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Abstract

This Project Work on Information Security focuses on regulating personal data disclosure among third parties, providing a simple implementation within the Android framework. To increase their privacy, data owners can purposefully create *Sticky Policies*, metadata to describe which users or services can access the personal information they stick to.

First, we describe the state of the art in terms of literature and existing algorithms for *Sticky Policy* implementation; then, we analyze the available concrete solutions and their weaknesses. Finally, we present our solution and its features, including considerations about future improvements.

In the last chapter, we show performance measurements and comparisons to support our work and decisions.

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Chapter 1

Introduction

Personal data increasingly fuel Internet applications development and spread, especially since the birth and diffusion of Big Data. Users are often unaware of the gathering, processing and storage of their data, mostly because of the obfuscation behind license agreements and the technical notions necessary to understand these processes. Data may also be moved across country borders, to be processed under different laws and regulations, with processing systems so complex to ultimately make it impossible to understand which service provider had the right to process what.

Leaving out the risks originating for accidental data disclosure by such applications, for example due to security breaches, users may wish to increase their data protection, especially in fields as medical care and financial services. More specifically, we would like a tool to selectively reduce data disclosure, preventing unwanted usage from third parties.

Current solutions include state laws about data usage and protection, business frameworks and service-level agreements, which prove to be inefficient and ineffective. Many research studies have thus advanced the suggestion of a different tool, called *Sticky Policies*, to ensure data protection and control its disclosure. *Sticky Policies* are essentially machine-readable metadata which specify the correct usage of the data they travel with [10]: through encryption, they prevent policy non-compliant use.

In this study, we focus on the mobile environment, and in particular on smartphones. A few solutions already exist, but often they fail to protect personal data with the desired granularity. Moreover, services and application run in remote cloud systems, and data is stored in distributed systems managed through complex automated procedures. Due also to the difficulty in complying with strict Data Regulation laws (e.g. GDPR), many companies are *outsourcing* this task through Single Sign-On procedures: personal data is gathered and processed by large and structured organizations, and external services rely on simple APIs for user authentication.

In general, any communication via smartphone flows through a server or

a cloud and thus it would be more realistic to implement a solution which integrates with an open-source app or service adding a layer of data protection. At a high level, the data owner and sender would be able to select any condition to be verified before the recipient could access that data on the same app. In case of non-compliance, simply the data wouldn't be disclosed, while in case the access was granted, it would be possible to prevent illegal data sharing outside the app.

We would like to provide a proof-of-concept solution aimed, in particular, at Android devices. This context is exceptionally varied and quickly evolving, features which pose a limit to the extensiveness of the proposed solution. Other limitations derive from the lack of free, open-source implementations of the studied cryptographic schemes, and of open-source mobile applications.

In this project work, we start by analysing the most recent and relevant proposals about this matter, comparing different technical approaches and existing solutions. Then, we introduce a solution of our own, which tackles this issue within a limited scope of action. Finally, we present our conclusions about this work.

Chapter 2

Sticky Policies in literature

To implement *Sticky Policies* we first focus on the context for application. In a simple use-case, user Alice wants to share some personal data with user Bob through an application, which we will call *Service Provider*. We can generalize this situation for all those cases in which a service provider is fed with some personal data in order to supply the data owner with a service. To protect her privacy, Alice will specify which entities are allowed to use her data, and for which purposes through a *Sticky Policy*. The policy will be attached to the data so as to stick with them persistently, and the data will be obfuscated to prevent unauthorized access.

Most of the suggested solutions regarding this issue share a similar low-level architecture. Thus, we can recognize three basic common entities, which are essential to the development of *Sticky Policies*. They are the following:

- The *Data Owner* has a finite collection of data, which she wants to protect through fine-grained policies.
- A trusted entity which is in charge of securely storing data and generating encryption keys.
- A *Service Provider* should be considered as third party which requests data usage.

The role and implementation of the trusted entity changes according to the chosen encryption scheme and protocol.

We will now examine the main solutions available in literature, and consider their main advantages and disadvantages. It is worth saying beforehand that every solution cannot overlook the trust in the chosen third party: mainly, because once the data is decrypted it can be shared by the third party without any concern; secondly, due to the need of proving the remote hardware machines to be reliable (i.e. it always behaves the way it should, for the intended purpose). This latter issue has been dealt with through the use of Trusted Platform Modules [5].

2.1 Hybrid Cryptosystem

In this scenario, we use both asymmetric and symmetric cryptography to achieve the required *stickyness* of the policies. In a possible use-case, the service provider receives data, encrypted with a symmetric one-time-use key K, together with the policy and K, both encrypted with the public key of the *Trust Authority* and signed by the user. The service provider will interact with the Trust Authority to prove its reliability, eventually receiving the symmetric key K.

The *Trusted Authority* or *Policy Enforcement Point* always mediates the data exchange. It is a semi-trusted third party which checks the compliance of the service provider with the specified policies before releasing the symmetric keu K. A formal protocol for message exchange is suggested in [10]:

```
Policy, Enc(PubTA, K||h(Policy)), Sig(PrivUser, Enc(PubTA,
                K||h(Policy))), Enc(K, PII).
```

This ensures that the policy always sticks to its data, and its integrity can be verified through a secure hashing function. Moreover, the combined usage of TA's public key and the data owner's private key ensure both confidentiality and authenticity.

This implementation relies heavily on the Public Key Infrastructure, and requires procedures for management and verification of X.509 certificates. For what concerns the PEP, it must be always reachable from the internet and, together with the Certification Authority, may be a target for attacks: first, it constitutes a *single point of failure*; additionally, if compromised, it could infect the data owner (for example through phishing attacks) or act as a man in the middle, decrypting `PII`.

In both cases, this solution proves to be computationally heavy and it does not solve the main issue of trusting the service provider not to illegitimately share data.

2.2 Attribute-Based Access Control

The Attribute-Based Access Control (ABAC) paradigm well fits our environment: by describing users and objects through a set of attributes, it allows fine-grained policy specifications for data protection. However, it requires a precise definition of the descriptive attributes and the implementation of the architecture required to process and enforce policies.

The XACML standard [13] provides a valid reference by defining not only the attributes and structure for rules, but also the components in the architecture. For the sake of simplicity, suppose we need only the *Policy Enforcement Point* from the whole XACML standard implementation, since we assume that the data owner has a client-side module to generate the

required XML policies. The data owner trusts the *Policy Enforcement Point* to be both a secure storage for its personal data and to evaluate correctly the reliability and compliance of the service provider.

This solution allows a better data description in terms of granularity, and it is also more efficient once the architecture has been implemented; nonetheless, it shows the same weaknesses as the Hybrid Cryptosystem. Additionally, the effort required for architecture implementation and rule generation should not be underestimated. It is also remarkable that the mobile environment evolves quickly and is exceptionally fragmented and varied, conditions which make it more difficult to establish fixed descriptive attributes.

In this context, we can also consider Ciphertext-Policy Attribute-Based Encryption [2]. This solution does not require an intermediate entity to evaluate the policies before forwarding sensitive data to the recipient, because this assessment is embedded in the cryptographic scheme so that no unauthorized individual can decrypt it. In particular, the data owner chooses a set of attributes defining an *access tree*, the structure used at a lower level to bind attributes to the ciphertext and ensure that only individuals that satisfy the access tree can decrypt the obfuscated text.

This solution requires an available trusted entity for key generation, but does not strictly need a *Policy Enforcement Point*. It is possible to leverage on a secure storage to ease access from service providers, even though the level of trust required from this third entity is low due to data being encrypted by the data owner. As highlighted by Tang [14], a drawback of CP-ABE occurs when a private key is compromised and it is necessary to issue a new one: there is a non-negligible amount of risk related to the possibility for a potential attacker to decrypt all the ciphertexts associated with the attribute set of the compromised key.

2.3 Identity-Based Encryption

The Identity-Based Encryption (IBE) paradigm proposed by Shamir [12] can be purposely used to realize *Sticky Policies* [8].

IBE is an asymmetric cryptographic scheme which eliminates the need of the Public Key Infrastructure together with X.509 certificates, requiring only a trusted entity to generate private keys when needed. The public key should be an identifying, non-repudiable attribute, e.g. the email address: when an encrypted text is received, the recipient asks the key-generation centre to issue the corresponding private key, thus being able to decrypt the text.

In [8], Mont describes a cryptographic scheme for *Sticky Policies* based on IBE and coupled with a Trusted Platform Module. The encryption key is a XML document containing the formalization of the policy, thus reaching the desired *stickyness* for *Sticky Policies*. Any tampering or policy non-

compliance will prevent the Trust Authority from generating the correct decryption key. Additionally, the Trust Authority will check the reliability of the requester before issuing the decryption key.

Finally, as shown by Shamir [11], Mont suggests to increase the security level through a *threshold scheme*, involving several Trust Authorities for key issue. In a *(k,n)* threshold scheme, the key is divided into $2k-1$ parts, and at least k pieces are necessary to encrypt or decrypt: as a disadvantage, it proves to be less efficient than a simple IBE scheme.

Tang [14] suggests a similar solution, in which the key is a string containing the identity of the recipient concatenated with some attributes or constraints, e.g. time stamps, so to make IBE finer-grained.

Both of the approaches require a new key generation every time the policy is changed, which could be inefficient in contexts as mobile devices communication; moreover, even if they do not directly use attributes in the encryption, there is still the need of a standard definition. When using Mont's solution, an XML grammar specification is necessary to avoid generating different keys for equal policies improperly written, while in Tang's case a specification should be issued to determine which attributes to use and their order.

2.4 Proxy Re-Encryption

The Proxy Re-Encryption scheme [4] can also be taken into consideration as an implementation for *Sticky Policies*, and is particularly suited to the mobile environment.

Communication and data sharing through mobile devices is supported by remote servers instead of happening point-to-point. In this context, the remote server is the Proxy, which re-encrypts data from the sender Alice's signature to the receiver Bob's. The server can be untrusted, as the scheme never produces plain text and is unidirectional and resistant to collusion attacks. To implement *Sticky Policies*, Alice sends a policy with the encrypted data: a *Policy Enforcement Point* evaluates Bob's policy compliance, and data is re-encrypted and forwarded with the re-encryption key generated by the server.

The Proxy Re-Encryption scheme can be implemented either through Identity Based Encryption or Public Key Encryption, and in this latter case provides the benefit of Alice encrypting only for the Proxy, which will then be in charge of re-encrypting with a different key for every recipient.

The Proxy Re-Encryption scheme shows some advantages with respect to the other schemes mentioned: key and policy updating are performed by informing the proxy, and no vulnerability affects previous ciphertexts encrypted with those keys or conditions thanks to the re-encryption. Disadvantages of PRE are highlighted in [14]: even though the scheme requires

a lower level of security, a compromised Proxy could generate re-encryption keys for any receiver, potentially exposing personal data to any of its recipients. To address this issue, Tang presents the Type-based PRE, which introduces the notion of *data categories*, as an additional input parameter to the re-encryption key generation. With TPRE, compromise of a re-encryption key does not affect keys with a different type, and key revocation is dealt with just creating a new re-encryption key relating to a new data type (which includes the previous one).

2.5 Existing implementations and libraries

Nearly each of the possibilities considered in chapter 2 has a dedicated implementation. For Cyphertext-Policy Attribute-Based Encryption there is the `cpabe` toolkit [1], available in the C language. This library provides an encryption scheme such that each private key is associated with a set of attributes rather than with the identity of the data owner. Attributes can be provided as strings from standard input or from a file; moreover, it is possible to combine more than one attribute or rule through predefined operators as 'and', 'or', '>', '<'.

2.5.1 Java Pairing Based Cryptography Library for IBE

For Identity-Based Encryption we can rely on the Java Pairing Based Cryptography Library [3]. Private keys are generated from identities alone as well as combined with attributes describing the authorized audience, and it is possible both do encrypt and sign data. Both [3] and [1] depend on the Pairing-Based Cryptography Library [6], developed in the C language.

Listing 2.1: Java mock class for IBE implementation

```
1  // Setup
2  AsymmetricCipherKeyPair keyPair = engine.setup(64, 3);
3  // KeyGen
4  Element[] ids = engine.map(keyPair.getPublic(), "angelo", "de_
       caro", "unisa");
5  CipherParameters sk0 = engine.keyGen(keyPair, ids[0]);
6  CipherParameters sk01 = engine.keyGen(keyPair, ids[0], ids[1]);
7  CipherParameters sk012 = engine.keyGen(keyPair, ids[0], ids[1],
       ids[2]);
8  // Encryption
9  byte[][] ciphertext0 = engine.encaps(keyPair.getPublic(), ids
       [0]);
10 byte[][] ciphertext01 = engine.encaps(keyPair.getPublic(), ids
       [0], ids[1]);
11 byte[][] ciphertext012 = engine.encaps(keyPair.getPublic(), ids
       [0], ids[1], ids[2]);
12 // Decrypt
13 byte[] cleartext0 = engine.decaps(sk0, ciphertext0[1]);
14 System.out.println(new String(cleartext0) + "");
```

As shown in Listing 2.1, the private key is generated providing several strings in place of the data owner's identity. Different cyphertexts are produced using different attributes as a key, and the same `CipherParameters` are needed to decrypt correctly.

The functions `encaps` and `decaps` provide encryption and decryption mechanisms. After practical experiments, it results that [3] is a proof-of-concept implementation and it is thus not suited for actual use. The main reasons behind this lay in the implementation of the aforementioned functions: in fact, the `encaps` function does not take any plaintext in input, but it is generated inside its body by the function `process()`. As we can see from Listing 2.2, this function calls `processBlock` supplying as input an empty byte array instead of an actual input.

Listing 2.2: Excerpt from PairingKeyEncapsulationMechanism class

```
1  package it.unisa.dia.gas.crypto.jpbc.kem;
2
3  import {...}
4
5  public abstract class PairingKeyEncapsulationMechanism extends
       PairingAsymmetricBlockCipher implements
       KeyEncapsulationMechanism {
6
7      private static byte[] EMPTY = new byte[0];
8
9      // some other functions...
10
11     public byte[] processBlock(byte[] in) throws
       InvalidCipherTextException {
12         return processBlock(in, in.length, 0);
13     }
14
15     public byte[] process() throws InvalidCipherTextException {
16         return processBlock(EMPTY, 0, 0);
17     }
18 }
```

It is possible to modify the source code by opening a file, or supplying a run-time byte array containing the information to encrypt, and calling `processBlock` purposely:

```
return processBlock(dataArray, 0, dataArray.length);
```

To obtain the encrypted text it is also necessary to modify the last statement in the `processBlock` function called by `process`. In fact, as shown in the documentation for class `PairingAsymmetricBlockCipher`, the function `byte[] processBlock(byte[] in, int inOff, int inLen)` takes as second and third arguments the offset and the length of data, thus requiring an invocation like the following:

```
return processBlock(in, 0, in.length);
```

The complete content of the mentioned classes is available in Appendix B.

After performing data encryption, though, the `Assert` statements to verify correct decryption fail, which leads us to think that this is only a proof-of-concept implementation. For this reason, and due to the unsuitableness of the available [1] and [6] in the chosen context for this project, we have thus decided to proceed to the implementation of Sticky Policies with a hybrid cryptosystem.

Chapter 3

A simple implementation

First, we set up the necessary entities to implement *Sticky Policies*: an Android client and a web server. The client was developed using Android Studio and emulated through the Android Emulator with a Nexus 5X device running Android 7.0 and API level 24. The Trusted Authority was developed using Eclipse and run on Apache Tomcat 8; the communication was implemented through HTTP protocol.

The app was also tested in a Samsung tablet (SM-T230) running Android 4.4.2 and API level 19, to test performance on a real device with lower level API and operating system, together with a different screen dimension.

In this solution, *Sticky Policies* are realized via XML files and paired with personal data through the combination of symmetric and asymmetric cryptography. This approach is presented in [10], and an example XML policy was created taking as a reference the one presented in the same paper. Following this specification, we present a protocol for the communication of two Android clients, called for simplicity Alice and Bob.

Alice generates an XML policy to regulate data access, encrypting it with a symmetric key generated locally. The policy and the key are then encrypted with the Trusted Authority's public key and signed by Alice. Purposely, Alice should obtain the public key of the Trusted Authority and also a key pair for herself: in our solution, we use self-signed X509 Certificates generated by combining the Java Cryptography Architecture and the Bouncy Castle cryptography APIs for Java. Alice thus contacts the Trusted Authority to obtain its public key, and shares her own if the Trusted Authority is not the issuer of her certificate.

Bob obtained Alice's encrypted data and an attached policy in clear text, together with other encrypted data to guarantee integrity, confidentiality and non-refusal of the policy and data. In particular,

- Integrity is granted for the policy in plain text by sharing its digest, encrypted with the Trusted Authority's public key.
- Confidentiality is granted both for the personal data, which is shared

encrypted, and for its symmetric key which is encrypted together with the policy's digest

- Non-refusal is granted for all of the shared data thanks to the signing function applied by the data owner.

To decrypt Alice's data, Bob must follow these steps:

- Bob asks the Trust Authority to release the symmetric key, presenting the encrypted data signed by Alice.
- The Trust Authority evaluates the policy and Bob's reliability, submitting some challenges for him to complete.
- If trusted, Bob receives the symmetric key to decrypt Alice's personal data.

Data is exchanged through POST requests over a channel which is assumed to be secure.

Once the Trust Authority receives a request from the client, it checks the correct specification of the policy before proceeding to decrypt and verify the payload received. This operation is performed by a server-side parser which matches the XML file with a standard XSD grammar. In case of errors, no symmetric key is released.

The specification of the XSD grammar can be found in Appendix A.

3.1 Program flow and architecture

We start by analysing the application flow before data is shared, given that Alice has installed an instance of the StickyPolicyApp.

The data owner can either share a simple text message (shown in Figure 3.1) or a regular file inside his phone (for example an image, in Figure 3.2), chosen through a picker. Consequently, the underlying application generates a fitting policy depending on the data shared and on the owner itself, which is then passed to the next `Activity` for encryption and sharing. In this solution, for the sake of simplicity, the generated policy contains mock data, except for the X509 Certificate serial number and the data type. Possible future works include adding an interactive policy generator to allow the user to define sharing constraints.

A certificate exchange is then initiated between the client and the server, to perform both signature and encryption inside the app and to allow the Trusted Authority to run security checks on data, when requested access by third parties. Subsequently, the policy and data are processed following the specification presented in [10]: the data is encrypted with a one-time-use symmetric key generated at the moment, and together with a digest of the

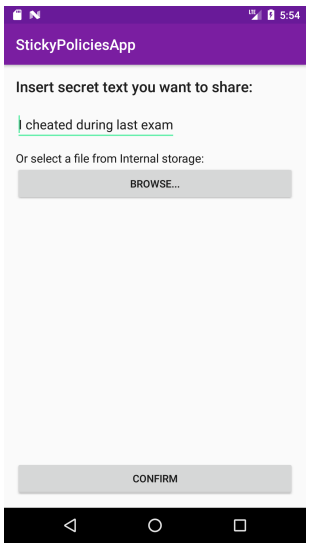

Figure 3.1: Sharing secret text

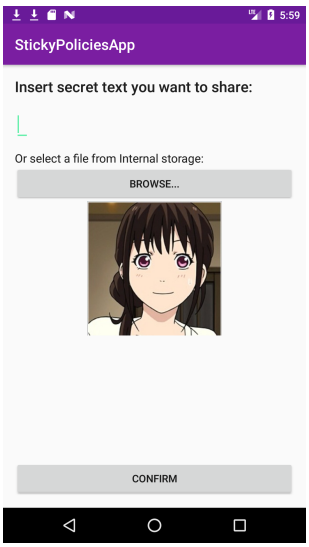

Figure 3.2: Sharing a personal image

policy they are first encrypted with the public key of the Trusted Authority, then signed with the data owner's private key.

It is now possible for Alice to safely share her data, sending it to Bob. Data is transferred inside the body of POST requests in JSON form. To safely and efficiently perform data serialization and deserialization we used the `com.google.code.gson` library and implemented an ad-hoc private class to hold both policy and encrypted data in a single GSON object. For this purpose, we tested also the libraries `org.json` and `org.jabsorb`, which though proved to be unsuitable and less efficient.

Let's now consider the StickyPoliciesApp to be running on Bob's device, and to have just received a secret message from Alice. Bob forwards to the Trusted Authority the plain-text policy together with the signed key and digest, removing the encrypted personal data from the new request body. At this point, the Trusted Authority may check Bob's reliability and submit a few challenges to prove it, eventually disclosing the symmetric key to access Alice's secret message.

Both the communication and the cryptographic primitives are performed inside `AsyncTasks`: this keeps the main UI thread responsive and prevents the app from freezing due to intensive, network-dependent computation.

3.1.1 Android Client Implementation

The StickyPoliciesApp consists of a few `Activities`. The launcher allows either to send private data or to access received messages, but can be extended to include new functionalities, as the aforementioned policy editing.

Navigation within the activities is made through explicit `Intent`s: as specified within the Android security guidelines, implicit `Intent`s may introduce security hazards as it is not known which service will respond to the intent, and the user has no control over it.

The first activity is in charge of data sharing: once the data type of the shared information is determined, it requests from the `CryptoUtils` class the data owner's certificate to retrieve its serial number, edits the sticky policy so that it matches both personal data type and certificate SN; finally, it creates a `Bundle` to pass these objects to the following activity, invoked explicitly.

The `PolicyClient` class is in charge of communication operations: it performs a certificate exchange with the Trusted Authority and it encrypts data, sending them to Bob. These operations are performed via dedicated `AsyncTask`s which are started in the `onResume()` method, so that the main UI thread is built without delay. Both tasks simply prepare data for the HTTP request, invoke a library function to handle it at a lower level and parse the results. For example, this is how the data owner's certificate is shared:

Listing 3.1: AsyncTask from PolicyClient class

```
@Override
protected byte[] doInBackground(URL... urls) {
    String responseBody = null;
    URL searchUrl = urls[0];
    try {
        responseBody = NetworkUtils.getResponseFromHttpUrl(
    searchUrl, "POST", postData, applicationJsonContentType);
    } catch (IOException e) {
        e.printStackTrace();
        Log.d(TAG, "Error when sending encrypted POST: " + e.
    getMessage());
    }
    Gson gson = new Gson();
    return gson.fromJson(responseBody, byte[].class);
}
```

where `NetworkUtils` is a public class exposing `static` methods for network management. As for data encryption, operations are performed following the specification in [10], and an excerpt of the code is shown in Listing 3.2.

Listing 3.2: Excerpt from PolicyClient class

```
byte[] pii;
byte[] encrPiiAndIV = new byte[0];
byte[] keyAndHashEncrypted = new byte[0];
byte[] signedEncrKeyAndHash = new byte[0];
try {
    // 1) obtain policy: obtained in Bundle
    // 2) generate symmetric disposable encryption key
    byte[] encodedSymmetricKey = CryptoUtils.
    generateSymmetricRandomKey();
```

```
9       byte[] initializationVec = CryptoUtils.generateSecureIV();
10      // 3) encrypt PII
11      byte[] encryptedPii = CryptoUtils.encrDecrSymmetric(Cipher.
        ENCRYPT_MODE, encodedSymmetricKey, initializationVec, pii);
12      // 4) hash policy
13      byte[] policyDigest = CryptoUtils.calculateDigest(policy.
        getBytes(Charset.forName("UTF-8")));
14      // 5) append policy and  digest, encrypt with PubTa
15      ByteArrayOutputStream byteArrayOutputStream = new
        ByteArrayOutputStream();
16      byteArrayOutputStream.write(encodedSymmetricKey);
17      byteArrayOutputStream.write(policyDigest);
18      keyAndHashEncrypted = CryptoUtils.encryptAsymmetric(
        taPublicKey, byteArrayOutputStream.toByteArray());
19      // 6) sign
20      signedEncrKeyAndHash = CryptoUtils.sign(keyAndHashEncrypted)
        ;
21
22      encrPiiAndIV = new byte[initializationVec.length +
        encryptedPii.length];
23      System.arraycopy(encryptedPii, 0, encrPiiAndIV, 0,
        encryptedPii.length);
24      System.arraycopy(initializationVec, 0, encrPiiAndIV,
        encryptedPii.length, initializationVec.length);
25  } catch (Exception e) {
26      e.printStackTrace();
27      mSearchResultsTextView.setText("Sorry, some errors happened
        while encrypting your data.\nDon't worry, your privacy is
        still safe!\nPlease try again later.");
28  }
```

In Listing 3.2, we omit try-catch blocks for error handling. To stop the application flow when fatal errors occur (e.g. data encryption fails), a high-level `SecurityException` is thrown and a message is delivered to the user, prompting him to retry later. The same approach is applied inside the whole application: errors are managed locally and a high-level message is shown to the user in case of critical exceptions.

Finally, Bob can access the received data in a third `Activity`, in which he shares part of his `EncryptedData` with the Trusted Authority and receives back the encrypted symmetric key and the initialization vector.

3.1.2 Java Server Implementation

We realized the Trusted Authority as a web server exposing two services, reachable via the corresponding servlets hosted in the servlet container Apache Tomcat: `PolicyServer/certificates` and `PolicyServer/access`.

The first servlet is in charge of sharing the Trusted Authority's `X509 Certificate` in `PEM` format, and it also manages the data owners who register to the TA. Certificates are accepted in `PEM` format. The state is kept server-side inside the `ServletContext`, which is bound to the container's life cycle

rather than to the single user or session, and certificates are stored in a `HashMap<BigInteger, X509Certificate>`. The `HashMap` is a data structure which allows quick access and prevents duplicate addition: thus, when a user "Bob" asking for data access sends a message in which the certificate SN does not match any of the `HashMap` entries, the request will be refused. This behaviour requires the state to be shared between the two servlets, possible thanks to the use of a Java Bean.

The second service provides data access: JSON data is received in POST requests, containing plain-text policies together with signed key and digest. The servlet checks validity and integrity of the policy, verifying the signature and decrypting the obtained data to retrieve the symmetric key. If any of these procedures fails, the entire process is interrupted and the access request is refused with an error code corresponding to the cause of the error. For example,

Listing 3.3: Excerpt from DataAccessServlet class

```
1  //check if digests are equal
2  if(!(CryptoUtilities.compareDigests(retrievedPolicyDigest,
       computedPolicyDigest))) {
3      endConnection(response, HttpServletResponse.SC_FORBIDDEN, "
       Computed policy hash does not match with the sent one.
       Suspected message tampering.");
4      return;
5  }
6  //verify signature
7  boolean correctTASignature = CryptoUtilities.verify(
       dataOwnerCertificate.getPublicKey(), signedEncrKeyAndHash,
       keyAndHashEncrypted);
8  if(!correctTASignature) {
9      endConnection(response, HttpServletResponse.SC_FORBIDDEN, "
       Data Owner's signature didn't match. Suspected forgery.");
10     return;
11 }
12
13 private void endConnection (HttpServletResponse response, int
       responseStatusCode, String message) {
14     PrintWriter out = response.getWriter();
15     out.println(message);
16     response.setStatus(responseStatusCode);
17 }
```

In a future improved version of this app, the symmetric key could be encrypted with Bob's public key before sharing, requiring Bob to register at the Trusted Authority first. This development depends on the dimension of encrypted symmetric key together with the initialization vector, which is currently shared every time together with the key; their overall size must not exceed the size of the modulus for the generated Trusted Authority's key pair. Other possible improvements include the implementation of policy-specified `actions`, as for example informing the data owner when data access

is granted.

As it is, our web server shows the same weaknesses we described in the previous chapter, regarding secure storage and network attacks; moreover, additional weaknesses are introduced by the communication with a potential malicious client. In other words, no check is performed on the payload (content-type, dimension, user-agent) and the client is considered to be always trusted.

3.2 Structure of an XML policy

The policy file is constructed by the data owner in order to specify which set of users can access her data. Policies are shared over the internet as strings, thus formats like XML or JSON represent the best choice in terms of interoperability and ease of use. Choosing the XML format over a new, custom implementation for Sticky Policies enables the use of well-known corroborated libraries and best practices, available due to XML widespread. Moreover, the document format is designed for data transfer and to be self-descriptive: its structure and content can easily be regulated through grammars and specifications.

Sticky Policies have been designed with a general and comprehensive structure, so as to allow broader usage than the one proposed in this solution. The main components of a Sticky Policy are the following:

- List of the Trusted Authorities where Bob can ask for data access. They are specified by Alice and they include all the servers in which she registered her certificate.
- Details about the Data Owner, which are used server-side to retrieve the correct certificate and public key.
- One or more policies, specifying fine-grained constraints about the attached data. They may vary in target, time validity, requirements, etc, specifying different requirements for different target users or services. The complete specification is available in Appendix A.

Each field within the policy is detailed in the grammar, where are specified constraints about its values, position, number or occurrences, etc. Some of these constraints describe logical evidence - e.g. each policy refers to a single Data Owner:

```
<xs:element name="owner" type="ownerType" maxOccurs="1"
    minOccurs="1" />
```

as well as real-world constraints - e.g. days can range from 1 to 31:

```
<xs:simpleType name="dayType" >
    <xs:restriction base="xs:positiveInteger">
        <xs:minInclusive value="1" />
```

```
        <xs:maxInclusive value="31" />
    </xs:restriction>
</xs:simpleType>
```

and finally programming constraints - e.g. a `X509Certificate`'s serial number is represented throgh a `BigInteger`, which is mapped to a `xs:unsignedLong`:

```
<xs:element name="certificateSerialNumber" type="xs:unsignedLong
    " maxOccurs="1" minOccurs="1" />
```

3.2.1 XML Validation and Parsing

Policies are parsed server side: this control step includes validation, i.e. checking both syntax and semantics of the document. In Java, it is possible to realize an XML parser through a `SAXParser`, a low-level implementation which scans the whole document and for each start tag and end tag found fires and event, handled by callback methods to retrieve the content between the tags. While this allows to gain in efficiency and is suited also to parse large documents, it constitutes and ad-hoc tailored solution, unsuited for dynamic environments.

Document parsing is performed by a `ContentHandler`, in which callback methods are defined: we chose to implement them via the subclass `DefaultHandler` and its methods `startElement`, `characters`, `endElement`.

In our solution, we implemented also a `XMLErrorChecker` for error handling. This parser provides three different types of errors: fatal errors, errors and warnings, although by default only fatal errors are fired. In these cases, the parser cannot continue and the method performs `System.exit(1)`, while nonfatal errors are generated when the document fails some validity constraints (e.g. invalid tag, tag not allowed...). We redefined the default behaviour by firing `SAXException`s also for nonfatal errors, due to the considerable importance of having a well-formed and valid document. These exceptions are then caught by the caller, at a higher level of the call stack, and handled by refusing the data disclosure request.

3.3 About cryptography

Cryptography constitutes a considerable part of the whole project. All cryptographic functions are realized as static, and are accessible as if they were an external library both in the client and server. Both of them rely on the Java Cryptography Architecture together with Bouncy Castle APIs. They include X509 Certificate generation, sign, verify and asymmetric encryption operations as well as symmetric key generation and encryption. Finally, it is possible to generate also message digests. Provider names, algorithms and key size are fixed parameters within the application and it is

not possible for the user to choose any; future developments may give her the chance to choose between algorithm implementations corresponding to different levels of security.

3.3.1 Message Digests

Computing message digests is an important part of this security protocol: first, it proves policy's integrity by matching the received digest with the one computed server-side from the plain-text policy; second, it lowers the size of the data to be encrypted, giving it a fixed dimension of 32 bytes. In fact, policy files can potentially grow in size and, were the policy not to be hashed before asymmetric encryption, it could introduce a weakness within RSA's encryption method. If the overall dimension of the symmetric key and policy were greater than the dimension of the modulus for asymmetric encryption, either the dimension of the modulus would increase, or encryption would be performed after splitting the whole data into blocks of size lower than 1024 bits.

The cryptographic hash function used in this project is the SHA-256 function, and the implementation is the one provided by the class `java.security.MessageDigest`. To obtain a message digest it is necessary to follow a three-step procedure: first, an instance of `MessageDigest` is retrieved for the specified algorithm; then, it receives as input the text to hash and, finally, the `digest()` function is called.

Listing 3.4: Excerpt from CryptoUtilities class

```
1  import java.security.MessageDigest;
2  import java.security.DigestException;
3  import java.security.NoSuchAlgorithmException;
4
5      public static byte[] calculateDigest(byte[] text) throws
       DigestException {
6          try {
7              MessageDigest md = MessageDigest.getInstance(
       digestAlgorithm);
8              md.update(text);
9              return md.digest();
10         } catch (NoSuchAlgorithmException cnse) {
11             throw new DigestException("Couldn't make digest of
       partial content " + cnse.getMessage());
12         }
13 }
```

Digests are compared with the `MessageDigest.isEqual(byte[] first, byte[] second)` function, which does a simple byte compare, as reported by the Java documentation.

Switching from SHA-256 to SHA-512 could increase efficiency in our case, thanks to the chosen device having a x86_64 architecture and being SHA-512 based on 64-bits words. Furthermore, this would not pose any prob-

lem in terms of API availability since both of them are available since API level 1+. Switching to SHA-512 would double the size of the produced digest, leaving only 64 bytes of space to encode the symmetric key. Keeping into consideration previous observations about having a maximum data size of 128 bytes, we have preferred a smaller message digest also in terms of bandwith consumption and foreseeing a possible symmetric-key dimension increase. Initialization vectors may also be shared in the remaining 64 bytes, and their dimension may vary depending on the encryption algorithm.

3.3.2 X509Certificates

The Bouncy Castle library provides functionalities to create self-signed X509 Certificates, chosen for the sake of simplicity. In a more realistic implementation, certificates should be issued by a Certification Authority, and the Trust Authority should additionally perform certificate verification (e.g. expiration and revocation). To construct the `X509Certificate`, we use 1024-bit asymmetric keys generated for the RSA algorithm, and the Bouncy Castle security provider. 2048-bit long keys could be more appropriate depending on the confidentiality of the information shared, on the mobile device and network possibilities.

Both the Trust Authority and the Data Owner need a certificate to store and share securely their public key. `X509Certificate` construction follows a similar procedure for the both of them, with few exceptions. In case the Trusted Authority works also as a Certification Authority, then

```
BasicConstraints constraints = new BasicConstraints(true);
```

while for the mobile device we use a `false` parameter. Moreover, in both cases, certificates are created and handled as singleton objects, to prevent inappropriate duplicates: the methods and fields to generate and store certificates are `private`, and their content can be retrieved through accessor methods, which also control the instance creation.

Among the Bouncy Castle library there is the LightCrypto implementation [15], available for phones or devices with limited computational power. It allows the creation of key pairs and certificates, but their interoperability with the Java Cryptography Architecture is limited and so a conventional certificate implementation is preferred.

Certificates are shared from both client and server in PEM format using a `JcaPEMWriter` for serialization and a `CertificateFactory` for deserialization. This format has been preferred to ASN.1 as easier to send in a HTML request body, it being a `String` rather than a `byte[]`.

3.3.3 Asymmetric Key Generation and Encryption

As mentioned in subsection 3.3.2, asymmetric keys are generated with a modulus length of 1024 bits. We use a `KeyPairGenerator` specifying both

the algorithm (AES) and the security provider (Bouncy Castle).

Listing 3.5: Excerpt from CryptoUtilities class

```
String BC = org.bouncycastle.jce.provider.BouncyCastleProvider.
    PROVIDER_NAME;

KeyPairGenerator keyPairGenerator = KeyPairGenerator.getInstance
    (asymmKeyGenAlg, BC);
keyPairGenerator.initialize(1024, new SecureRandom());
taKeys = keyPairGenerator.generateKeyPair();
```

In this project, asymmetric encryption and signature is used to communicate with the Trusted Authority, and as such the same cryptographic methods are implemented server side. Security considerations in this matter have their basis in the RSA Cryptography Specification [9].

The security protocol described in [10] requires to implement the signature with appendix scheme since it appends a message and its signature when communicating to the Trusted Authority. For the sign and verify methods we chose the `SHA256WithRSA` algorithm.

Regarding asymmetric encryption, which is performed before the sign operation, the `RSA/ECB/OAEPPadding` algorithm was preferred to the `RSA/ECB/PKCS1Padding` due to proven resistance to chosen-ciphertext attacks. The reason is related with the predictability of padding schemes applied during encryption, and in particular when the plain text dimension is higher than the dimension of the modulus. In these cases, the original text is split in many blocks, which are then hashed and padded before encryption to avoid a potential attacker to recombine them and still verify successfully.

In the previous and following subsections has been highlighted how it was better to have an overall data size lower than the modulus: in fact, it is good practice not to rely on asymmetric encryption for large data also for its inefficiency, but proper choice of the implementation algorithm guarantees that no additional weakness is introduced in case it should happen.

3.3.4 Symmetric Key Generation and Encryption

In this subsection, we will refer always to cryptographic operations happening on the Android devices, since the Trusted Authority never receives personal data.

The specification in paper [10] asks for a symmetric one-time-use key to encode personal data. Symmetric keys can be generated via a `KeyGenerator` with an algorithm-specific initialization, not providing `SecureRandom` to rely on the implementation of the highest-priority installed provider. This raises the reliability of the proposed solution, as symmetric keys are never reused and are unrelated. The available algorithms for encryption and key generation depend on the chosen security `Provider`, which is in our case the Bouncy

Castle provider. Available key generation algorithms include AES for symmetric encryption, in particular AES/ECB and AES/GCM/NOPADDING: since the former has known weaknesses and it is not suited to large-size file encryption, we considered switching to another `Provider`, namely AndroidOpenSSL provider. A working example using AES/ECB is shown in Listing 3.6. Invocation must specify `Cipher.ENCRYPT_MODE` or `Cipher.DECRYPT_MODE` to perform either encryption or decryption.

Listing 3.6: Example code with AES/ECB processing on Android device

```
private static String symmetricEncrAlgorithm = "AES";
private static int AES_KEY_SIZE = 256;

public static byte[] generateSymmetricRandomKey() {
    KeyGenerator keyGen = null;
    try {
        keyGen = KeyGenerator.getInstance(symmetricEncrAlgorithm);
    } catch (NoSuchAlgorithmException e) {
        e.printStackTrace();
        Log.d(TAG, "Error in generating the symmetric random key: " + e.getMessage());
    }
    keyGen.init(AES_KEY_SIZE);
    SecretKey secretKey = keyGen.generateKey();
    return secretKey.getEncoded();
}

public static byte[] encrDecrSymmetric(int cipherMode, byte[] encodedSymmKey, byte[] originalText) {
    SecretKeySpec skeySpec = new SecretKeySpec(encodedSymmKey, symmetricEncrAlgorithm);
    byte[] processedText = new byte[0];
    try {
        Cipher cipher = Cipher.getInstance(symmetricEncrAlgorithm);
        cipher.init(cipherMode, skeySpec);
        processedText = cipher.doFinal(originalText);
    } catch (NoSuchAlgorithmException | NoSuchPaddingException | InvalidKeyException | IllegalBlockSizeException | BadPaddingException e) {
        e.printStackTrace();
        if (cipherMode == Cipher.ENCRYPT_MODE)
            Log.d(TAG, "Error in symmetric encryption: " + e.getMessage());
        if (cipherMode == Cipher.DECRYPT_MODE)
            Log.d(TAG, "Error in symmetric decryption: " + e.getMessage());
        throw new SecurityException(e.getMessage());
    }
    return processedText;
}
```

The Bouncy Castle provider also offers implementations for several Password Based Encryption methods, using AES/CBC with different key lengths, salt and padding options. We did not consider any of those algorithms as they are out of the scope of this project: encryption must be performed with a one-time-use secret, while using a fixed password would definitely reduce the security level. Moreover, PBE requires many iterations in order to process a secure derived key (around 100 000 or 200 000), which could impact on efficiency and performance.

The implemented solution makes use of a AES/CBC/PKCS5Padding algorithm is available with the AndroidOpenSSL provider: the Cipher Block Chaining operation mode is more secure than Electronic Codebook, and is suited to work in this context as a block cipher mode. Padding is needed due to unpredictable size of the policy, which may not be a multiple of the block size (128 bits). In the Cipher Block Chaining mode an initialization vector is needed at the beginning of each encryption / decryption process to be XOR'd with the first block of plain text: to obtain it we rely on the Java class `SecureRandom`, and we create a initialization vector of the same size of a block in CBC. It is worth highlighting how we ask `secureRandom.nextBytes(iv);` to generate the initialization vector to avoid reuse of previous configurations; weaknesses may also be introduced from a repetitive initialization value for the `SecureRandom` present in some implementations. Furthermore, when creating a symmetric key we need to specify `"AES"` as input parameter, while for the encryption and decryption methods we add the initialization vector:

Listing 3.7: Example code with AES/CBC processing on Android device

```
1  private static String symmEncrAlg = "AES/CBC/PKCS5Padding";
2  private static final String androidOpenSSLProviderName = "
       AndroidOpenSSL";
3
4  public static byte[] encrDecrSymmetric(int cipherMode, byte[]
       encodedSymmKey, byte[] initializationVector, byte[] clearText
       ) {
5      SecretKeySpec skeySpec = new SecretKeySpec(encodedSymmKey,
       symmEncrAlg);
6      byte[] encryptedText = new byte[0];
7      try {
8          Cipher cipher = Cipher.getInstance(symmEncrAlg,
       androidOpenSSLProviderName);
9          cipher.init(cipherMode, skeySpec, new IvParameterSpec(
       initializationVector));
10         encryptedText = cipher.doFinal(clearText);
11     } catch (InvalidAlgorithmParameterException |
       NoSuchAlgorithmException | NoSuchPaddingException |
       InvalidKeyException | IllegalBlockSizeException |
       BadPaddingException | NoSuchProviderException e) {
12         e.printStackTrace();
13         if (cipherMode == Cipher.ENCRYPT_MODE)
14             Log.d(TAG, "Error in symmetric encryption: " + e.
       getMessage());
```

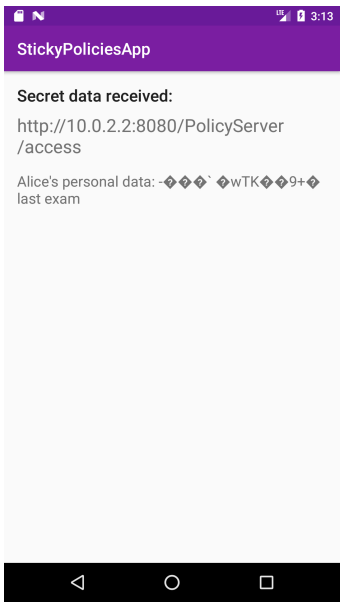

Figure 3.3: Decrypted text in Bob's device.

```
15          if (cipherMode == Cipher.DECRYPT_MODE)
16              Log.d(TAG, "Error in symmetric decryption: " + e.
    getMessage());
17          throw new SecurityException(e.getMessage());
18      }
19      return encryptedText;
20  }
```

The initialization vector must be shared between Alice and Bob to allow correct decryption. Despite it not being a secret, initialization vector reuse or publication may introduce weaknesses in the cipher mode, leaking information about the first plain text block. On the other side, initialization vector reuse or publication may be desirable in terms of network and bandwith consumption: thus, it is suggested that each solution is tailored to the specific use-case. In the implemented StickyPoliciesApp we generate and share a new initialization vector every time, it being a proof-of-concept project. We also observed that with a 256 bit symmetric key and a 128 bits initialization vector the constraint on the total data size being lower than 128 bytes is respected.

Other observations on the initialization vector involve the self-correcting property of Cipher Block Chaining: if Bob knows the correct key, but not the initialization vector, he will still be able to access part of the message, as shown in Figure 3.3.

The AES/CBC encryption scheme does not include integrity protection, meaning that a potential attacker could manipulate the encrypted data without Bob knowing it. The attacker would though have to forge a specific

encrypted text, because `cipher.doFinal()` will otherwise throw exceptions as `BadPaddingException` if the encrypted text is not properly padded or the provided symmetric key is incorrect (for the provided text). Differently, if the attacker manages to substitute the key sent from the Trusted Authority with a forged key, and also manipulates the encrypted data received by Bob with a correspondingly forged text, the encryption succeeds. This situation should never happen under the assumption that the connection is secure.

Data integrity could be realized with a MAC scheme: encrypted data could be signed by Alice before sharing, yet presenting issues on both security and efficiency of the operation. A better solution could be signing the message digest, which has a fixed size and would not introduce security weaknesses nor inefficiency in computation and bandwith consumption.

In cases in which the required level of security is higher and integrity is necessary in addition to confidentiality, another solution may involve the AES/GCM/NOPADDING encryption offered by the Bouncy Castle provider. GCM stands for Galois/Counter Mode, which is a mode of operation for symmetric block ciphers providing authenticated encryption (Authenticated Encryption with Associated Data, AEAD, as described in [7]). From the specification we understand that it is possible to use AES/GCM with keys either 128 or 256 bits long, and that the operations of authenticated encryption and decryption both need a secret key, a nonce, a plain or obscured text and the associated data.

From the code shown in Appendix C we can see that GCM encryption mode can be only implemented on devices which support API level 19 or higher, while AES/CBC has no limitation in this sense. Moreover, GCM would require a protocol redefinition to share the associated data: they account for authenticity and they are necessary, together with the nonce, in the decryption process.

3.4 Security Considerations in Android

When designing the security of an Android application, the first stage involves writing a correct Manifest. It is important not to give any unnecessary permission to the app, and eventually ask for runtime permissions if the API level allows it.

In this project, the only required permission is

```
<uses-permission android:name="android.permission.INTERNET" />
```

to establish communications with the Trusted Authority web server and with other peers and services. As it is, no other permission is required, but were the app to be further developed, additional permissions may be necessary, as for example `READ_EXTERNAL_STORAGE`.

Another important security consideration concerns networking: in this project work, the web server is hosted at localhost thanks to the Apache

Tomcat container, but in a real-world use case the implementation will differ, thus requiring a few changes also in the Android application. These edits involve secure networking: using `HttpsURLConnection` instead of `HttpURLConnection` together with `SSLSocket` to implement encrypted socket-level communication. This would make concrete our initial hypothesis of a secure communication channel.

In case this project is used with an actual Certification Authority, it will be necessary to define a Network Security Configuration for the considered CA, and to properly store keys in the Android `KeyStore`.

Chapter 4

Performance and Conclusions

We have presented a project work on Information Security in which we tackle the matter of privacy and personal data sharing on mobile devices. In this context, we provide a tool control how data is shared in terms of recipients and scope of use: by implementing *Sticky Policies* it is possible to describe detailed and fine-grained constraints for each shared file. *Sticky Policies* are metadata that sticks to the data they describe through the application of cryptographic processes, and provided that third parties are trusted and will not illicitly share personal data with others, *Sticky Policies* will always travel together with the data they refer to.

To obtain data access, third parties must ask a Trusted Authority and may be subject to its examination, aimed at assessing the service's reliability.

In this work, we have implemented both a data owner and a data consumer, who communicate through an Android device application; the Trusted Authority is represented by a web server in Java, which exposes the aforementioned functionalities on Java servlets.

Let us now observe the performance of the StickyPoliciesApp using the Android Profiler available within Android Studio. The Android Profiler shows CPU, memory and network usage with the passing of time, but can be used only if the Android OS is 5.0 or higher (Lollipop): thus, it is not possible to test the application on a concrete device and we will just show results regarding the Android emulator.

Our first experiment is very simple: we suppose Alice wants to share a very short string of data. We test the application using as input `I cheated during last exam` (which counts 5 words and 26 characters), a string so simple that it could be the data owner Social Security Number, credit card number and pin, or Netflix username and password. As we can see from Figure 4.1, we have two network usage peaks both in download and upload (avg speed 5KB/s) which match certificate sharing between client and server, followed by a higher peak corresponding to Alice sharing her encrypted data to Bob (avg speed 20KB/s UL, 3KB/s DL) and him asking the Trusted

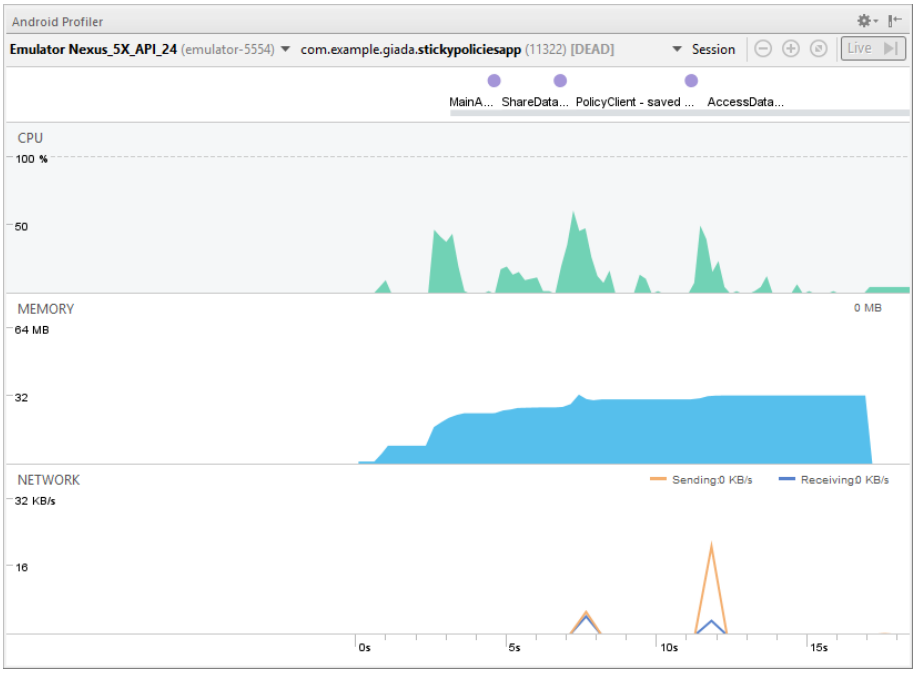

Figure 4.1: StickyPoliciesApp test with 5 words processing.

Authority to be granted access.

For what concerns CPU usage, we have three main peaks of duration lower than a second and occupation between 30% and 50%. The memory is mainly allocated for code and java usage, and it goes from 9MB at the instantiation of `MainActivity` to 32MB when `AccessDataActivity` terminates.

Next, we slightly increase the difficulty of the experiment, sharing a text document of 101 words and 605 characters. Network usage is equally divided in two moments of comparable magnitude: approximately 5KB/s in DL and UL followed by 17KB/s in UL and 2KB/s in DL. Memory usage has increased of about 10MB from the previous experiment, similarly divided between Java and code memory usage. CPU bursts have increased in number, but the percentage is usually around 25% and the timespan of each burst is approximately 10 ms long; three main bursts are still present. Graphs from the Android Profiler are shown in Figure D.1.

Finally, we share a text with 1000 words (for a total count of 6804 characters): as we can observe from Figure D.2, network usage radically increase, transmitting up to 91.8KB/s UL, 4KB/s DL when sharing data between Alice and Bob - this communication takes about 20 ms.Memory usage increases linearly, starting from 20MB at the instantiation to 37MB when the last activity stops. We can observe also more frequent CPU bursts: on average, the intensity has little increase in percentage, but the highest peaks reach

up to 60% even though they last less than a second.

A different approach

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Appendix A

XSD Grammar for Sticky Policies

```
<?xml version="1.0" encoding="utf-8" ?>
<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema">
    <xs:element name="stickyPolicy" type="stickyPolicyType" />

    <xs:complexType name="stickyPolicyType">
        <xs:sequence>
            <xs:element name="trustedAuthority" type="xs:string"
     maxOccurs="unbounded" minOccurs="1" />
            <xs:element name="owner" type="ownerType" maxOccurs=
    "1" minOccurs="1" />
            <xs:element name="policy" type="policyType"
    maxOccurs="unbounded" minOccurs="1" />
    </xs:sequence>
    </xs:complexType>

    <xs:complexType name="policyType">
        <xs:sequence>
            <xs:element name="target" type="xs:string" maxOccurs
    ="unbounded" minOccurs="1" />
            <xs:element name="dataType" type="dataType"
    maxOccurs="unbounded" minOccurs="1" />
            <xs:element name="validity" type="dateType"
    maxOccurs="1" minOccurs="1" />
            <xs:element name="constraint" type="xs:string"
    maxOccurs="unbounded" minOccurs="1" />
            <xs:element name="action" type="xs:string" maxOccurs
    ="unbounded" minOccurs="1" />
        </xs:sequence>
    </xs:complexType>

    <xs:complexType name="ownerType">
        <xs:sequence>
            <xs:element name="referenceName" type="xs:string"
    maxOccurs="1" minOccurs="1"  />
            <xs:element name="ownersDetails" type="xs:string"
```

```
    maxOccurs="unbounded" minOccurs="1"  />
27          <xs:element name="certificateSerialNumber" type="
    xs:unsignedLong" maxOccurs="1" minOccurs="1" />
28      </xs:sequence>
29  </xs:complexType>
30
31  <xs:simpleType name="dataType" >
32      <xs:restriction base="xs:string">
33          <xs:enumeration value="picture" />
34          <xs:enumeration value="text" />
35          <xs:enumeration value="video" />
36          <xs:enumeration value="audio" />
37          <xs:enumeration value="position" />
38      </xs:restriction>
39  </xs:simpleType>
40
41  <xs:complexType name="dateType">
42      <xs:sequence>
43          <xs:element name="day" type="dayType" />
44          <xs:element name="month" type="monthType" />
45          <xs:element name="year" type="yearType" />
46      </xs:sequence>
47  </xs:complexType>
48
49  <xs:simpleType name="dayType" >
50      <xs:restriction base="xs:positiveInteger">
51          <xs:minInclusive value="1" />
52          <xs:maxInclusive value="31" />
53      </xs:restriction>
54  </xs:simpleType>
55
56  <xs:simpleType name="monthType" >
57      <xs:restriction base="xs:positiveInteger">
58          <xs:minInclusive value="1" />
59          <xs:maxInclusive value="12" />
60      </xs:restriction>
61  </xs:simpleType>
62
63  <xs:simpleType name="yearType" >
64          <xs:restriction base="xs:positiveInteger">
65          <xs:minInclusive value="2017" />
66          <xs:maxInclusive value="2027" />
67          </xs:restriction>
68  </xs:simpleType>
69 </xs:schema>
```

Appendix B

Java Pairing Based Cryptography Library

Here are reported the complete classes from [3], mentioned in chapter 3.

In this class we have a `main` function to show a sample usage of IBE cryptography.

Listing B.1: AHIBEDIP10.class

```
1  package it.unisa.dia.gas.crypto.jpbc.fe.ibe.dip10;
2
3  import it.unisa.dia.gas.crypto.jpbc.fe.ibe.dip10.engines.
       AHIBEDIP10KEMEngine;
4  import it.unisa.dia.gas.crypto.jpbc.fe.ibe.dip10.generators.
       AHIBEDIP10KeyPairGenerator;
5  import it.unisa.dia.gas.crypto.jpbc.fe.ibe.dip10.generators.
       AHIBEDIP10SecretKeyGenerator;
6  import it.unisa.dia.gas.crypto.jpbc.fe.ibe.dip10.params.*;
7  import it.unisa.dia.gas.crypto.kem.KeyEncapsulationMechanism;
8  import it.unisa.dia.gas.jpbc.Element;
9  import it.unisa.dia.gas.jpbc.Pairing;
10 import it.unisa.dia.gas.plaf.jpbc.pairing.PairingFactory;
11 import org.bouncycastle.crypto.AsymmetricCipherKeyPair;
12 import org.bouncycastle.crypto.CipherParameters;
13 import org.bouncycastle.crypto.InvalidCipherTextException;
14
15 import java.util.Arrays;
16
17 import static org.junit.Assert.*;
18
19
20 /**
21  * @author Angelo De Caro (jpbclib@gmail.com)
22  */
23 public class AHIBEDIP10 {
24     public AHIBEDIP10() { }
25
26     public AsymmetricCipherKeyPair setup(int bitLength, int
```

```
    length) {
27      AHIBEDIP10KeyPairGenerator setup = new
    AHIBEDIP10KeyPairGenerator();
28      setup.init(new AHIBEDIP10KeyPairGenerationParameters(
    bitLength, length));
29      return setup.generateKeyPair();
30  }
31
32  public Element[] map(CipherParameters publicKey, String...
    ids) {
33      Pairing pairing = PairingFactory.getPairing(((
    AHIBEDIP10PublicKeyParameters) publicKey).getParameters());
34
35      Element[] elements = new Element[ids.length];
36      for (int i = 0; i < elements.length; i++) {
37          byte[] id = ids[i].getBytes();
38          elements[i] = pairing.getZr().newElementFromHash(id,
     0, id.length);
39      }
40      return elements;
41  }
42
43  public CipherParameters keyGen(AsymmetricCipherKeyPair
    masterKey, Element... ids) {
44      AHIBEDIP10SecretKeyGenerator generator = new
    AHIBEDIP10SecretKeyGenerator();
45      generator.init(new
    AHIBEDIP10SecretKeyGenerationParameters(
46              (AHIBEDIP10MasterSecretKeyParameters) masterKey.
    getPrivate(),
47              (AHIBEDIP10PublicKeyParameters) masterKey.
    getPublic(),
48              ids
49      ));
50      return generator.generateKey();
51  }
52
53  public CipherParameters delegate(AsymmetricCipherKeyPair
    masterKey, CipherParameters secretKey, Element id) {
54      AHIBEDIP10SecretKeyGenerator generator = new
    AHIBEDIP10SecretKeyGenerator();
55      generator.init(new
    AHIBEDIP10DelegateGenerationParameters(
56              (AHIBEDIP10PublicKeyParameters) masterKey.
    getPublic(),
57              (AHIBEDIP10SecretKeyParameters) secretKey,
58              id
59      ));
60      return generator.generateKey();
61  }
62
63  public byte[][] encaps(CipherParameters publicKey, Element
    ... ids) {
64      try {
```

```
65              KeyEncapsulationMechanism kem = new
    AHIBEDIP10KEMEngine();
66              kem.init(true, new AHIBEDIP10EncryptionParameters((
    AHIBEDIP10PublicKeyParameters) publicKey, ids));
67
68              byte[] ciphertext = kem.process();
69
70              assertNotNull(ciphertext);
71              assertNotSame(0, ciphertext.length);
72
73              byte[] key = Arrays.copyOfRange(ciphertext, 0, kem.
    getKeyBlockSize());
74              byte[] ct = Arrays.copyOfRange(ciphertext, kem.
    getKeyBlockSize(), ciphertext.length);
75
76              return new byte[][]{key, ct};
77          } catch (InvalidCipherTextException e) {
78              e.printStackTrace();
79              fail(e.getMessage());
80          }
81          return null;
82      }
83
84      public byte[] decaps(CipherParameters secretKey, byte[]
    cipherText) {
85          try {
86              KeyEncapsulationMechanism kem = new
    AHIBEDIP10KEMEngine();
87
88              kem.init(false, secretKey);
89              byte[] key = kem.processBlock(cipherText);
90
91              assertNotNull(key);
92              assertNotSame(0, key.length);
93
94              return key;
95          } catch (InvalidCipherTextException e) {
96              e.printStackTrace();
97              fail(e.getMessage());
98          }
99          return null;
100     }
101
102     public static void main(String[] args) {
103         AHIBEDIP10 engine = new AHIBEDIP10();
104
105         // Setup
106         AsymmetricCipherKeyPair keyPair = engine.setup(64, 3);
107
108         // KeyGen
109         Element[] ids = engine.map(keyPair.getPublic(), "angelo"
    , "de_caro", "unisa");
110
111         CipherParameters sk0 = engine.keyGen(keyPair, ids[0]);
```

```
112         CipherParameters sk01 = engine.keyGen(keyPair, ids[0],
    ids[1]);
113         CipherParameters sk012 = engine.keyGen(keyPair, ids[0],
    ids[1], ids[2]);
114 
115         CipherParameters sk1 = engine.keyGen(keyPair, ids[1]);
116         CipherParameters sk10 = engine.keyGen(keyPair, ids[1],
    ids[0]);
117         CipherParameters sk021 = engine.keyGen(keyPair, ids[0],
    ids[2], ids[1]);
118 
119         // Encryption/Decryption
120         byte[][][] ciphertext0 = engine.encaps(keyPair.getPublic()
    , ids[0]);
121         byte[][][] ciphertext01 = engine.encaps(keyPair.getPublic
    (), ids[0], ids[1]);
122         byte[][][] ciphertext012 = engine.encaps(keyPair.getPublic
    (), ids[0], ids[1], ids[2]);
123 
124         // Decrypt
125         assertEquals(true, Arrays.equals(ciphertext0[0], engine.
    decaps(sk0, ciphertext0[1])));
126         assertEquals(true, Arrays.equals(ciphertext01[0], engine
    .decaps(sk01, ciphertext01[1])));
127         assertEquals(true, Arrays.equals(ciphertext012[0],
    engine.decaps(sk012, ciphertext012[1])));
128 
129         assertEquals(false, Arrays.equals(ciphertext0[0], engine
    .decaps(sk1, ciphertext0[1])));
130         assertEquals(false, Arrays.equals(ciphertext01[0],
    engine.decaps(sk10, ciphertext01[1])));
131         assertEquals(false, Arrays.equals(ciphertext012[0],
    engine.decaps(sk021, ciphertext012[1])));
132 
133         // Delegate/Decrypt
134         assertEquals(true, Arrays.equals(ciphertext01[0], engine
    .decaps(engine.delegate(keyPair, sk0, ids[1]), ciphertext01
    [1])));
135         assertEquals(true, Arrays.equals(ciphertext012[0],
    engine.decaps(engine.delegate(keyPair, sk01, ids[2]),
    ciphertext012[1])));
136         assertEquals(true, Arrays.equals(ciphertext012[0],
    engine.decaps(engine.delegate(keyPair, engine.delegate(
    keyPair, sk0, ids[1]), ids[2]), ciphertext012[1])));
137 
138         assertEquals(false, Arrays.equals(ciphertext01[0],
    engine.decaps(engine.delegate(keyPair, sk0, ids[0]),
    ciphertext01[1])));
139         assertEquals(false, Arrays.equals(ciphertext012[0],
    engine.decaps(engine.delegate(keyPair, sk01, ids[1]),
    ciphertext012[1])));
140         assertEquals(false, Arrays.equals(ciphertext012[0],
    engine.decaps(engine.delegate(keyPair, engine.delegate(
    keyPair, sk0, ids[2]), ids[1]), ciphertext012[1])));
```

```
141     }
142 }
```

This class shows which methods are called when encrypting and decrypting.

Listing B.2: PairingKeyEncapsulationMechanism.class

```
1  package it.unisa.dia.gas.crypto.jpbc.kem;
2
3  import it.unisa.dia.gas.crypto.jpbc.cipher.
       PairingAsymmetricBlockCipher;
4  import it.unisa.dia.gas.crypto.kem.KeyEncapsulationMechanism;
5  import org.bouncycastle.crypto.InvalidCipherTextException;
6
7  /**
8   * @author Angelo De Caro (jpbclib@gmail.com)
9   */
10 public abstract class PairingKeyEncapsulationMechanism extends
       PairingAsymmetricBlockCipher implements
       KeyEncapsulationMechanism {
11     private static byte[] EMPTY = new byte[0];
12     protected int keyBytes = 0;
13
14     public int getKeyBlockSize() {
15         return keyBytes;
16     }
17
18     public int getInputBlockSize() {
19         if (forEncryption)
20             return 0;
21
22         return outBytes - keyBytes;
23     }
24
25     public int getOutputBlockSize() {
26         if (forEncryption)
27             return outBytes;
28
29         return keyBytes;
30     }
31
32     public byte[] processBlock(byte[] in) throws
       InvalidCipherTextException {
33         return processBlock(in, in.length, 0);
34     }
35
36     public byte[] process() throws InvalidCipherTextException {
37         return processBlock(EMPTY, 0, 0);
38     }
39 }
```

Listing B.3: Excerpt from PairingAsymmetricBlockCipher class

```
1  package it.unisa.dia.gas.crypto.jpbc.cipher;
```

```
2
3  import it.unisa.dia.gas.jpbc.Pairing;
4  import org.bouncycastle.crypto.AsymmetricBlockCipher;
5  import org.bouncycastle.crypto.CipherParameters;
6  import org.bouncycastle.crypto.DataLengthException;
7  import org.bouncycastle.crypto.InvalidCipherTextException;
8  import org.bouncycastle.crypto.params.ParametersWithRandom;
9
10 /**
11  * @author Angelo De Caro (jpbclib@gmail.com)
12  */
13 public abstract class PairingAsymmetricBlockCipher implements
       AsymmetricBlockCipher {
14     protected CipherParameters key;
15     protected boolean forEncryption;
16
17     protected int inBytes = 0;
18     protected int outBytes = 0;
19
20     protected Pairing pairing;
21
22     /**
23      * Return the maximum size for an input block to this engine
       .
24      *
25      * @return maximum size for an input block.
26      */
27     public int getInputBlockSize() {
28         if (forEncryption) {
29             return inBytes;
30         }
31
32         return outBytes;
33     }
34
35     /**
36      * Return the maximum size for an output block to this
       engine.
37      *
38      * @return maximum size for an output block.
39      */
40     public int getOutputBlockSize() {
41         if (forEncryption) {
42             return outBytes;
43         }
44
45         return inBytes;
46     }
47
48     /**
49      * initialise the cipher engine.
50      *
51      * @param forEncryption true if we are encrypting, false
       otherwise.
```

```
52      * @param param         the necessary cipher key parameters.
53      */
54     public void init(boolean forEncryption, CipherParameters
    param) {
55         if (param instanceof ParametersWithRandom) {
56             ParametersWithRandom p = (ParametersWithRandom)
    param;
57 
58             this.key = p.getParameters();
59         } else {
60             this.key = param;
61         }
62 
63         this.forEncryption = forEncryption;
64         initialize();
65     }
66 
67     /**
68      * Process a single block using the basic cipher algorithm.
69      *
70      * @param in    the input array.
71      * @param inOff the offset into the input buffer where the
    data starts.
72      * @param inLen the length of the data to be processed.
73      * @return the result of the cipher process.
74      * @throws org.bouncycastle.crypto.DataLengthException the
    input block is too large.
75      */
76     public byte[] processBlock(byte[] in, int inOff, int inLen)
    throws InvalidCipherTextException {
77         if (key == null)
78             throw new IllegalStateException("Engine not
    initialized");
79 
80         int maxLength = getInputBlockSize();
81 
82         if (inLen < maxLength) {
83             System.out.println("inLen: " +inLen + "; maxLength:
    " + maxLength);
84             throw new DataLengthException("Input too small for
    the cipher.");
85         }
86         return process(in, inOff, inLen);
87     }
88 
89     public abstract void initialize();
90     public abstract byte[] process(byte[] in, int inOff, int
    inLen) throws InvalidCipherTextException;
91 }
```

Appendix C

GCM Encryption Example

```
1  private static final String bouncyCastleProviderName = org.
       bouncycastle.jce.provider.BouncyCastleProvider.PROVIDER_NAME;
2
3  private static String symmKeyGenAlg = "AES";
4  private static int AES_KEY_SIZE = 256;
5  private static String gcmEncrAlg = "AES/GCM/NoPadding";
6  private static int GCM_NONCE_LENGTH = 12; // in bytes
7  private static int GCM_TAG_LENGTH = 16; // in bytes
8
9  private final static String TAG = CryptoUtils.class.
       getSimpleName();
10
11 public static byte[] generateSymmetricRandomKey() {
12     KeyGenerator keyGen = null;
13     try {
14         keyGen = KeyGenerator.getInstance(symmKeyGenAlg);
15     } catch (NoSuchAlgorithmException e) {
16         e.printStackTrace();
17         Log.d(TAG, "Error in generating the symmetric random key
       : " + e.getMessage());
18     }
19     keyGen.init(AES_KEY_SIZE);
20     SecretKey secretKey = keyGen.generateKey();
21     return secretKey.getEncoded();
22 }
23
24 @RequiresApi(api = Build.VERSION_CODES.KITKAT)
25 public static GCMParameterSpec getGCMParameterSpec() {
26     byte[] nonce = new byte[GCM_NONCE_LENGTH];
27     secureRandom.nextBytes(nonce);
28     GCMParameterSpec spec = new GCMParameterSpec(GCM_TAG_LENGTH
       * 8, nonce);
29     return spec;
30 }
31
32 @TargetApi(Build.VERSION_CODES.KITKAT)
33 @RequiresApi(api = Build.VERSION_CODES.KITKAT)
```

```
34 public static byte[] processGCM (int mode, byte[] encodedSymmKey
       , AlgorithmParameterSpec spec, byte[] aad, byte[]
       originalText) {
35     SecretKeySpec skeySpec = new SecretKeySpec(encodedSymmKey,
       gcmEncrAlg);
36     Cipher cipher = null;
37     try {
38         cipher = Cipher.getInstance(gcmEncrAlg,
       bouncyCastleProviderName);
39     } catch (NoSuchAlgorithmException | NoSuchProviderException
       | NoSuchPaddingException e) {
40         e.printStackTrace();
41         Log.d(TAG, "Error in symmetric GCM encryption: " + e.
       getMessage());
42         throw new SecurityException(e.getMessage());
43     }
44     try {
45         cipher.init(mode, skeySpec, spec);
46     } catch (InvalidKeyException |
       InvalidAlgorithmParameterException e) {
47         e.printStackTrace();
48         Log.d(TAG, "Error in symmetric GCM encryption: " + e.
       getMessage());
49         throw new SecurityException(e.getMessage());
50     }
51     cipher.updateAAD(aad);
52     byte[] cipherText = new byte[0];
53     try {
54         cipherText = cipher.doFinal(originalText);
55     } catch (IllegalBlockSizeException | BadPaddingException e)
       {
56         e.printStackTrace();
57         Log.d(TAG, "Error in symmetric GCM encryption: " + e.
       getMessage());
58         throw new SecurityException(e.getMessage());
59     }
60     return cipherText;
61 }
```

Appendix D

Android Profiler Graphs

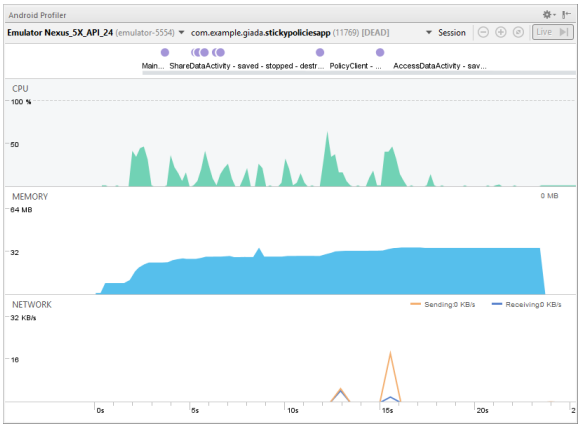

Figure D.1: StickyPoliciesApp test with 101 words processing.

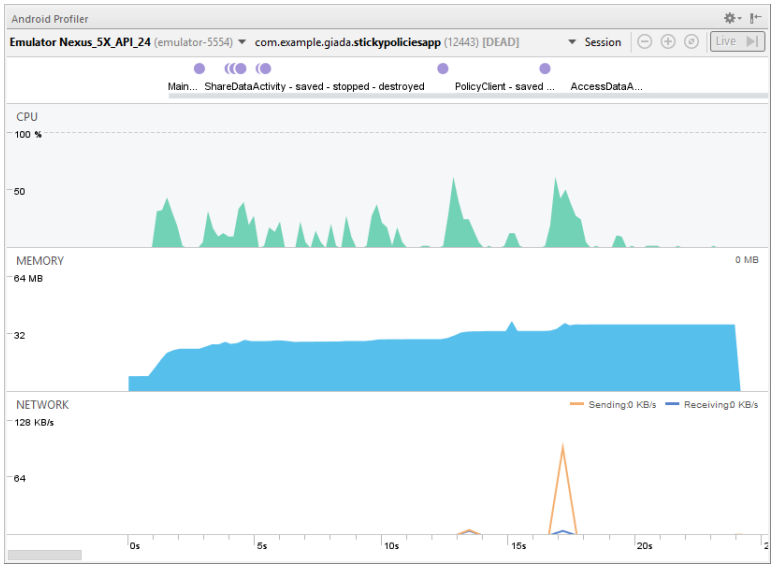

Figure D.2: StickyPoliciesApp test with 1000 words processing.