An empirical study of the power consumption of cryptographic primitives in Android

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May 11, 2017

Abstract

Green computing has become a growing trend in computing, pursuing the goal of helping software developers to pay more attention to produce energy-efficient software. This is specially relevant for battery-powered mobile applications, where minimizing the energy-consumption is required to both mitigate the greenhouse effect and to extend the battery lifetime. In this paper we analyze the energy-consumption of cryptographic primitives in Android devices. Our ultimate goal is to help Android application developers, especially those who are not experts on security, to choose the most energy efficient cryptographic algorithms considering different security providers and different security transformations. We have performed our experiments using an energy profiling tool based on the PowerTutor application. Our results show that this type of energy efficiency studies are necessary, because selecting the most energy efficient configuration depends on many factors, and some of the conclusions are not so obvious.

1 Introduction

The percentage of global emissions attributable to Information Systems is expected to further increase in the coming years, due to a proliferation of Internet-connected mobile appliances (e.g., mobile phones or tablets). As a result, the development of applications for battery-powered mobile appliances should consider of highest priority to minimize the energy consumption to both mitigate the greenhouse effect and extend the battery lifetime. However, developers are not always aware of the energy consumed by their software solutions \cite{21,23}. Trying to face this issue, Energy-aware software development (or Green Computing \cite{17}) has become a growing trend in computing, pursuing the goal of helping software developers to pay more attention to the energy-efficiency of software \cite{11,15,3}.
People use mobile devices mostly to send and receive more or less private information, making security an important concern in the development of mobile applications. Cryptographic algorithms are used to provide authentication, confidentiality and integrity, providing different security levels. Traditionally, the implementation of cryptographic primitives requires significant energy to process data, and some recent studies show that this is also true for mobile phones [7, 19]. Therefore, software developers should be aware of the power consumption impact of using cryptographic algorithms in their applications. Recently, several experimental studies have been conducted to investigate the energy consumption of concrete implementations of cryptographic algorithms and security protocols for different devices [7, 20, 24, 28]. But they focus on other aspects of security (e.g., communication) or try to answer different questions. In many cases, the main goal of these studies is to compare the power consumption of different cryptographic primitives of a single implementation (i.e., a concrete security provider or API), neglecting the point of view of the developer that may be interested in exploring the use of alternative cryptographic providers. Indeed, these studies do not cover all the variability of security alternatives from different viewpoints — i.e., different cipher modes and padding, concrete default configurations for each provider and different security level, remaining still many open research questions.

In this paper we will focus on studying the energy consumption of cryptographic primitives from the point of view of the application developer. We have focused this study for Android devices, the most popular operating system of mobile devices in recent years. So, our goal is to help Android application developers to choose the most energy efficient cryptographic algorithms considering different implementation libraries (i.e., cryptographic providers). The target audience of the experimental study presented in this paper is a software developer not expert in security issues, specifically with poor knowledge of crypto algorithms’ internals and that is interested in knowing the energy consumed by different security providers.

We have performed our experiments for three different providers (i.e., IAIK, BC and SC) and the most used cryptographic algorithms with different combinations of key size, mode and padding. In this paper we will provide empirical evidence for answering specific questions that developers concerned of power consumption should ask. Considering Android devices and different crypto providers, our research questions try to give a recommendation about using one or another crypto provider to the developers, or to explore the relationship between security and energy consumption. In addition, considering software developers tend to use the default security transformation offered by providers (i.e., the default configurations), we have measured the energy consumption of these transformations to see the cost in terms of energy power of incrementing the security in each crypto provider.
We have performed our experiments using an energy profiling tool that is based on the PowerTutor \cite{32} application. We decided to use a software tool since they allow finer-grained measurements and also because the experiments can be reproduced, which with hardware solutions is not always possible. PowerTutor has been adapted to automate the profiling procedure, but without modifying the energy model procedures. The application uses a theoretical energy model built for the phone models HTC G1, HTC G2 and Nexus one. Two different mobile phones have been used in the experiments to validate the results, but for simplicity we will only show the data obtained with the Nexus one. Notice that this application, as well as many other profiling mechanisms \cite{2,13,16,18,31,32}, provides an estimation of the power consumption. However, this is not a limitation because for our study the exact amount of Jules that are consumed by a concrete configuration is not relevant. Instead, we are interesting on establishing comparisons between the energy consumed by the different configurations.

After this introduction the paper is organized as follows. Section 2 describes our experimental setup, discussing first the high variability of cryptographic providers, primitives and configuration parameters and then selecting the ones considered in our study. Then, the energy profiling tool used to perform our experiments is described in Section 3. The experimental results are presented and analyzed in Section 4, and the thread to validity in Section 5. Finally, Section 6 presents the related work and Section 7 the conclusions and future work.

## 2 Related Work

Energy consumption has become a central issue of mobile applications. Applications providing similar services can have different energy consumption and both software developers and mobile users need to be aware of these differences. The number of papers that focuses on the generation of energy profiles of different characteristics of mobile applications has increased in the last years considerably, being some of them \cite{30,27,33,8,22,6,19,20,24,28,7}. Although many proposals of these proposals \cite{30,27,33,8,22,6,19} are for the Android platform, not much attention has been paid yet to the energy consumption of Android cryptographic primitives.

Thus, in this section we focus on those proposals that generate energy profiles for cryptographic primitives, which are the ones closer to our approach. As said, many of these proposals are interested on generating energy profiles for mobile applications \cite{7,20,24,28}, but do not focus on the Android operating system. All of them calculate and compare the energy consumption of different cryptographic primitives, varying different parameters, such as the key sizes and the analyzed operations. In some works the ultimate goal goes beyond the mere comparison of energy consumptions.
For instance, the work in [7] focuses on the use of encryption in secure communications and the work in [24] analyzes the consumption of cryptographic primitives in the context of the SSL protocol. However, only the work in [7] takes into consideration that the algorithms can work on different modes (e.g., ECB, CBC, CFB, OFB, CTR and CCM). The rest of the proposals do not give any information about the mode they are using. Moreover, none of them consider different paddings or different security providers and they do not indicate the ones they are using in their experiments. The default modes selected by the providers are neither considered. Since the provider, the mode and the padding can influence the security level it is impossible to really know the security level that these proposals are analyzing. Moreover, since the provider, the mode and the padding that are used in the experiments are unknown, the experiments cannot be reproduced and the results of different proposals are not comparable among them. The main differences between these approaches and our work is that our analysis takes into consideration all the parameters that may influence energy consumption of cryptographic primitives—i.e., different crypto providers, different algorithms and operations, different modes and different paddings. Concretely, we focus on those transformations (algorithm/mode/padding) that are the default ones selected by the providers and in those that are the recommended ones by security standards.

An approach with similar goals than ours, but focusing on performance evaluation instead of energy-consumption evaluation, is [14]. In this paper authors consider different cryptographic providers for Android, including the ones considered in our study, and evaluate the performance of different algorithms taking into consideration not only the key length and the different primitives, but also the mode and the padding selected in the transformations. In our study, we have taken the algorithms’ requirements for developing secure applications from this paper, since they were recopilated based on the information available in the different security standards.

3 Experimental setup

In this section we describe the variables that are taken into consideration in our experimental study. Firstly, we describe the selected cryptographic providers. Then, the available Android cryptography primitives are described, and the reasons for selecting the ones used in our study are provided. Finally, the default modes used by each provider are detailed.

3.1 Cryptographic providers

The Java Cryptography Extension (JCE) [29] is an API that provides a uniform framework for the implementation of security features. There are different Cryptographic Service Providers that supply concrete implementations
of a subset of the cryptographic services. Three cryptographic providers for JCE have been taken into consideration in this paper, BouncyCastle (BC), SpongyCastle (SC), and IAIK.

BouncyCastle is an independent cryptographic provider that can be executed in any Java platform. Android has included a reduced and adapted version of the BouncyCastle library in the system, therefore Android users have access to cryptographic primitives without installing any additional library. SpongyCastle is also an adaptation of the original BouncyCastle library for the Android platform. SpongyCastle is not Android distribution dependent and includes the implementation of most known cryptographic primitives. At first sight, SpongyCastle and BouncyCastle include the implementation of the same algorithms, but they were adapted by different providers. Therefore, by analyzing and comparing the power consumption between BouncyCastle and SpongyCastle primitives it will be possible to verify if the modifications of BouncyCastle performed by Android provider have a positive or negative influence in the power consumption.

IAIK is a library deployed in the Graz University of Technology. IAIK is a well known cryptographic provider, and although the source code it is not available, it has an educational license. IAIK has been optimized for speed and memory consumption and thus has been included in our study to verify if it is greener comparing to other providers. Other libraries have been considered during the application design phase, as for example FlexiCore (FC). FlexiCore is an open source library deployed by Technische Universität Darmstadt, but we have discarded it due to the limited number of cryptographic primitives supported, the differences on the primitives nomenclatures and because it is not possible to use with FlexiCore the keys generated with other providers. These reasons make difficult to execute all the test with the same keys, which is one of the settings of our experiments.

The versions of each provider have been chosen based on its availability in the Android platform and the Android API level of the devices used in the evaluation, and are: IAIK Version 5.3, BC Version 1.45 and SC Version 1.54.

3.2 Android Cryptography Primitives

Android documentation classifies the cryptographic primitives into three categories: MAC (Message Authentication Code), Cipher and Sign.

A MAC algorithm is a symmetric key cryptographic technique to provide integrity and message authentication –i.e. to identify the originator of a message. Both the sender and the receiver share a symmetric key. Table 1

\[\text{https://www.bouncycastle.org/}\]
\[\text{https://rtyley.github.io/spongycastle/}\]
\[\text{http://jcewww.iaik.tu-graz.ac.at/}\]
\[\text{https://www.flexiprovider.de/}\]
details the MAC algorithms available in Android.

| Name                  | Supported (API Levels) |
|-----------------------|------------------------|
| HmacMD5               | 1+                     |
| HmacSHA1              | 1+                     |
| HmacSHA224            | 1–8, 22+               |
| HmacSHA256            | 1+                     |
| HmacSHA384            | 1+                     |
| HmacSHA512            | 1+                     |
| PBEwithHmacSHA        | 1+                     |
| PBEwithHmacSHA1       | 1+                     |

A Cipher algorithm is used to encrypt and decrypt information. A distinction is made between symmetric key encryption algorithms, where the same keys are used for encrypting and decrypting the information; and asymmetric key encryption algorithms, where different keys are used. In addition, cipher algorithms support different modes and padding. Ciphers process data blocks of fixed size. However, the size of messages is usually larger than the block size. Hence, the message has to be divided into a series of sequential message blocks. The cipher mode determines the way in which the cipher operates on these blocks and has a significant influence on the security level provided by the algorithm. The padding is a technique to add bits to the message in order to change its length, either to obtain a fixed length required by the algorithms, or to prevent length extension attacks. Table 2 details Cipher algorithms available in Android, including the modes and padding supported by them.

A Sign algorithm is used to create digital signatures so that a person or entity can be bound to the digital data. The receiver can then verify the authenticity of the signature. The digital signature scheme is based on public key cryptography, using a public-private key pair. Table 3 details Sign algorithms available in Android.

### 3.3 Cryptography Primitives Selected

Initially, the primitives to be evaluated were the Android cryptographic primitives listed in section 3.2. However, the PowerTutor application requires the use of specific smartphones models; in our case, the phones selected are HTC G1 and Nexus one. The Android API level 10 is the maximum API level in these smartphones. Therefore, only the primitives available in the API level 10 can be used.

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5. [https://developer.android.com/reference/javax/crypto/Mac.html](https://developer.android.com/reference/javax/crypto/Mac.html)
6. [https://developer.android.com/reference/javax/crypto/Cipher.html](https://developer.android.com/reference/javax/crypto/Cipher.html)
7. [https://developer.android.com/reference/java/security/Signature.html](https://developer.android.com/reference/java/security/Signature.html)
Table 2: Cipher Algorithms available in Android

| Cipher                          | Mode | Padding                  | API Level |
|---------------------------------|------|--------------------------|-----------|
| AES                             | CBC  | ISO10126Padding          | 1+        |
| BLOWFISH                        | CFB  | NoPadding                | 10+       |
| DES                             | CTR  | PKCS5Padding             | 1+        |
| DESede                          | CTS  |                          | 1+        |
| PBEwithMD5andDES                | ECB  |                          | 1+        |
| PBEwithSHA1andDESede            | OFB  |                          | 1+        |
| RC4                             | ECB  | NoPadding                | 10+       |
| RSA                             | ECB  | OAEPPadding              | 1+        |
|                                  | None | OAEPwithSHA-1            | 10+       |
|                                  |      | MGF1Padding              |           |
|                                  |      | OAEPwithSHA-256          | 10+       |
|                                  |      | MGF1Padding              |           |
|                                  |      | PKCS1Padding             | 1+        |

Moreover, due to the large variability of cryptographic primitives we have narrowed the primitives selected to those that will allow software developers to maximize the security levels of their applications, according to the information provided by security experts and security standards [12, 11, 10, 4].

Defaults configurations used by the cryptographic providers are also considered. In the case of MAC primitives (table 1), the primitive HmacSHA224 cannot be used for the BouncyCastle provider.

Table 3: Sign Algorithms available in Android

| Algorithm | Hash | API Levels |
|-----------|------|------------|
| DSA       | NONE | 1+         |
|           | SHA1 | 1+         |
| DSS       | NONE | 1–19       |
| ECDSA     | NONE | 11+        |
|           | SHA1 | 11+        |
|           | SHA256 | 11+       |
|           | SHA384 | 11+      |
|           | SHA512 | 11+      |
| RSA       | NONE | 17+        |
|           | MD5  | 1+         |
|           | SHA1 | 1+         |
|           | SHA256 | 1+       |
|           | SHA384 | 1+       |
|           | SHA512 | 1+      |
The National Institute of Standards and Technology (NIST) approved two block cipher algorithms from the cipher primitives in table 2, therefore only the AES and the DESede algorithms are included. In the case of digital signatures NIST approved three algorithms RSA, DSA and ECDSA. According to table 3, ECDSA is not available in API 10, therefore only the RSA and the DSA algorithms are the ones selected in the case of the sign primitive. For generating and verifying message/data authentication codes there is an unique algorithm HMAC. This algorithm is based on the cryptographic hash function [12], and in this case, NIST approved the following secure hash algorithms to be included in the Android platform: SHA-1, SHA-224, SHA-256, SHA-384, and SHA-512. Although MD5 is no longer recommended by NIST, we consider it since it is still widely used.

The key configuration for each primitive are: AES 128, 192, 256 bit keys and DESede 112, 168 Keys. In the case of asymmetric primitives the configuration is RSA 512, 1024 and 2048 bit length keys, and DSA 1024 and 2048 bits, although BC do not have support to 2048 bits length. Finally, MAC keys depend on the selected providers. IAIK provider generates the following key length HmacMD5 512 bits, HmacSHA1 512 bits, HmacSHA224 512 bits, HmacSHA256 512 bits, HmacSHA384 1024 bits, HmacSHA512 1024 bits. Whereas BC and SC providers by default generates the following key length HmacMD5 128 bits, HmacSHA1 160 bits, HmacSHA224 224 bits, HmacSHA256 256 bits, HmacSHA384 384 bits, HmacSHA512 512 bits.

Summarizing, ten primitives have been selected for evaluation of three providers in two smartphones with different hardware configuration as described in table 4.

|                      | HTC G1                      | Nexus One                   |
|----------------------|-----------------------------|-----------------------------|
| OS                   | Android OS, v2.3.4 (Gingerbread) | Android OS, v2.3.6 (Gingerbread) |
| Chipset              | Qualcomm MSM7201A           | Qualcomm QSD8250 Snapdragon S1 |
| CPU                  | 528 MHz ARM 11              | 1.0 GHz Scorpion            |
| Memory               | 192 MB RAM                  | 512 MB RAM                  |
| Battery              | Removable Li-Ion 1150 mAh   | Removable Li-Ion 1400 mAh   |

3.4 Default modes

When the JCE API is used, java programmers must choose a correct transformation for each primitive. First, the programmer selects a cipher prim-

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Footnotes:

[8] http://csrc.nist.gov/groups/ST/toolkit/block_ciphers.html
[9] http://csrc.nist.gov/groups/ST/toolkit/digital_signatures.html
[10] http://csrc.nist.gov/groups/ST/toolkit/message_auth.html
[11] http://csrc.nist.gov/groups/ST/toolkit/secure_hashing.html
[12] BC provider does not support this option in API level 10.
[13] Experimental data have been obtained for both mobiles, but only the data generated with the Nexus One was included due to space reasons.
itive, i.e., the AES primitive. Then, according to the information shown in table 2, the programmer selects one mode operation and one padding option. The triplet algorithm/mode/padding will define the transformation selected. For instance, if a programmer wants to cipher with the AES cipher in CBC mode and PKCS5Padding, this is done with the following Java code:

```java
Cipher c = Cipher.getInstance("AES/CBC/PKCS5Padding");
```

Software developers who are not experts in security can easily get to know about the cryptographic primitives available – i.e. the AES algorithm to cipher, but probably they may have poor knowledge about the mode and padding variables. Moreover, due to the large number of possibilities to be chosen (see table 2) and the difficulty to know which ones are the most secure, in many cases they just omit these variables and instantiate the algorithms with the default values, which are selected by the providers. This is possible because the JCE API allows the programmers to get a default transformation for the selected algorithm with the following Java code:

```java
Cipher c = Cipher.getInstance("AES");
```

The default configurations for the cryptographic primitives selected in our study are shown in tables 5 and 6. However, these default configurations are not necessarily the most secure ones, and this is because we are interested in considering these default configurations in our experimental study. On the one hand, we want to measure the energy consumed by the default configurations used by most non-expert software developers to see if they are making a good decision from the point of view of energy consumption. Moreover, we want also to analyze if it is possible to use other transformations that provide a higher level of security without incurring in a large increment of energy consumption. Notice that it was not straightforward for us to know which were the default modes for each provider. We had to extract this information from the data obtained in our experimental results. This means that software developers that decide to use the default modes do not really know the values that they are using for the mode and padding variables.

Although BC has NONEwithRSA as the default transformation, Android API 10 does not support this transformation, therefore the developer gets an exception `Signature RSA implementation not found`. In this case the developer must detail the transformation or otherwise the information cannot be signed.

In [9] authors analyzed 11748 applications available in Google Play. In 5656 of these applications, developers only specified the cipher algorithm to perform encrypt or decrypt operations omitting the mode and the padding.
Table 5: IAIK default modes

| Cipher | Key Size | Transformation               |
|--------|----------|------------------------------|
| AES    | 128 bits | AES/ECB/PKCS5Padding         |
| DESede | 168 bits | DESede/ECB/PKCS5Padding      |
| RSA    | 1024 bits| RSA/ECB/PKCS1Padding         |
| Sign   | 1024 bits| NONEwithRSA                  |

Table 6: BC & SC default modes

| Cipher | Key Size | Transformation               |
|--------|----------|------------------------------|
| AES    | 192 bits | AES/ECB/PKCS5Padding         |
| DESede | 168 bits | DESede/ECB/PKCS1Padding      |
| RSA    | 2048 bits| RSA/NONE/NoPadding           |
| Sign   | 2048 bits| NONEwithRSA                  |
| DSA    | 1024 bits| –                            |

In consequence, Java determines the default transformation —i.e., the ECB transformation, which it is not considered secure. Therefore, 50% of analyzed applications had a low security level because developers are not aware of the default transformation configurations or have a lack of knowledge of security transformations.

4 Energy profiling tool

Several proposals exist to estimate the energy consumption of mobile applications in Android [2, 13, 16, 18, 31, 32]. As stated in [1], their main differences are on whether they are hardware or software-based and on the measurement granularity (application, process, thread, method). Many of them [2, 13, 32] are based on the definition of a power model based on direct measurements in specific devices. These models generally provide quite precise estimations, although they are built only for a few devices. Others [25] use the power information provided by some mobile processor and thus work for all devices with that processor. Since our analysis bases on the comparison of the energy consumption of different combinations of provider/algorithm/mode/padding, and thus we are not interested on the absolute consumption values, our approach should provide similar results with any of these tools.

We initially considered the use of the TrephProfiler [25] application, because power profiling is available for all devices with a Qualcomm Snapdragon processor. However, energy profiling at the method level does not
work properly in TrephProfiler for short duration methods, as is our case. Thus, we search for a profiling tool where method-level profiling was possible and we found that PowerTutor was a good option for our experimental study. Thus, our energy profiling tool is based on the PowerTutor project, described on [32]. Basically, PowerTutor is an Android application to profile energy consumption based on the CPU, network interface, display, and GPS elements. The application uses a theoretical energy model built exclusively for three phone models: HTC G1, HTC G2 and Nexus one.

The original PowerTutor application was designed to visualize the consumption information, but it requires the interaction with the user to store the information into a log file. Thus, the application is very useful to measure the power information of our cryptographic primitives, but it was not an easy task to automate the profiling procedure. In order to automate the procedure, several changes had to be included into the application, without any modification to the energy model procedures.

The profiling platform designed to collect consumption information in our experimental study is shown in Figure 1. Firstly, we modify the PowerTutor application to include into the application an Android mechanism for automatically collecting the energy consumption information (BroadcastReceiver). Moreover, a Crypto application has been deployed with all cryptographic primitives detailed in section 3.3. The goal of this application is to execute the cryptographic primitives, as is shown in Figure 1. The primitive to be evaluated will be between two commands that activate and deactivate the profiling service of the PowerTutor application. The activation process sends a string that represents the cryptographic primitive to be evaluated. The string will be the name of the log file that will be stored automatically when the profiling service is deactivate. In this way, the Powertutor application is used without the user interaction and the evaluation can be automatized. The generated logs are then processed in a desktop computer in order to provide the information in a format that can then be analyzed by software developers.

The first execution of the application generates a bundle of keys necessary for cryptographic primitives, to perform the cipher/decipher and sign/verify operations. The goal of key generation and store is twofold; all the operation will be done, evaluated and compared with the same keys and we save a substantially time of key generation in each execution. The operations available in each cipher primitive are Encryption, Decryption and Key Generation. In the case of sign primitives, the operations available for evaluation are Sign, Verify, and Key Generation. Finally, in HMAC primitives we consider MAC, and Key Generation. The ciphered and signed messages are also stored so that the decipher and verify operations can be executed with the same values for all the providers.

\[\text{http://ziyang.eecs.umich.edu/projects/powertutor/documentation.html}\]
5 Experimental results

In this section we will present the experimental planning and the energy profile results. The measurement unit used in our experiments along the paper is milliwatts (mw).

5.1 Objectives and research questions

The methodology of this study is defined according to the goal-question-metrics approach [5] as follows: "Analyze crypto primitives offered by three different security providers for Android, from the point of view of software developers". To achieve this goal we set the following research questions (RQs):

**RQ1. Which crypto provider is the most energy efficient for different operations of crypto primitives?** This question aims at studying whether the power consumption of crypto primitives implemented by alternative providers is significantly different. This information is crucial to make more informed decisions when selecting crypto providers to develop secure
software considering energy efficiency.

RQ2. What is the cost of increasing the security level in terms of power consumption? This question explores the influence of key length in the power consumption of alternative implementations of the cryptographic algorithms.

RQ3. Which transformation, comparing the default and the recommended transformations, is the most energy efficient for different crypto providers in Android? Programmers non expert in security will normally select the default transformation. Thus, RQ3 explores the relationships between security and power consumption by calculating the amount of energy required when we replace the default transformation by a more secure one.

We will answer to these questions for cryptographic algorithms that are considered by security standards as the most secure ones. They implement confidentiality, authentication and integrity properties. Programmers will require one or many of them in their developments. Moreover, each cryptographic algorithm provides a set of methods that developers will invoke more or less frequently. The available methods for confidentiality are key generation, encrypt and decrypt. The methods implemented by authentication algorithms are key generation, sign, sign with hash, verify and verify with hash. For data integrity we only have the HMAC operation. In order to answer RQ1 the power consumption for each cryptographic operation (i.e., encrypt, decrypt, etc.) will be calculated separately. As shown in table 2 block cipher algorithms offer six modes of operation, although only three of them are considered secure or recommended modes: CBC, CFB and OFB [26]. Afterwards, these three modes are compared to the default mode to answer RQ3. The specific padding used for each of the tested transformation is also indicated.

5.2 Confidentiality energy profiles

The algorithms analyzed for confidentiality are AES, DESede and RSA. The energy profiles of the key generation operation for these algorithms are shown in table 7 for symmetric algorithms and the upper part of table 8 for the asymmetric one. The information of the encrypt/decrypt operations for the same algorithms are shown in table 9 for the AES algorithm, table 10 for the DESede algorithm and table 11 for the RSA algorithm. In tables 9, 10 and 11 the upper part shows the energy consumption for the default transformations and the lower part shows the energy consumption for the transformation recommended by security standards. The answers to our research questions are as follows.

RQ1. Which crypto provider is the most energy efficient for different operations of crypto primitives?
• **Key generation (tables 7 and 8).** For the AES and DESede algorithms the energy expenditure of the three providers is quite similar, and very low. However, there is not a provider that is the greenest one for any key length. The energy profile of the RSA algorithm is completely different. The key generation for large primes performed by the RSA algorithm is time consuming and resource intensive, what has a high impact on the energy initially consumed by the application. For this reason, this is the most energy consuming algorithm for this operation. As shown in the table, the BC provider is the most energy efficient, being the consumption similar to the SC one. On the other hand, the IAIK provider almost quadruples the consumption of other suppliers in recommended key length (2048).

• **Encrypt/Decrypt (tables 9, 10 and 11).** In the default mode of AES (table 9), IAIK has the lowest consumption in the encryption operation, whereas BC and SC have similar consumption. Furthermore, in the case of the decryption operation BC shows the lowest consumption in the default mode, and IAIK has the higher consumption. The result data shows a curious information among providers when change from encryption to decryption. IAIK consumes 3 times more in the decryption operation than in the encryption operation, whereas BC and SC maintain similar consumptions. Focusing on the default mode of DESede (table 10), and selecting the encryption operation, SC is the cleanest provider, although if the decryption operation is selected IAIK is the cleanest one. It is interesting to note that, for some keys in the SC provider the energy consumption of the decryption operation doubles the consumption of encryption. For the RSA algorithm (table 11), the encryption and decryption operations consume much less than the key generation for all providers. But, the winner will depend on the operation, being the SC for encryption and IAIK and SC for decryption, which consume more or less the same for any key length.

**Answer to RQ1:** The experimental data indicates that it is not possible to choose “the greenest provider”. Thus, software developers need to perform a fine-grained analysis of the security level required by the application and of the operations that will be more frequently executed in order to choose the greenest provider to their specific necessities. Moreover, the data indicates that the external providers consume less energy than the Android security library, confirming our hypothesis that it is interesting to explore different security providers.
**Key recommendation:** Applications that encrypt files frequently (e.g., to store them in a repository), but they do not need to decrypt them very frequently they can use either BC or SC, with the default transformation (the security is the recommended one). But if the functionality of the application requires to cipher some data that will be frequently consulted, then the greenest and most secure option is to use SC.

| AES Key Generation |
|--------------------|
| Key Length | IAIK | BC | SC |
| 128 | 0,14 | 0,13 | 0,14 |
| 192 | 0,17 | 0,13 | 0,10 |
| 256 | 0,23 | 0,29 | 0,17 |

| DESede Key Generation |
|------------------------|
| Key Length | IAIK | BC | SC |
| 112 | 0,11 | 0,17 | 0,27 |
| 168 | 0,29 | 0,30 | 0,13 |

| RSA Key Generation |
|--------------------|
| Key Length | IAIK | BC | SC |
| 512 | 110,74 | 42,72 | 63 |
| 1024 | 1099,83 | 341,25 | 396,53 |
| 2048 | 9343,71 | 2425,94 | 2488,03 |

| DSA Key Generation |
|--------------------|
| Key Length | IAIK | BC | SC |
| 1024 | 1,88 | 3383,49 | 3480,54 |
| 2048 | 12,49 | - | 46569,72 |

**RQ2.** What is the cost of increasing the security level in terms of power consumption? In our experiments we increase the security level by increasing the key length.

- **Key generation (table 7).** In AES, the increment in the key size from 128 to 192 has no negative impact in the power consumption regardless of the provider, so we can increment the security level at a low energy cost. On the other hand, the increment between 192 to 256 increases the energy consumption for
Table 9: AES Encrypt-Decrypt primitives

| Key Length | Encrypt | Decrypt |
|------------|---------|---------|
|            | IAIK    | BC      | SC      |
|            | IAIK    | BC      | SC      |
| 128        | 0.17    | 0.17    | 0.14    | 0.23    | 0.17    | 0.14    |
| 192        | 0.13    | 0.32    | 0.31    | 0.33    | 0.17    | 0.32    |
| 256        | 0.10    | 0.34    | 0.21    | 0.34    | 0.21    | 0.23    |

Table 10: DESede Encryption-Decryption

| Key Length | Encrypt | Decrypt |
|------------|---------|---------|
|            | IAIK    | BC      | SC      |
|            | IAIK    | BC      | SC      |
| 112        | 0.43    | 0.42    | 0.32    | 0.30    | 0.47    | 0.33    |
| 168        | 0.39    | 0.38    | 0.37    | 0.34    | 0.43    | 0.62    |

all providers. Specifically, the key increment in the BC provider doubles the energy consumption. The same situation can be observed for the DESede algorithm, where an increment in the key length duplicates the energy consumption in the IAIK and BC providers, whereas in SC the consumption is reduced by half. Finally, for the RSA algorithm, the IAIK provider almost quadruples the consumption of other suppliers for the recommended key length (2048). In this case, the cost of increasing the key length is from 10 to 6 times. For IAIK the cost of moving from 512 to 1024 is 10 times, 8 for the BC and the smallest is SC (6 times). The increment of the key from 1024 to 2048 is around 9 for IAIK

Table 11: RSA Encryption and Decryption

| ECB_PKCS1Padding | Encrypt | Decrypt |
|------------------|---------|---------|
|                  | IAIK    | BC      | SC      | IAIK    | BC      | SC      |
| Key Length       |         |         |         |         |         |         |
| 512              | 0.82    | 0.34    | 0.40    | 1.35    | 2.14    | 1.20    |
| 1024             | 2.11    | 0.53    | 0.58    | 3.48    | 4.20    | 3.68    |
| 2048             | 5.00    | 1.08    | 1.06    | 8.00    | 17.11   | 7.81    |

| ECB_NoPadding    | Encrypt | Decrypt |
|------------------|---------|---------|
|                  | IAIK    | BC      | SC      | IAIK    | BC      | SC      |
| Key Length       |         |         |         |         |         |         |
| 512              | 0.15    | 0.25    | 0.20    | 1.29    | 2.68    | 1.67    |
| 1024             | 0.25    | 0.25    | 0.33    | 3.59    | 4.44    | 4.10    |
| 2048             | 0.60    | 0.69    | 0.53    | 7.86    | 11.18   | 7.46    |

| NONE_NoPadding   | Encrypt | Decrypt |
|------------------|---------|---------|
|                  | IAIK    | BC      | SC      | IAIK    | BC      | SC      |
| Key Length       |         |         |         |         |         |         |
| 512              | 0.30    | 0.30    | 0.31    | 1.21    | 2.96    | 1.26    |
| 1024             | 0.20    | 0.38    | 0.23    | 3.76    | 4.53    | 4.04    |
| 2048             | 0.69    | 0.62    | 0.72    | 7.71    | 10.86   | 8.00    |

and 7 for BC and 6 for SC. So, the result is that for key generation the key length impacts a lot the energy consumption. The energy expenditure of the IAIK is the highest, specially for a key length of 2048. For the SC provider the key increment is uniform and in IAIK and BC the increment from 1024 to 2048 is smaller than from 512 to 1024.

- Encrypt/Decrypt (tables 9, 10 and 11). In AES (table 9), due to the low consumption level of symmetric algorithm, compared to asymmetric algorithms, there is not a quick response to this question. BC has an upward trend, IAIK shows an downward trend in the encryption operation and SC does not show a determined trend. To sum up, BC shows the highest consumption to higher key length in the encryption operation. On the contrary, in the decryption operation IAIK has the highest energy consumption and BC the lowest one. In the DESede algorithm (table 10), the cost of incrementing the length key is quite similar among providers in the encryption operation. Otherwise, in the decryption operation, SC provider suffers the highest consumption increment. Finally, in RSA (table 11), a modification of the key size
implies doubling the consumption in most of the providers in both operations and in all modes, except in the case of the decryption operation of recommended mode for BC provider, where doubling the key length implies to multiply fourfold the consumption.

**Answer to RQ2:** The answer is different for key generation and encryption/decryption operations and symmetric and asymmetric algorithms. For key generation in symmetric cryptography the cost of increasing the security level is uniform in all providers and almost insignificant. However, in asymmetric cryptography, RSA, to cover high security requirements is quite costly, move from 1024 to 2048 key length is translated to an energy increment from 6 times for SC to 8 times for IAIK. Focusing on encryption/decryption operation in symmetric algorithms, there are not huge differences on the energy consumption due to the key length. However, in the RSA algorithm there is a huge difference depending on the provider and on the operation evaluated, i.e. a variation from 1024 keys to 2048 keys in decryption operation for the Android default provider quadruples the energy consumption. Regarding asymmetric cryptographic, the increment of the security supposes a huge increment of energy, the exact value relies on the provider selected.

**Key recommendation:** In the case of symmetric key generators, there is not a huge variation in consumption for long keys. Therefore, programmers can increment the security of their applications with any security concern. That is not the case of asymmetric algorithms where the developer must to be aware about the security since an increment in the key length involves a huge variation in the energy consumption. Regarding the encryption and decryption operations, symmetric keys have a similar behavior than the process of key generation. Nevertheless, the increment of key length in encryption and decryption operations can be an expensive decision, therefore to make the right decision software developers might need to use an assistant tool.

**RQ3. Which transformation, comparing the default and the recommended transformations, is the most energy efficient for different crypto providers in Android?** The default transformations for the three providers were described in section 3.4.

- **Key generation.** In the AES algorithm, the BC provider produces the highest increment on energy consumption when the default option is changed to a more secure one. The energy consumption is doubled. On the contrary, the increment of key length in IAIK and SC supposes an energy increment of 1.6 times. For DESede, the default mode matches to the recommended one, 168
key length. Finally, in the RSA algorithm IAIK generates 1024 key length whilst in BC and SC the default mode matches to the recommended one. Increasing the key length is an expensive task, an increment from 6 to 8 times. In this case IAIK is the most energy consumer.

- **Encrypt/Decrypt** In the case of block ciphers there are several modes recommended, one of the aforementioned modes is CBC. For AES and DESede we have selected one of them in order to clarify the comparison. In AES (table 9), focusing on the encryption operation in CBC mode and PKCS5Padding padding, the consumption is similar among the providers. IAIK and SC shows up an upward trend whereas BC is the opposite, although the highest consumption value is the same but with different key length. In the decryption mode, IAIK shows up the highest value in the largest key length. In DESede (table 10), the change of the default mode to the recommended mode for the IAIK provider does not produce any substantial energy variation. In other way, BC and SC suffer a remarkable consumption increment, especially the BC provider. In the case of the decryption operation, BC maintains as the most consuming provider, but IAIK also suffers an increment. To sum up, we can conclude that changing from the default mode to one of the recommended mode is translated to an increment of energy consumption. Finally, in the RSA algorithm (table 11), the default transformation for IAIK is ECB_PKCS1Padding, the one used in this experimentation, but they recommend a key length of 1024 bits. On the other hand, the BC and SC default transformation is None_NoPadding with a key length of 2048 bits. So, for the default transformation the IAIK is the greenest.

### Answer to RQ3
The range of options that confidentiality cryptographic primitives present to us is broad. In the majority of the cases, the consumption of AES and DESede algorithms is very low compare to RSA algorithm, less than 1 mW. Overall, a variation from the default mode to one of the recommended mode is translated to an increment of energy consumption in the three algorithms evaluated.

### Key Recommendation
Highest key length might be selected only when the application has a high security requirements. If a moderated level of security can be applied, a high percentage of energy can be saved. In the same way, the user must choose AES or DESede above RSA.
5.3 Authentication energy profiles

The algorithms analyzed for authentication are the RSA and the DSA algorithms. The energy profiles of the key generation operation for these algorithms are shown in table 8. The information for the sign/verify operations for the same algorithms are shown in table 12 for the RSA algorithm and on table 13 for the DSA algorithm. Analyzing all this information the answers to our research questions are as follows.

RQ1. Which crypto provider is the most energy efficient for different operations of crypto primitives?

- **Key generation (table 8).** The consumption of RSA key generation has already been discussed in the confidentiality section. The consumption of DSA key generation for BC and SC provider are almost equal (table 8). Unfortunately, BC does not provide 2048 key length. On the other hand, the energy consumption for IAIK provider is extremely low compare to the others providers.
- **Sign/Verify (tables 12 and 13).** As expected, table 12 shows that the cost of signing with RSA is much higher than the cost of verifying the signature. As we have previously stated, BC has not support for the default mode, therefore it cannot be compared with the other two providers. Between SC and IAIK, SC shows a higher consumption for both operations, sign and verify. In the case of DSA, providers have the same behavior in case of not using a hash function, SC has a little bit more energy consumption in both operation sign and verify.

**Answer to RQ1:** We only have two alternative providers since BC does not offer the RSA authentication functionality without hashing. There is a clear winner for the sign operation, the IAIK. In the case of DSA algorithm, any provider can be selected without a high energy penalty.

**Key recommendation:** The clear greenest cryptographic provider for authentication with RSA is IAIK for any key length, using or not using hashing. Instead of using the default transformation, it is recommended to use hashing and the largest key length since there is not energy consumption penalty.

RQ2. What is the cost of increasing the security level in terms of power consumption?

- **Key generation (table 8).** The consumption of RSA key generation has already been discussed in the confidentiality section.
Table 12: RSA Sign and Verify, without and SHA-1 hash

| Key Length | Sign - IAIK | Sign - BC | Sign - SC | Verify - IAIK | Verify - BC | Verify - SC |
|------------|-------------|-----------|-----------|---------------|-------------|-------------|
| 512        | 1.68        | -         | 3.39      | 0.24          | -           | 0.19        |
| 1024       | 10.00       | -         | 17.96     | 0.20          | -           | 0.39        |
| 2048       | 22.04       | -         | 25.07     | 0.69          | -           | 0.81        |

SHA-1 (Recommended)

| Key Length | Sign - IAIK | Sign - BC | Sign - SC | Verify - IAIK | Verify - BC | Verify - SC |
|------------|-------------|-----------|-----------|---------------|-------------|-------------|
| 512        | 1.93        | 3.82      | 9.03      | 0.29          | 0.68        | 0.41        |
| 1024       | 9.53        | 14.75     | 12.27     | 0.44          | 0.65        | 0.53        |
| 2048       | 21.07       | 27.69     | 21.97     | 0.79          | 1.13        | 0.94        |

Table 13: DSA Sign and Verify without and SHA-1 hash

| Key Length | Sign - IAIK | Sign - BC | Sign - SC | Verify - IAIK | Verify - BC | Verify - SC |
|------------|-------------|-----------|-----------|---------------|-------------|-------------|
| 1024       | 2.58        | 2.10      | 2.27      | 2.88          | 2.83        | 2.97        |
| 2048       | 11.19       | -         | 11.92     | 18.03         | -           | 18.97       |

| Key Length | Sign - IAIK | Sign - BC | Sign - SC | Verify - IAIK | Verify - BC | Verify - SC |
|------------|-------------|-----------|-----------|---------------|-------------|-------------|
| 1024       | 2.48        | 2.17      | 2.33      | 2.89          | 2.82        | 2.90        |
| 2048       | 10.71       | -         | 12.83     | 19.81         | -           | 15.45       |

About DSA algorithm, a security increment requires a high level of energy from 6 to 13 times in the case of IAIK and SC respectively. It is important to underline than key generation of 2048 key length using SC provider is the most expensive operation of the evaluated operations.

- **Sign/Verify (tables 12 and 13)**. They key length impacts linearly the power consumption, so there is an energy penalty but at comparatively low cost. The BC provider do offer RSA authentication with SHA1, but at a comparatively high cost (i.e., is the least energy efficient). So the IAIK algorithm is the winner again. In DSA, the cost of raising the key length has similar result between 4 and 5 times in sign operation and 6 times in the case of verify operation, in default and recommend transformation.
Answer to RQ2: IAIK is, by far, the most consumption provider for generating RSA keys, however is the cleanest option for generating DSA keys. In contrast, BC and SC are the best options for generating RSA keys, but not for DSA keys. Moreover, the increment of key length of SC is 13 times in DSA and 6 times in RSA. In the case of IAIK, the increment is 6 times in DSA and 8 times in RSA. Regarding signature operation, in DSA algorithm an increment of key is translated to increment 4 times the energy in IAIK and 5 times in SC. With respect to RSA algorithm IAIK produces higher variations on the energy 2 times against 1.5 for SC. Surprising in the case of verification operation both case shows a notable increment, in DSA algorithm both providers IAIK and SC the increment value is 6 times. In RSA algorithm SC triples the consumption whereas SC doubles it.

Key recommendation: In asymmetric keys, developers can choose between BC or SC for RSA key generation. Otherwise if the developer needs to create a DSA key, the IAIK provider shows the lowest consumption values. Keys generated with one provider can be used with the rest of providers. We followed this recommendation in our testing application to save time in each test and execute each test under the same condition. With reference to sign and verify operations, if we sum the cost of both operations RSA algorithm is the cleanest solution although the sign operation is higher than DSA. Therefore, when the application only has to perform sign operation, DSA would be the selected algorithm.

RQ3. Which transformation, comparing the default and the recommended transformations, is the most energy efficient for different crypto providers in Android? The default transformations for the three providers were described in section 3.4.

- Key generation (table 8). Regarding the RSA algorithm, BC and SC the default key size is the recommended one. IAIK has 1024 key length as default mode, therefore moving to recommended key length is an expensive task. In the case of DSA algorithms, all the providers have as default mode a key length smaller than the recommended one. In the case of the BC provider, it is not possible to change to a recommended mode. SC provider has an elevated increment, 13 times from default to recommended mode.

- Sign/Verify (tables 12 and 13). What is interesting here is to assess the energy impact of including hashing in the RSA authentication function. Is it clear that for the two providers that offer the two options (i.e., with or without hashing) the impact is
non existent. So, it is possible to augment the security without a penalty in the power consumption. In same way, the inclusion of a recommend hash function in DSA has not impact on the energy consumption. Focus on sign operation, IAIK provider has a consumption lower than in the previous case, whereas SC is a little bit higher. On the other hand, in the verify operation is quite the opposite IAIK increase the consumption and SC decrease it.

| Answer to RQ3: RSA has not available information in the BC provider, and the remaining providers has similar cost between default and recommended transformation. In the case of DSA, IAIK provider shows a decrease when use SHA-1 hash algorithm to perform signature operation. However, in the verification mode, IAIK shows an increment between default and recommend mode. SC provider has the opposite behavior than IAIK. To sum up, moving from default to recommended mode has not negative influence in the energy consumption. |
|---|

| Key recommendation: Move from default transformation to recommended one has similar cost, therefore there is not a reasonable doubt to choose the default transformation, just only the lack of knowledge. |

5.4 Integrity energy profiles

The energy profiles of the key generation and integrity generation operation in the HMAC algorithms are shown in table 14. Analyzing all this information the answers to our research questions would be the following:

**RQ1. Which crypto provider is the most energy efficient for different operations of crypto primitives?**

- **Key generation (table 14).** SC is, in the majority of cases, the provider with the lowest consumption in the generation key procedure. BC and IAIK have similar energy expenditure although BC shows a peak consumption in HmacSHA512 algorithm.

- **MAC (table 14).** In most of the cases, IAIK is the provider with higher consumption. BC provider shows the lowest consumption in the following cases: HMAC with SHA1, SHA384 and SHA512, whereas in the case of MD5 and SHA224, SC is the lowest option. IAIK is the best option only for the SHA256 selection.

| Answer to RQ1: The SC is the better proposal to generate key to HMAC algorithms. However, the programmer must to decide for MAC generation between BC and SC depend on which algorithm wants to use. |
Key recommendation: In the same way as asymmetric algorithms, programmers will choose the cleanest provider to generate the required keys, in this case, SC provider. These keys can be used to perform integrity procedure selecting the desired algorithm with any provider.

RQ2. What is the cost of increasing the security level in terms of power consumption?

- **Key generation (table 14).** Overall, the use of recommend algorithms shows higher consumption than the only option not considered secure, MD5 algorithm.
- **MAC (table 14).** Quite the opposite than key generation procedure, in the generation of authentication codes, the recommended algorithm are more expensive than non recommended one.

Answer to RQ2: In this case programmer has a bundle of functions available with similar functionality. The HMAC with MD5 algorithm is the only one not considered secure. HMAC with MD5 has a consumption higher than the majority of the available algorithm for key generation, however it is the cleanest option for MAC generation.

Key recommendation: The developer must make a choice between recommend algorithms based on SHA. The selection will rely on functional or cryptographic requirements more than energy expenditure.

RQ3 is not applicable to this profile, due to these algorithms does not required transformation to perform the cryptographic operation.

| Algorithm         | IAIK | BC  | SC  | IAIK | BC  | SC  |
|-------------------|------|-----|-----|------|-----|-----|
| HmacMD5           | 0.41 | 0.40| 0.32| 0.41 | 0.41| 0.33|
| HmacSHA1          | 0.33 | 0.39| 0.20| 0.43 | 0.35| 0.39|
| HmacSHA224        | 0.39 | -   | 0.13| 0.59 | -  | 0.53|
| HmacSHA256        | 0.36 | 0.30| 0.27| 0.54 | 0.66| 0.57|
| HmacSHA384        | 0.62 | 0.53| 0.27| 0.92 | 0.58| 0.71|
| HmacSHA512        | 0.38 | 0.87| 0.28| 1.06 | 0.61| 0.93|

6 Threads To Validity

In this section, we will discuss internal validity, reliability and external validity of the study presented in this paper. The internal validity intends to
explore if the energy results are influenced or not by other factors. The reliability is related with how the experiment was conducted and if others can replicate it with the same results. And finally, the external validity analyses if the data obtained in the experiments can be generalized or not.

Regarding the internal validity, we should analyse first how precise are the results obtained. We have opted by PowerTutor a software solution, instead of making the measures with more precise tools implemented in hardware. We have chosen PowerTutor since the results provided by this tool have been validated in different studies. Although hardware solutions provide higher precision measurements, it is more difficult to be sure of what part of the software in execution is the responsible of such consumption. To mitigate this we have replicated the experiments in two different mobile phones obtaining similar results. Also, we are not interested in reporting absolute energy values, but to give recommendation to developers based on comparative results.

Another threat to the internal validity of our experiment is related to analyse if the differences in energy consumption of the cryptographic algorithms are caused by the concrete implementations of the different security providers and not by other factors. To mitigate this threat we have used the same procedure and configuration parameters to measure energy data for all the alternative implementations.

Another internal threat is that the set of parameters we have considered in our experiment for answering the questions is not exhaustive, so there could be other parameters that influence the energy consumption of cryptographic algorithms implementations. Indeed, we have simplified this study for sign and cypher operations by using a fix data length. We could have tested how the energy consumption changes when the data length varies. However, including a new parameter in our experiments would have complicated a lot the comparative analysis and the answers to the proposed questions. We think that this simplification do not threat the validity of the results, but developers must know that the conclusions raised in this paper can be considered valid only for a data length of 100 bytes. Exploring the influence of this parameter in the key results is part of our future work.

Another threat is related with the procedure we have used to analyse and interpret the data. The results of the experiment suggest that data follows a normal distribution for the majority of algorithms, except for key generation algorithms, (i.e., DSA and RSA). For former algorithms we have not considered the out of range values that introduce a non desired bias in the results. We have seen that after removing these values the absolute results were slightly different, but the results of the comparative study and the recommendations were not altered by this fact. For those values that do not follow a normal distribution we have removed the 5% of the top and another 5% of the bottom and we have calculated the mean of the resulting values.
To mitigate reliability threats, different researchers have performed the data collection and the analysis procedure. Also, all the scripts and source code are available, and therefore anyone can reproduce our experiments and test the validity of our findings presented here. Thanks to the use of a software energy measurement tool the reproducibility of our experiment is higher than others that use hardware solutions.

Concerning the external validity we have identified two threats. First, we have not tested our findings in third party applications. So, we do not consider the cost of invoking the cryptographic algorithms. We think that by not considering this, we can provide results independent from the application that is using these algorithms. However, we cannot report about the energy savings of real applications that use our recommendations. This will be the following step in our research work. The second threat is about the generalization of the results to all mobile phones and Android versions. The problem here is that we need a reliable software energy measurement tool able to measure nanoseconds, i.e., the execution time in smart phones with high performing CPUs (e.g., snapdragon). As far as we know, this is actually does not exist. Initially, we have tried the Trepn Profiler, an energy measurement tool for snapdragon mobile phones, but the energy measures can not be recorded due to the processor speed of Snapdragon CPUs is too high compared to the required execution time of cryptographic primitives. To mitigate this we have used the most recent implementations of the external providers IAIK and SC that can be used with recent mobile phones and Android versions.

7 Conclusions

The experiments carried out in this paper provided interesting information to software developers about how different cryptographics providers behave from an energy consumption point of view. Different cryptographic operations of different algorithms configured using different transformations have been analyzed for confidentiality, authentication and integrity. The study mainly focused on the default configurations selected by the provider and the configurations recommended by security experts.

According to the experimental data we can say that there is not a crypto provider that can be considered the greenest one for all the algorithms, operations and transformations. Thus, the relevance of this study is in the fine-grained information that it provides and that can be used to do a reasoned decision about which is the best provider for the necessities of each application. It is also very interesting to know that for some providers software developers can increase the level of security of their application without incurring in a too high increment in the energy consumption. Anyway, software developers need to be careful because this does not happen for all the
providers. The analysis performed in this paper helps to take that decision. Finally, for some providers the default and the recommended transformations are the same so non expert software developers can use default transformations and be sure that their applications have an appropriate level of security. However, this does not happen for all the providers so software developers interested on reducing energy consumption need to be careful to avoid choosing those providers where an increment on security also implies a considerable increment on the energy consumption. Finally, another interesting conclusion is that the external providers consume less energy than the Android security library in many cases, confirming our hypothesis that it is interesting to explore different security providers.

8 Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

9 Acknowledgments

This work is supported by the projects Magic P12-TIC1814 and HADAS TIN2015-64841-R (co-financed by FEDER funds).

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