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UNIVERSITÀ DI ROMA

Data Leak Detection in Mobile Applications

Confidentiality of Personal Data

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Academic Year 2022/2023

Data Leak Detection in Mobile Applications

Master thesis. Sapienza University of Rome

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This thesis has been typeset by L^AT_EX and the Sapthesis class.

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Acknowledgments

Acknowledge n1

Acknowledge n2

TODO:

- *Abstract*
- *Akcknowledgments*
- *Collaboration with IPS*

Abstract

Briefly describe the whole content of the thesis.

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Chapter 1

Introduction

Mobile applications are now part of our daily life. Everyone of us make use of different applications during their daily routine. There are applications for literally every kind of necessity: we would like to know what the weather will be like in the next days in our city, we would like to keep track of our fitness training that every morning we do in the neighbourhood, or we would like to know how the traffic is on the way back to our home. Using these applications is becoming a real habit, and like any other habit we do not ask ourselves anymore why are we doing it, or how are we doing it.

Going through the years it is becoming much more common to hear about the terms *data breaches* or *data leak* on a multitude of online applications. The whole amount of data that users has put in their account can be exposed to leak of this kind.

Nowadays people tend to use applications without even realise the amount of informations they are delivering to the network, profile pictures, email addresses and phone numbers, and so on. All of these data are private informations, maybe the user does not like to share to everyone else, but just with the system on order to get the customized experience the application is offering.

Mobile applications handle private data of millions of different users, therefore it is mandatory checking the robustness and any kind of protection implemented in the application, in order to make it resilient to possible leaks of user informations.

1.1 Personal Data

The concept of personal data is something I would like to make clear. There are multiple definitions and laws defining the scope of this kind of informations. As stated by the European Commission [1]:

Personal data is any information that relates to an identified or identifiable living individual. Different pieces of information, which collected together can lead to the identification of a particular person, also contribute personal data.

Personal data that has been de-identified, encrypted or pseudonymised but

can be used to re-identify a person remains personal data and falls within the scope of the GDPR. [...]

The GDPR protects personal data regardless of the technology used for processing that data - it is technology neutral and applies to both automated and manual processing. [...]

Practical examples of informations falling in the category of personal data are - name and surname, address, phone number, date of birth, but also photographs, ip addresses, location informations.

Dealing with mobile applications, personal informations are often typed in directly by the user, most likely at the moment of the creation of a new user profile, but not only. Some personal data might be shared automatically during the use of such application, like ip address or advertising phone identifier.

These information not necessarily are mandatory to access the services offered by the application. Personal data might contribute to some advertising service bundled within the application to keep track of the user data, or these data might be sent to some logging service implemented in the application in order to retrieve statistics on the users utilizing that application.

1.2 Goals

Goal of the study in this thesis is to check if software features expose it to the risk of providing more information than planned.

A mobile application might share private informations with or without our accord in different moment while using it. For instance our contact list might be shared while using an application when synchronizing our friend list.

Goal is therefore ensuring there is no leak of private data for the whole activity and at any moment for a specific application.

The work was conducted by examining applications running on Android operative system. Different mobile applications have been analyzed belonging to three different area of interests:

- Weather: General applications *without* user authentication.
- Health & Fitness: Applications *with* user authentication and *some* interaction between users.
- Maps & Navigation: Sophisticated applications *with* user authentication and *continuous* interactions with server or other users.

The order in which the applications have been investigated has been decided basing on an increasing complexity and notoriety of them. Starting from weather forecast applications that generally do not require any kind of user authentication, going through fitness applications that let the user customize and share fitness routines to other users, and finally analyzing applications that manage geographical informations to retrieve real time traffic data.

1.3 Methodologies

Since the goal is to detect any personal data leak while using the application, dynamic analysis is the main method used to investigate applications behaviour. In particular each mobile application has been inspected starting from the **network traffic analysis**, generated by the application at runtime.

Every action carried out by the user in the context of an application will generate some request to a server. Notice that mobile applications do not communicate only with the server offering that service. Indeed in the implementation of a mobile application there are different activities, each one provide a different service - for example advertisement services, logging services, push notification services, and so on. Every request is therefore generated by the application and might potentially include our personal data.

Where the network sniffing offered a spotlight for some in-depth study, a **static analysis** has been adopted going through an examination of the code of the application. Static analysis on an Android application is really dispersive and time consuming. An Android Package file (APK) can contain hundreds of thousands of Java classes. The majority of the compiled applications is stripped from the symbols, so methods and classes names cannot be directly found in the source code. Most of the time a simple obfuscation method like symbols stripping combined with the high number of classes, it is sufficient to hide something very interesting, for instance the method used to compute the *Authorization header* in an HTTP request.

To know more about the static and dynamic analysis tools I used in the practice, go to Chapter 3.

1.4 Collaboration with IPS

Da definire ...

Chapter 2

Fundamentals

This chapter is dedicated to illustrate some fundamental knowledge in order to fully understand the work I have done while investigating specific applications. Some of them are technologies arised in last ten years, improving not only the efficiency but also the stability and portability of the standard development of mobile applications. Generally Android mobile applications are client implementations for specific services. The scenario is therefore the classic client-server communication model where each client interacts with one or more server.

First of all client and server must establish a connection between them, hopefully a *secure connection*. This is the first topis explained in this section. Client and server, that means mobile application and application server, agree to find a secure way to communicate each other.

Once the connection is established there are lots of ways in which an application can send information. This is the problem of the data serialization. Informations can be represented using different Interface Description Languages (IDL). Starting from the classic JSON or XML format, passing through binary. Each representation has advantages and disadvantages. In particular there is a section dealing with an IDL that is widely used in mobile application, that is *Protocol Buffer*.

After having described the iteration of a standard mobile application, there is a section explaining the concept of *gRPC*. As I said most of the mobile applications reflect the client-server paradigm. It is modern framework able to delegate some procedure in the client to the server, improving performance and portability of the application service.

Finally the last section of this chapter deals with a new network procol called *QUIC*, a modern evolution of the HTTP/2 protocol used by most of the recent applications.

2.1 HTTPS: HTTP over TLS

As stated in the online documentation for Android Developers [2] it is a good practice to protect applications data using the **Transport Layer Security (TLS)** along with the standard HTTP protocol.

TLS is a protocol designed to provide communications security over a computer

network. It provides *confidentiality*, *authentication* and *integrity* meaning that: data is encrypted for third parties, ensure that both parties actually are who they pretend to be, ensure that data is not modified in the transit.

A server (or web application) that wants to use TLS must have installed an **SSL certificate** on the machine. This certificate is released by a **Certificate Authority (CA)** for a specific domain, and contains important informations on the owner of that domain together with the public key of the server.

Every time a client wants to establish a connection with a server using TLS, the TLS Handshake procedure is issued.

There are also some mitigations Android mobile application developer can use in order to limitate authority checks

2.1.1 SSL/TLS Handshake

During the TLS handshake both mobile application and server exchange informations to set up a bidirectional encrypted connection. For this reason TLS version (1.0, 1.2, 1.3, etc) and cryptographic suite are agreed. Moreover the client verifies the authenticity of the server basing on its certificate. Finally both the endpoints will generate session keys to encrypt and decrypt the messages they will exchange each other. Once data are encrypted, they are signed with a Message Authentication Code (MAC), so that the receiver can verify the integrity of the data sent over the network.

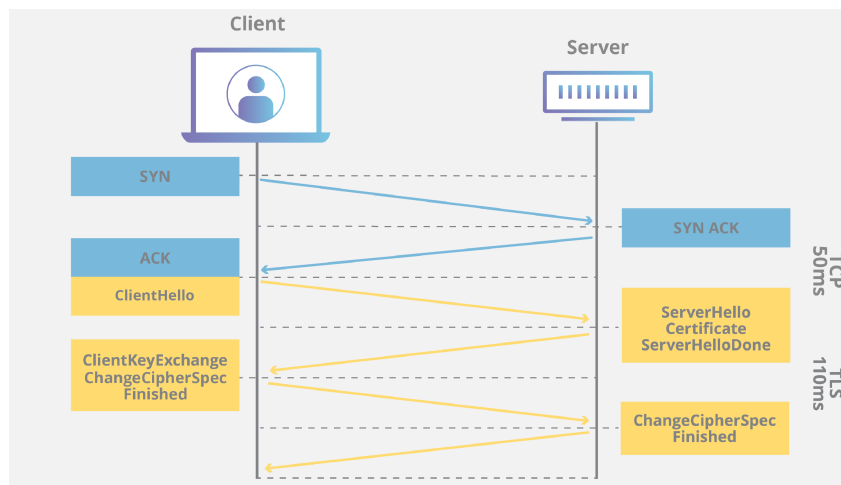


Figure 2.1. TCP Handshake and TLS Handshake communication flow needed to set up a secure connection. [3]

From the performance point of view, the whole process of the TLS handshake needs both the endpoints to communicate before the data are actually transmitted over the network. In particular in the TLS versions < 1.3, two round trip time are needed to set up the whole connection (*110ms*). This amount of time added to the standard TCP three-way-handshake (*50ms*) to establish the session between client and server, results in average in less then *0.2 seconds* spent only to set up a secure connection without actually sending any application data yet.

As I said TLS makes possible to exchange information over a non-secure channel by providing confidentiality, authentication and integrity.

2.1.2 Certificate Verification

A procedure I would like to stress is the certificate validation routine that happens at the really start of every TLS handshake. At the moment the client wants to establish a connection with the server, it needs the certificate to check the server is the actual endpoint the client want to talk with. The first thing the client does is to check that the certificate showed by the server is not expired, and that the server domain name matches with the one reported in the certificate. The next step performed by the client is to verify that the certificate has been signed by the certificate authority that authorized it. This procedure is done by verifying that the issuer's CA name matches the owner's CA name at the above level, and using the owner's CA signature and public key to verify the certificate is properly signed. The process is repeated until a CA trusted by the client is met, usually a root CA.

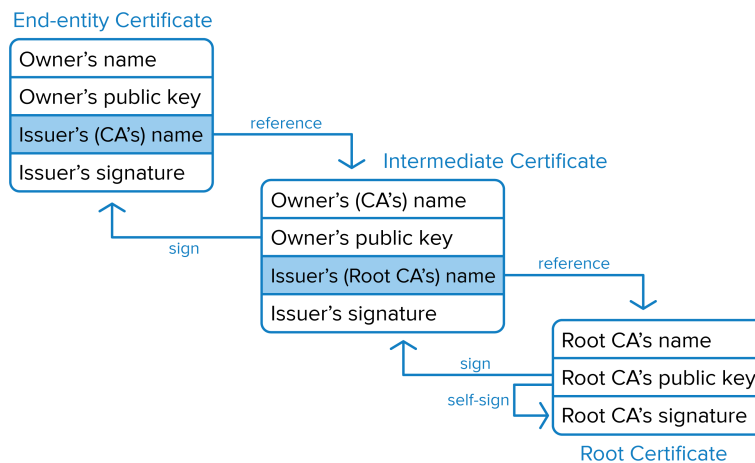


Figure 2.2. TLS Certificate verification chain. [4]

Usually certificates are bought by companies that want to implement a secure connection with their clients. In this way the certificate obtained by the server is inserted in the tree of certificates, and every client can verify its authenticity. Note also that every machine can generate a self-signed certificate. What is indeed important is checking if the server certificate is linkable to a trusted Certificate Authority.

The Android operative system handles by itself a list of trusted certificates. These certificates belong to two categories: system certificates and user certificates. *System certificates* are used by default to verify all other certificates. So if we are using an application trying to connect to an application service, if the certificate obtained by the web service is traceable to one certificate already present in the system store, then the certificate is accepted and the connection is established.

Notice that since the release of Android 7 Nougat, it is impossible to install any CA at system level without having root privileges on the device.

On the other way *user certificates* are installable even at user level, and are used to verify certificates when directly expressed by the application.

2.1.3 Man-in-The-Middle

Man-In-The-Middle (MITM) is an attack able to disrupt the security properties delivered by the TLS protocol. As the name suggests the attacker positions himself between the server and the client. The attacker acts like a proxy server intercepting every connection incoming from the client, pretending to be the real server, and forwarding them to the real server, pretending to be the real client.

On one side, at the moment of the TLS handshake, the client verifies the identity of the server, so the attacker needs to reproduce the handshake with the client in order to let it trust the attacker. As described in the last section, the authenticity check is performed through the exhibition of the server certificate. In this case the client needs to trust the certificate of the attacker. After having checked the identity of the server, the TLS handshake can continue following the standard procedure: client and attacker agree on a pre-master shared key and the encrypted communication will take place.

On the other side the attacker needs to act as the real client for the server, so that every connection intercepted will be redirected to the server, and every response obtained will be delivered to the client. This is made possible by starting a new connection between attacker and server. The attacker will authenticate the server by checking its certificate and completing the standard TLS handshake with it. At this point the attacker has performed two different TLS handshakes, one with the client faking to be the server, and one with the server faking to be the client. The man in the middle is now able to read messages sent or received from the client and forward or deliver them to the server.

A man-in-the-middle attack is what made possible the analysis of the communication protocol of every application I investigated. After having *placed* ourselves inbetween client and server we will be able to understand what exactly is the protocol adopted by an android application and analyze each message looking for a possible leak detection of users personal data. For more specifics on how I performed a MitM attack for my case studies, read the chapter *Testing Environments*, sections *HttpToolkit*[Section 3.2.1] and *BurpSuite*[Section 3.2.2].

2.1.4 SSL Certificate Pinning

If the MitM attack results in the loss of authenticity in an HTTPS communication, the **SSL Certificate Pinning** is a hardening process that can be adopted in order to deliver an additional layer of security to the software. Pinning certificates or public keys is a countermeasure that allow web servers to control the risk of man-in-the-middle attacks or CA compromise.

The whole process of certificate verification described in the previous section is skipped, the application will indeed only validate certificates or public keys that are

pinned to the application. A MitM attacker will not be able to intercept messages anymore. The connection will be blocked right in the middle of client's and attacker's TLS handshake. The application implementing a certificate pinning method in fact will not trust anymore the attacker's certificate, and the connection will be dropped by the attacker's proxy.

There are two ways of implementing this hardening technique. The first one is by *preloading* the public key or certificate in the client at development time, so that every fake server trying to connect to the client is rejected during the TLS handshake phase. The second one happens at runtime by installing the *pin* in the client once upon the connection is established by using the HTTP Public Key Pinning (HPKP) header, indicating the public key and the max age of validity for that specific pin. This second approach has been adopted by Chrome and Firefox for their browsers, but after some years new security issues has been discovered about it. Indeed in case of bad implementation (for example a pin of an incorrect public key) could bring to denial of service, but even in case of compromised server the consequences can be devastating for a longer time if HPKP is implemented, a bad pin might be established from an attacker that had the control of the server (HPKP Suicide [6]). For this reason the public key pinning is now highly discouraged for web browsers.

In Android application SSL certificate pinning is a solution still able to protect from MitM attacks. The implementation is generally done by pinning a specific certificate inside the application logic at development time. There are multiple ways to implement a certificate pinning in Android as explained in [7]. Among them two approaches can be identified:

1. basing on *Network Security Configuration*: A pretty simple certificate pinning implementation made possible by specifying a *<domain-config>* tag in the network security configuration file present in the application. A *pin-set* of *pin* can be specified for the whole application.
2. basing on the *network library*: Many different network libraries exist for Android application (i.e. *OkHttp*, *Retrofit*, *Volley*, and so on). Each one of them provide methods to skip the standard certificate validation procedure and implement the certificate pinning procedure.

2.1.5 Certificate Transparency

Certificate Transparency (CT) is a security standard adopted by browsers for monitoring and logging discrepancies in the certificate verification procedure. The whole system is maintained by a set of certificate logs handled by Certification Authorities and many browsers. These logs assume the form of *Merkle trees* (also noticed as *hash tree*), they are publicly verifiable, in append-only mode. The goal of this standard is to keep track of all valid certificates ever issued for a specific domain.

This is the scenario: a domain owner implementing a web service requests a new certificate from a CA. Before releasing the new certificate, it submits the *hash digest* of that certificate to one or more certificate logs, receiving a *Signed Certificate*

Timestamp (SCT) signed by the log provider. Once signed, the CA can now send back the certificate with embedded the SCT to the domain owner asking for the certificate. Every HTTPS connection to that web service will be served using that certificate. When a user wants to use the web service, browsers or mobile apps will query the trusted certificate log to find a record matching with the SCT of the certificate received by the web service.

In Android operative system, an example of application implementing the Certification Transparency mechanism is the Chrome browser. As we said above (see Certificate Verification [Section 2.1.2]) Android certificates can be placed at system level or user level. Every application will use by default the system store to verify others certificates, and so does Chrome, if not specified differently. This application will choose whether to use the Certificate Transparency or not, basing on which store the certificate root is installed. When a certificate showed by any web service it is checked, if the root certificate met is present in the system certificates store then Chrome decides to also verify the Certificate Transparency requirement. On the other way if we are testing a web service showing a certificate that is inside the user certificates store, then the Certificate Transparency procedure is not applied.

2.2 Protocol Buffers

2.3 gRPC

2.4 QUIC Protocol

Chapter 3

Testing Environment

In this chapter is described the whole environment where I settled the investigation of each Android mobile application discussed in this thesis.

Core of the environment is the *Android Studio* framework, offering both an Integrated Development Environment (IDE) and testing features for Android mobile applications. Here I configured an emulated device where I could run the application cases I investigated.

Once installed the specific application I had to analyze the *network traffic* generated by itself. Generally it is rare a single tool is perfect for all the applications to analyze, this is the reason why I used different tools to inspect the network traffic generated by an application, instead of just sticking with one tool. Starting from the standard-de-facto in packet inspection *Wireshark* program, ending to tools acting like proxy servers between the client application and the server. Some of these tools are able to automatically install and configure a man (MitM attack [2.1.3]) in the middle of the communication, others might need some manually configuration. The whole amount of informations exchanged between application and server is hidden somewhere in the communication. It might be more or less difficult to find them, but all the informations are there, in those packets.

Some tools revealed to be really useful while investigating the network traffic of the applications. Dynamic instrumentations tools are softwares able to inspect at runtime what is happening in the mobile application. On the other way, static instrumentation tools offer a view of the application basing on its code.

3.1 Android Studio

Android Studio is the center of the testing environment. Other than a complex IDE software, it provides a complete testing suite for Android mobile applications. Once installed the software, it enables the access to the Android Device Manager tool, where the user can create an emulator for a specific Android device choosing among phones, tablets, wearOS or TVs.

In this section I will explain how I prepared the android virtual device in order to obtain a working environment that made possible the application investigation.

3.1.1 Android Virtual Device (AVD)

For my purpose study case I created an *Android Virtual Device* (AVD) phone with the same properties of the *Pixel 3a* phone developed by Google, that is 5.6" screen size, 1080x2220 resolution, 440dpi density. The device is running *Android 13*, also known as *Tiramisu* version, or *API 33*, on *x86_64* architecture. In the really first step while selecting the hardware we would like to use for the virtual device, some device definitions are enabled to run the Play Store software, and so it is for our Pixel 3a device. This is really useful since I had not to download and install manually each applications on the device. Indeed it is made possible using the Google Play store directly from the emulated device. Here there is the full property list of the device I used:

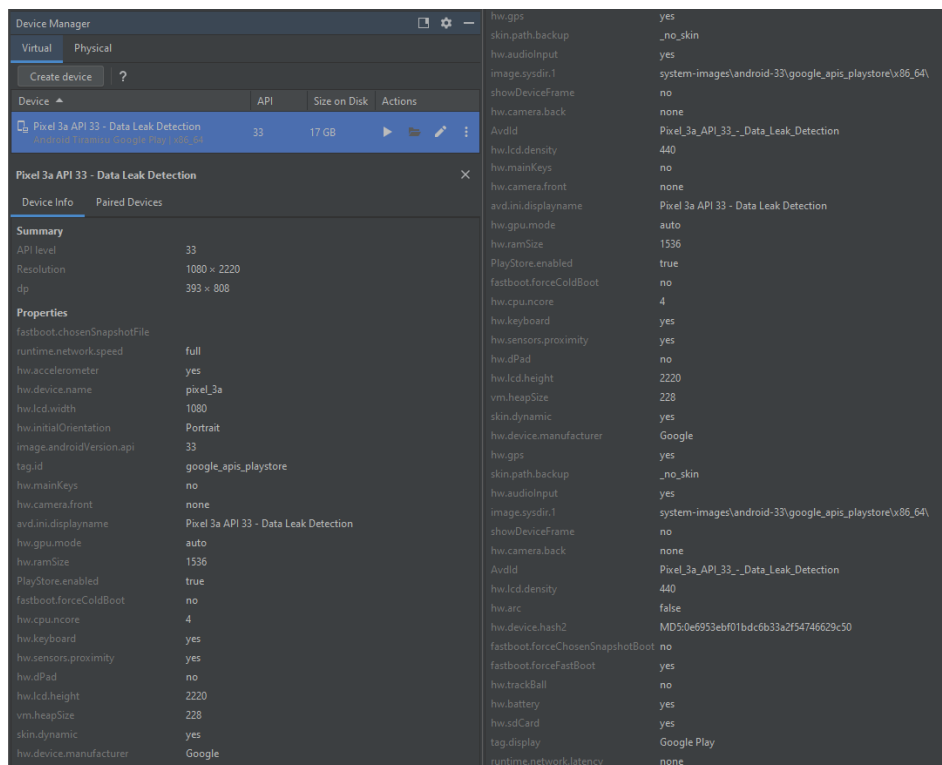


Figure 3.1. Android Virtual Device (AVD) specifics

Once created the new virtual device (in my case called "*Pixel 3a API 33 - Data Leak Detection*"), it is possible to run it through the Android Device Manager. For simplicity I created a simple *.bat* file to run the virtual device without the need to open Android Studio everytime. Indeed there is a file called *emulator.exe* in a the folder where we installed the Android SDK. We can simply open the emulator by command line passing the name of our AVD and some optional arguments. Here it is how my command looks like:

```
C:\<Android_folder>\Sdk\emulator\emulator -feature -Vulkan
-memory 2048 -netdelay none -netspeed full -avd
```

```
Pixel_3a_API_33_-_Data_Leak_Detection
```

Listing 3.1. run_AVD.bat

More specifically the *-feature -Vulkan* argument will force the emulator to do not use the *Vulkan* graphic library. Since Android API 30 lots of android applications, such as Google Chrome, use this library to boost its performance. Anyway in some devices, especially for the emulated ones, might result in a massive slow rendering time. Other arguments are specifying to dedicate 2 Gb of RAM memory for the device, to not impose limits on the network speed and to not simulate any network delay.

3.1.2 Root privileges on virtual device

After having successfully created the AVD, it can result useful to get the *root privileges* on the device. In our case it is really mandatory since what we are going to do is intercept the communication protocol in the middle between application and server. As explained in the Section 2.1.3, the client application needs to trust the proxy server, and this is done by checking its certificate. Starting from the release of version *Nougat* (API ≥ 24), of Android operative system, it changed the behaviour adopted by android applications in trusting users. If before the application was checking both *user certificates* and *system certificates*, now it will check exclusively the installed system level certificates, therefore root privileges are mandatory.

There are so many tools that let a user obtain the root privileges on his phone. I personally have used the *rootAVD* tool available online [8]. The procedure is really simple, firstly run the command with argument *ListAllAVDs* to list all the AVDs on the machine. We will obtain the full path of our AVDs, that we will pass as argument when executing the tool from command line. The tool will make use the *adb* tool that Android Studio brings together with its development tools, so it is worth it to explain what it is.

3.1.3 Android Debug Bridge (adb)

As I said Android Studio offers a complete set of features to run and test android application. In particular by installing the *Android SDK Platform Tools* package from Android Studio, we will obtain a set of tools that make possible the debug of our application.

One of the most important tools is the Android Debug Bridge, more noticed as *adb*. It is a command line tool that let the user directly communicate with an android device, let it be a real device or a physical one. Basically it is a client-server program that runs both on our machine and android device. There is then a client, that is the command line tool, a daemon *adbd* running in the background of the android device, and a server managing the connection between client and daemon. For a complete understanding of the *adb* tool check the Android Developer guide [9].

3.2 Network traffic analysis

Once the virtual device is well configured as described above, let's start introducing some tools used in the study case. Each one of them has some strengths, one tool might work for an application but not work for another. They are listed below in order of complexity. *HttpToolkit* and *BurpSuite* are network traffic interceptors, that means every connection outgoing from our device will be intercepted by these applications, letting the user to inspect more or less accurately how the request are formed. *Wireshark* on the other way is a packet sniffing tool, meaning that it will capture any packet in the network, regardless of the protocol or port of them.

3.2.1 HttpToolkit

HttpToolkit[10] is an open-source tool for debugging, testing and building with HTTP(S). The strength of this tool relies on its simplicity for configuring the environment. Once downloaded the application it requires to connect to a source of traffic. In this case the network source to monitor is the android virtual device where the applications will run. HttpToolkit provides a variety of available sources, from the most famous browser (Chrome, Firefox, Safari, Edge), up to more complicated environment, such as Docker containers, virtual machines, Android devices or iOS devices. HttpToolkit itself will notify the user on which are the available sources of traffic at the start up. Since the scope of the study is investigating applications running on the android emulator, it is needed to download from Google Play the HttpToolkit application also on the virtual device. Once installed the android app, the HttpToolkit running on the computer will automatically notice the new source called "*Android device via ADB*". Just click on it and the whole proxy system is automatically configured.

In this phase it is crucial to understand what is happening:

- HttpToolkit is able to inject a custom certificate on our device, thanks to the ADB. Since we also have the root privileges on the android emulator, the certificate will be placed in the folder of the *System Certificates* that is */system/etc/security/cacerts* in the Android device.
- The respective HttpToolkit android application will be activated in order to set up a VPN, redirecting the whole network traffic directly via the Android Debug Bridge.
- HttpToolkit will copy to the device, again via ADB, a file containing the command used to start up the android Google Chrome application. This specific command will bypass the Certification Transparency check described in the section 2.1.5. The command looks like the following:

```
chrome --ignore-certificate-errors-spki-list=<
cert_digest>
```

As described in the certificate verification [Section 2.1.2] and MiTM [Section 2.1.3], this is the moment in which the HTTP(S) requests outgoing from the application case are intercepted by HttpToolkit, showing precisely each request detail. Then they are forwarded to the application server. Same happens for the HTTP(S) responses.

This tool requires almost no configuration on the user side, all is done automatically aside from the preparation of the AVD discussed in the above section.

3.2.2 BurpSuite

3.2.3 Wireshark

3.3 Dynamic instrumentation

3.3.1 Frida

3.3.2 Objection

3.4 Static instrumentation

3.4.1 GDA

Chapter 4

Application cases

4.1 Use Case: IlMeteo

4.1.1 General description

4.1.2 Study detail

4.1.3 Sensitive data

4.1.4 Other vulnerabilities

4.2 Use Case: Pacer

4.2.1 General description

4.2.2 Study detail

4.2.3 Sensitive data

4.2.4 Other vulnerabilities

4.3 Use Case: Waze

4.3.1 General description

4.3.2 Study detail

4.3.3 Sensitive data

4.3.4 Other vulnerabilities

4.4 Use Case: RadarBot

4.4.1 General description

4.4.2 Study detail

4.4.3 Sensitive data

4.4.4 Other vulnerabilities

4.5 Use Case: GoogleMaps

4.5.1 General description

4.5.2 Study detail

4.5.3 Sensitive data

4.5.4 Other vulnerabilities

Chapter 5

Conclusion

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