE*, it is the string used to identify the network services in the LAN when the *NsdHelper* perform the register and discover operations. It uses the syntax: "*_<protocol>.<transportlayer>*".
- *SERVICE_NAME*, it is the instance name: it is the visible name to other devices on the network. The name is visible to any device on the network that is using NSD to look for local services. The name, also, must be unique for any service on the network, and the NSD library automatically handles conflict resolution.

Since i want to give a flexible development API library it is possible to change this parameter by using the proper setter method or by passing two strings to the *NsdHelper* constructor. For example is possible to use:

- *setServiceType("_<protocol>.<transportlayer>")*
- *setServiceName("name")*
- *new NsdHelper("_<protocol>.<transportlayer>", "name")*

to change the configuration parameters when initializing the *NsdHelper* Class component.

Its main (public) methods are:

- *registerService(int port)*, this method performs the local network service registration, by using the variables described above and the service port passed as a parameter to this method.
- *discoverServices()*, this method performs the service discovery and resolution, by scanning the local network and saving found services in a list of resolved devices, containing the connection variables of the other compatible service in the network *IP* and *SERVICE_PORT*.
- *stopDiscovery()*, this is the method used to stop the service discovery mechanism.

Server

It is a standard Java Class component holding the server functionalities of the system. It is the components which opens the sockets and then waits and listens for invocations by other devices clients. It is responsible for the reconstruction of the intent object by using the received JSON-Intent from client, and also it has to allow the concurrency and let clients connect any time. To perform this duty my server component uses a multi-thread architecture: every time a client connects it starts a separated *server-thread* to communicate with it. Once received the

message the server translates it in a executable Android intent and then execute it by using one of the standard Android methods seen in the previous section when explaining the possible kind of messages.

Its main (public) methods are:

- *initializeServerSocket()*, this method initialize the *ServerSocket* Java component, by automatically selecting a free port in the LAN, which waits and listens for client connections.
- *startServer()*, this method is used to start the server-thread when a client performs an invocation, the started server-thread performs the operations contained in the received JSON-Intent message by reconstructing and passing it to the Android OS to be resolved.
- *stopServer()*, this method closes, and destroys, the server-thread when the client invocation is finished to avoid memory leaks when using the system.

Client

It is a standard Java Class component holding the client functionalities of the system. It is the components which connects to the server sockets of the other devices in the network and then sends the message containing the intent to be executed. It is responsible for the conversion of the intent object in a JSON-Intent to be sent on the socket. Once created the message the client send it to the selected server and then closes itself in an asynchronous way, without waiting any ACK message or the result of the invocation.

Its main (public) methods is:

- *startClient(Intent intent)*, this method send the intent, by translating it in a JSON-Intent, to the selected server. Then the client is automatically closed to avoid possible memory leaks when using the system.

IntentConverter

It is another *Helper Class*. It contains all the logic and methods used to perform the conversion of any Android Java Intent object in JSON-Intent objects, and viceversa, using the syntax proposed in the previous chapter. This standard Java Class does not have any variable or parameter, and does not need, also a special constructor. It has only two main Static public methods that can be invoked by using the Class name.

They are:

- *intentToJSON(Intent i)*, this is a Static method which performs the conversion from any Intent object, passed as parameter, to a JSON-Intent, returned by the method as a JSONObject, using the syntax created by me and explained in the previous chapter.
- *JSONToIntent(JSONObject j)*, this is a Static method which performs the reconstruction of the Java Intent object, by parsing a well formed JSONObject. It returns a fully working original Android Intent object.

LiquidAndroidService

This is the Android background working service which really performs the extension of the Android OS giving to it distributed functionalities. When this component is started it is responsible of the initialization of the server, and the registration of the network service in the LAN, by calling the methods of the classes explained above, respectively the Server and the NsdHelper. This is a sort of container for the server side components of the middleware. It is implemented as a foreground working Android service, thus when it is in execution the user is alerted by a notification. A foreground service is a service that the user is actively aware of and is not a candidate for the system to kill when low on memory. A foreground service must provide a notification for the status bar, which is placed under the Ongoing heading. This means that the notification cannot be dismissed unless the service is either stopped or removed from the foreground [14].

4.4.3 UI Components

I want now to explain how the users can control the distributed intent flow, by using standard Android UI components. Even if my system is supposed to run in background it is also necessary to have few UI component to control the background working mechanism.

MainActivity

This is the UI component responsible for control the entire system. It has four important functionalities:

- *Listen to implicit intents*, when an implicit intent needs to be resolved, the Android OS starts the resolution mechanism already described in Figure 2.4.

Listing 4.4: Intent filter example

```
1 <activity ...>
2     <intent-filter>
3         <action android:name="android.intent.action.
4             SEND" />
5         <data android:type="*/*" />
6         <category android:name="android.intent.
7             category.DEFAULT" />
8     </intent-filter>
9     <intent-filter>
10         <action android:name="android.intent.action.
11             SENDTO" />
12         <data android:scheme="mailto" />
13         <category android:name="android.intent.
14             category.DEFAULT" />
15     </intent-filter>
16 </activity>
```

It searches for the best activity for the intent by comparing it to intent filters based on three aspects: *Action*, *Data (both URI and data type)* and *Category*. A match is only successful if the actions and categories in the Intent match against the filter. So, to let the Liquid Android API listen for any kind of implicit intent, it must include an activity declared with any possible intent filter to be called when an intent need to be executed.

In Listing 4.4 there is an example of how an Activity needs to be declared in the manifest to be called by the OS when an implicit intent like the one in the JSON-Intent in the translation example, 4.2 is triggered. By extending the MainActivity component and adding any kind of intent filter to its declaration in the manifest, it is possible to listen practically to any type of existing implicit intents in the Android framework.

- *Find other devices in the network*, the MainActivity provides also this functionality by calling the methods of the NsdHelper class, and then it shows the resolved devices in the network in a ordered list.
- *Forward intents to selected devices*, once found the other devices in the network, the MainActivity let the user select on which device, or devices, forward the implicit intent it is managing at the moment. To perform this task the MainActivity starts the Client component and exploits its methods.
- *Start/stop the background service*, since when the background service is working the device is exposed to many threat, the user can control it by starting and stopping it every time it is needed by clicking on some special buttons in the MainActivity.

ResultActivity

This is the UI component which can be used when a received intent needs to send data or results back to the caller. This Activity implements the *onActivityResult()* callback method to manage the result or data produced by the received intent. In my framework API this problem is solved by using the files over the socket approach, described in 4.3.3, so when the callback is triggered results are sent to the caller through the socket as JSON-Intent messages or serialized files, by using the Client class to send a message to the Server component of the caller. It is necessary to have this activity since it is impossible to call the *startActivityForResult(intent)* method from a background service in Android.

4.4.4 Use Cases

As already said several times i will use this API to fully develop the Liquid Android Apk which will be a working solution for the first and third problematic scenario, but the Liquid Android API can be used as an Android library in the development of native Android distributed applications. By including my API in any development project it is possible to speed up the process by exploiting my working mechanism and my methods already developed. Since the API is in Java is just as easy to extend the classes and override some of my methods to

accomplish special purposes distributed systems.

Exploiting my system would be easy to develop for example:

- Distributed Android Computing systems, in which Android devices can share hardware resources to reach a common goal.
- Android Computer Cluster, in which Android devices can be seen as node of clusters to perform the same task, controlled and scheduled by software.
- Distributed Android File system, by refining the data management model.

Chapter 5

Case Study

In this chapter I will describe the real implementation of the system, which is the real solution of the problem faced by this thesis work: how it is possible to extend a mobile operating system, in this case Android, with distributed OS functionalities.

This chapter is mainly composed of three parts: the first one is a generic information section in which the proof of concept is explained in terms of technologies used, requirements to meet, goals and various technicalities. The second one is the report of the implementation and development of the application, with choices and descriptions of what has been done. The third part is a working demo of the just described system, with live working test cases. It contains screenshots of the application while it is running and a complete description to explain each case step by step.

5.1 Design Choices

5.1.1 Application Description

As already specified in the previous chapter my system has been implemented as a standard Android application, which can be installed on any Android device starting from the API level 19, Android 4.4 KitKat. The final APK package contains all the files needed for the system installation, and, once installed, the application performs the extension of the Android OS giving to it distributed functionalities. I will use the complete API described in [4.4](#) to implement a background working middleware to distribute implicit intent in a LAN to any Android device with the service installed. In this way every time one of the device, having the *Liquid Android* APK installed, triggers an implicit intent, my application could intercept and send it to any other device to be resolved and executed. The idea of this prototype is to prove that what I have stated, providing the theoretical solution, can work with a real configuration of Android devices in any LAN. Doing this, the thesis work is somehow "*proved*": my communication language, defined with a JSON file, is concretely usable and working, not to worry the users about the kind of implicit intent they need to execute in one of the devices in the network. The translation process does not represent an issue for my

application, because I have developed an automatic intent translator using the correct syntax proposed by me. I will not develop clients for third party systems, even if I stated that it would be possible, especially in Java environments, but I will implement a simple Android application client, generating some standard implicit intent to perform some test with my system.

5.1.2 Requirements

In this small subsection I want to provide a full list of requirements my application must meet. In order to be considered a solution of the given problem, it must fulfill the constraints listed in [3.5](#) and also comply with functional and non functional requirements.

Functional Requirements

Functional requirements are, indeed, the main functionalities the systems must have in order to properly work to perform desired task. The following lists summarize the main features of the system, so as to ensure a quick reference while reading this document:

- **FR1:** listen to implicit intents.
My application should declare itself, in the android manifest, as a multi-purpose application which can be used to resolve, basically, any kind of implicit intents, in order to be selected by the Android OS whenever an intent resolution process is triggered.
- **FR2:** JSON to Intent, and Intent to JSON, conversion.
My application must be able to perform the conversion using the JSON syntax i have explained in [4.3.2](#).
- **FR3:** forward implicit intents.
My application must be able to forward any of the implicit intent it can listen, to other LAN connected devices with the *Liquid Android APK* installed.
- **FR4:** receive and execute intents.
My application must be able to receive in any moment implicit intents, as JSON-Intent object, and then, let the OS resolve and execute them with its standard mechanisms.

Non-Functional Requirements

Non-functional requirements are important properties that my system must have in order to guarantee full functionalities. They are not specific for my problem but, they are general requirements a system needs to be considered complete. It is quite clear how a system can use my language but if it takes 15 minutes to perform a translation or to deliver a message it is completely useless. Non-functional requirements in this way complete my system, they are mainly:

- *Portability*: to have my application used by the largest number of users possible, so i have made the choice to use Android API level 19, to allow the installation of my system to, more or less, the 84% of Android devices currently active.
- *Stability*: system must be always available, and able to offer all its services. For example I should avoid possible system crashes during the delivery of a message from a device to another. In addition, data must be durable and not lost for any reasons.
- *Availability*: the services must be always accessible in time. In case of failures it is possible for the user to manually restart it to be again usable.
- *Reliability*: since data are shared among devices, reliability is essential. Users can base their actions on other users' actions and on the status of the devices. Moreover, I assume that the memory where data are stored is stable.
- *Efficiency*: within software development framework, efficiency means using as few resources as possible. Thus, the system will provide data structures and algorithms aimed to maximize efficiency. I will also try to use well known patterns reusing as many pieces of code as possible, taking care of avoiding any anti-patterns.
- *Extensibility*: my application must provide a design where future updates are possible. It will be developed in such a way that the addition of new functionalities will not require radical changes to the internal structure and data flow.
- *Maintainability*: also modifications to a code that already exists have to be taken into account. For this reason the code must be easily readable and fully commented.
- *Security*: Using a networking service security is always required. The fact that the system will be available only on LANs is the first step in this direction.

5.1.3 Used Technologies

This other subsection is an overview of the tools I have used to develop the Android application.

Android applications are written using Java code and any API level of the Android framework. The *Liquid Android APK* is been developed by using standard Android development tools and libraries without the need to rely on any third party API library. In particular I decided to make these choices.

- *Android API level 19*, as already explained several times I want that my system can be installed on the largest number of devices, so it is a compromise between the great innovation introduced starting from this API level, and the number of devices which can execute API level 19 apps.

- *Android NSD library*, it is a standard Android library I am using to register, discover and resolve my network service. It is an implementation of Zeroconf and it is compatible with other implementation such as Apple's Bonjour.
- *Standard Java libraries*, I decided to use only libraries included in standard Java development kit distribution, the most important are :
 - org.json*, used to manage the JSON file, which are the messages exchanged by the devices using my application;
 - java.net*, containing the classes which are useful to implement the socket network communication.

Technically, I used an IDE to help in development, in particular AndroidStudio based on IntelliJ IDEA, a modern solution released by Jet Brains. It contains modern tools to check Java compile time errors flagging them, and tools to check run time errors with a complete and verbose stack trace. Finally, it supports various VCS (Versioning control systems), to push the code inside repositories and to have a complete overview of commits and forks. I chose Git, one of the most famous VCS, and Bitbucket as repository to save my code.

5.1.4 Implementation

I have developed a fully working Android application called *Liquid Android*. I have build the application using the API library i have created and already presented in 4.4, so the structure of my code follows exactly the one presented with the *Liquid Android API* UML model, in Figure 4.7.

5.2 Working Demo

5.2.1 Live Test Cases

Chapter 6

Conclusions and Future Works

Figures Copyright

Chapter 2: State of Art

Chapter 4: Solution

The images that are not explicitly listed are made by me and no copyright is needed.

Bibliography

- [1] Android. *Intents*. 2017. URL: <https://developer.android.com/reference/android/content/Intent.html> (cit. on p. 47).
- [2] Android. *Security-Enhanced Linux in Android*. 2017. URL: <https://source.android.com/security/selinux/> (cit. on p. 12).
- [3] BOINC. *Open-source software for volunteer computing*. 2017. URL: <http://boinc.berkeley.edu/> (cit. on p. 37).
- [4] André B. Bondi. *Characteristics of scalability and their impact on performance*. WOSP '00, 2000. ISBN: 158113195X (cit. on p. 34).
- [5] Marshall Brain and Stephanie Crawford. *How Domain Name Servers Work*. 2011. URL: <http://computer.howstuffworks.com/dns.htm> (cit. on p. 24).
- [6] K.L. Calvert and M.J. Donahoo. *TCP/IP Sockets in Java: Practical Guide for Programmers*. The Practical Guides. Elsevier Science, 2011. ISBN: 9780080568782. URL: <https://books.google.it/books?id=lfHo7uMk7r4C> (cit. on p. 21).
- [7] Inhyok Cha et al. "Trust in M2M communication". In: *IEEE Vehicular Technology Magazine* 4.3 (2009), pp. 69–75 (cit. on p. 33).
- [8] S. Cheshire and D. Steinberg. *Zero Configuration Networking: The Definitive Guide*. Definitive Guide Series. O'Reilly Media, 2006. ISBN: 9780596101008. URL: <https://books.google.it/books?id=-R3jxPwQhUC> (cit. on p. 24).
- [9] Marshall Cline. C++ FAQ: "What's this "serialization" thing all about?" 2015. URL: <https://web.archive.org/web/20150405013606/http://isocpp.org/wiki/faq/serialization> (cit. on p. 48).
- [10] Android developer. *Application Fundamentals*. 2017. URL: <https://developer.android.com/guide/components/fundamentals.html> (cit. on pp. 10, 12).
- [11] Android developer. *Intents and Intent Filters*. 2017. URL: <https://developer.android.com/guide/components/intents-filters.html#Types> (cit. on p. 9).
- [12] Android developer. *Intents and Intent Filters*. 2017. URL: <https://developer.android.com/guide/components/activities/index.htmls> (cit. on p. 9).
- [13] Android developer. *Platform Versions*. 2017. URL: <https://developer.android.com/about/dashboards/index.html#Screens> (cit. on p. 7).
- [14] Android developer. *Running a service in the foreground*. 2017. URL: <https://developer.android.com/guide/components/services.html#Foreground> (cit. on p. 62).

- [15] Android developer. *Using Network Service Discovery*. 2017. URL: <https://developer.android.com/training/connect-devices-wirelessly/nsd.html#teardown> (cit. on p. 25).
- [16] Apple developer. *Bonjour for Developers*. 2017. URL: <https://developer.apple.com/bonjour/> (cit. on p. 25).
- [17] N. Elenkov. *Android Security Internals: An In-Depth Guide to Android's Security Architecture*. No Starch Press, 2014. ISBN: 9781593275815. URL: <https://books.google.it/books?id=y11NBQAAQBAJ> (cit. on p. 10).
- [18] HTC. *PLUG IN. BE A PART OF THE FUTURE*. 2017. URL: <http://www.htc.com/us/go/power-to-give/> (cit. on p. 38).
- [19] M. Frans Kaashoek Jerome H. Saltzer. *Principles of Computer System Design*. Morgan Kaufmann, 2009. ISBN: 9780123749574 (cit. on p. 15).
- [20] Greg Kroah-Hartman. *Linux Kernel in a Nutshell*. O'Reilly Media, 2006, p. 3 (cit. on p. 8).
- [21] Leslie Lamport. "Time, Clocks, and the Ordering of Events in a Distributed System". In: (1978) (cit. on p. 34).
- [22] sourceforge. *jmDNS*. 2011. URL: <http://jmdns.sourceforge.net/> (cit. on p. 25).
- [23] Verge Staff. *Android: A visual history*. 2011. URL: <http://www.theverge.com/2011/12/7/2585779/android-history> (cit. on p. 5).
- [24] A.S. Tanenbaum and M. Van Steen. *Distributed Systems Principles And Paradigms 2Nd Ed*. Prentice-Hall Of India Pvt. Limited, 2010. ISBN: 9788120334984. URL: <https://books.google.it/books?id=Fs4YrgEACAAJ> (cit. on pp. 12, 19).
- [25] *The Java® Language Specification*. Addison-Wesley, 2005. ISBN: 0321246780 (cit. on p. 20).
- [26] James Vincent. *99.6 percent of new smartphones run Android or iOS*. 2017. URL: <http://www.theverge.com/2017/2/16/14634656/android-ios-market-share-blackberry-2016> (cit. on p. 1).
- [27] Lars Vogel. *Android development with Android Studio - Tutorial*. 2016. URL: <http://www.vogella.com/tutorials/Android/article.html> (visited on 06/20/2016) (cit. on p. 8).
- [28] W3C. *Introducing JSON*. 2007. URL: http://www.w3schools.com/xml/xml_soap.asp (cit. on p. 49).
- [29] Computer Weekly. *Write once, run anywhere?* 2002. URL: <http://www.computerweekly.com/feature/Write-once-run-anywhere> (cit. on p. 21).