INTEGRACIÓN DE IDEMIX EN ENTORNOS DE IOT

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Ohana means family.
Family means nobody gets left behind, or forgotten.

— Lilo & Stitch

Dedicated to the loving memory of Rudolf Miede.

1939 – 2005

ABSTRACT

Short summary of the contents in English... a great guide by Kent Beck how to write good abstracts can be found here:

https://plg.uwaterloo.ca/~migod/research/beckOOPSLA.html

We have seen that computer programming is an art,
because it applies accumulated knowledge to the world,
because it requires skill and ingenuity, and especially
because it produces objects of beauty.

— Donald E. Knuth [11]

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Put your acknowledgments here.

Many thanks to everybody who already sent me a postcard!

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1 Members of GuIT (Gruppo Italiano Utilizzatori di TeX e LaTeX)

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LISTINGS

ACRONYMS

IoT Internet of Things

ZKP Zero-Knowledge Proof

P2ABCE Privacy-Preserving Attribute-Based Credentials Engine

PoC Proof of Concept

APDU Application Protocol Data Unit

BLOB Binary Large OBject

CoAP Constrained Application Protocol

1 INTRODUCTION

In recent years some new concepts have appeared in common people's vocabulary, like *machine learning*, *big data*, *artificial intelligence*, *automation*, etc., but there are two in particular that we are going to focus and try to combine: Internet of Things (IoT) and Internet Security & Privacy.

The IoT is a term with a wide range of interpretations [4], but a breaf definition could be the set of devices, mainly resource constrained, that are interconnected between them in order to achieve a goal. This includes from lampposts with proximity sensors that talk to each other in order to light up part of the street when a passerby walks by, to a sensor on your clothes that tells the washing machine how much detergent to use.

Security & Privacy, thanks to organizations like WikiLeaks, are now taken in consideration by any technology consumer, not only professionals. People are conscious about what their data can be used for, demanding more control over it.

And IoT has proved to not address neither security nor privacy, with recent events like the Mirai botnet DDoS attack on October 2016, considered the biggest DDoS in history [15], or like the multiple vulnerabilities affecting baby monitors [19].

A recent approach to address the problem of privacy is the *strong anonymity*, that conceals our personal details while letting us continue to operate online as a clearly defined individual [8]. One very promising way to achieve this is using Zero-Knowledge Proofs (ZKPs) , cryptographic methods that allows to proof knowledge of data without disclosing it. Furthermore, IBM has been developing a cryptographic protocol suite for privacy-preserving authentication and transfer of certified attributes based on ZKP, called Identity Mixer, Idemix for short [10].

To read more about ZKP aside the introduction done in this thesis, you can read my Mathematics thesis [20].

The goal of this project is to integrate Idemix with the IoT. It will be done using the ABC4Trust's Privacy-Preserving Attribute-Based Credentials Engine (P2ABCE), a framework that defines common architecture, policy language and data artifacts, but based on either IBM's Idemix or Microsoft's U-Prove [18]. This gives us a standardized language to exchange Idemix's messages between IoT devices and usual PCs.

1.1 MOTIVATION

1.2 CHALLENGES

1.3 GOALS

1.4 OUTLINE OF THIS THESIS

2 STATE OF THE ART

In this chapter we present the two dimensions of this project: the IoT development state and an introduction to IBM's privacy-preserving solution, Idemix.

2.1 INTERNET OF THINGS

The development for Internet of Things depends heavily on each target device. We can differentiate two big groups: those with enough processing power to act like an usual computer, and those constrained devices that can't perform arbitrary tasks, sometimes called *embedded*.

We can consider in the first category powerful ARM devices like Raspberry Pi 3, with a 64-bit architecture, 4 CPU cores, 1GB of RAM, which can even compile its own binaries, run the *Java Virtual Machine*, etc., working in practice like any other computer. These kind of devices do not present any major difficulty in terms of research.

What we will consider to be a more *pure* IoT device will be the constrained ones, where it's not trivial to develop any algorithm and run it successfully.

Very known devices fall into this category, like Arduino, powered by Atmel's AVR ATmega328 8-bit microprocessors, with 32KB of program flash memory, 2KB of SRAM, 16MHz of CPU [3]. It seems clear that memory and computation power are a very big issue to deal with when developing to this devices.

A step above in power we can find ESP8266, the most famous Espressif's microcontroller, with built-in WiFi antenna, a Tensilica 16bit RISC microcontroller at 80MHz, 50Kb of RAM, and 1MB flash memory [7]. The possibility of direct WiFi connectivity is its best selling point, putting the *Internet* in Internet of Things.

In another level of power we have microcontrollers usually found in routers, but used in many other applications, like the On-Board Units (OBU) used in Vehicular ad hoc networks (VANET). Characteristics in this range vary around a single core 32-bit CPU, at some hundreds MHz, with tens or hundreds MB of RAM and flash memory, which places them near the first IoT mentioned category.

Although one can code in assembly language for these microcontrollers, there exist C compilers, and many frameworks to build firmware binaries: Arduino Core, Contiki, propietary SDKs, Mongoose OS, ThreadX OS (Real-Time OS), OpenWrt, LEDE, etc. Each firmware targets specific ranges of devices, depending on processing power and memory limitations. For example, Arduino and Contiki aim for microcontrollers like Atmel's ATmega and TI's MSP430, but can also be used in ESP8266, a more powerful microcontroller.

In particular OpenWrt and LEDE (a fork of OpenWrt) are based on Linux, with optimized library binaries, providing many packages through *opkg* [16]. To compile C/C++ code, build the firmware or packages, a complete build system and cross-compiler toolchain can be installed in a x86 host, and using Makefiles select the target hardware [17].

Devices running OpenWRT and other Linux distros are in the limit between IoT categories, but the need of a cross-compiler marks that they belong to the second category.

Starting a big project development for IoT aiming the most constrained devices may not be a good idea. The lack of usual operative system tools (like POSIX), I/O, or even threads can make debugging a tedious task. With good programming practices one can start from the top and slowly end at the bottom with reliable code.

For this reason the current Proof of Concept (PoC) is developed on LEDE, Linux Embedded Development Environment [12], using the Onion Omega2 development board, a Mediatek MT688 microcontroller [14] with a 32-bit MIPS 24KEc CPU at 580MHz, 64MB of RAM and 16MB of flash and built-in WiFi. This development board uses LEDE as its firmware, but its CPU is also listed as compatible with ThreadX OS [21], a Real-Time Operative System for embedded devices.

The PoC will take advantage of the Linux system using files and sockets like in any other Linux desktop distribution, so we can focus on the project itself rather than the specific platform APIs for storage and connectivity.

2.2 IDEMIX

TODO: MOVE TO MOTIVATION The problem of Internet privacy has been approached by securing the transmission channel (e.g. SSL/TLS) and the data stored in both ends (strict access policies, local encryption, etc.). In the end, the data exists in two entities, the owner of the data and the service provider. The owner is the most interested in securing his data, and can apply as many measures as he wants, but only on his side of the table. The service provider that stores the user data needs it to provide the service, and a successful attack would reveal many users data, aside from how many measures each one used to protect it. The case of PlayStation Network outage in 2011 [1] affected 77 million accounts, with suspected credit card fraud, is an example of this kind of attacks.

Other solutions are based on minimal disclosure. Standards like OAuth offer secure delegated access to the user information and when registering to a new service, the user can give a key to access only the data they want from another trusted service. This lets the service provider to work with the OAuth server, offering the same service as before without knowing as much data.

But this is only minimizes how many services have our data. Our OAuth provider could be attacked, revealing all our data, or our service provider, revealing now less data.

IBM proposes a step forward using Zero-Knowledge Proofs:

> *If your personal data is never collected, it cannot be stolen.*

TODO: PONER DESCRIPCIÓN + FORMAL DE IDEMIX, LUEGO P2ABCE, Y METER QUE EN P2ABCE HABÍA UNA IMPLEMENTACIÓN DE SC BASADA EN C

3 OBJECTIVES AND METHODOLOGY

3.1 PROJECT DESCRIPTION

3.2 WORKING METHODOLOGY

3.3 DEVELOPMENT ENVIRONMENT

3.3.1 *Hardware*

To test our design in a realistic but easy to work with deployment, we used as the IoT device an Onion Omega2 development board, and as the delegation server a Raspberry Pi 3.

Onion Omega2

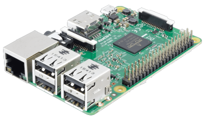
ONION OMEGA2: A device that falls inside the second category of IoT, powerful enough to run a familiar Linux environment, where we can develop and debug the first PoCs without troubling ourselves with non-related to the project problems.

Nonetheless, the Omega2 needs fine tunning to start operating, and basic knowledge of electronics is vital to make it work. The two main things to begin with Omega2 are:

- A reliable 3.3V with a maximum of 800mA power supply (a USB with a step-down circuit works fine), with quality soldering and wires to avoid unwanted resistances.
- A Serial to USB adapter wired to the TX and RX UART pins to use the Serial Terminal, in case WiFi doesn't work and no SSH is available, and because the connection is more reliable in case of wireless interferences.

MCU	Mediatek MT688 [14]
CPU	MIPS32 24KEc 580MHz
RAM	64MB
Storage	16MB
Firmware	LEDE (OpenWRT fork distro)
Connectivity	Wifi b/g/n
Power	3.3V 300mA

Table 1: Onion Omega2 Specifications.



Raspberry Pi 3

RASPBERRY PI 3: Another familiar environment, powerful enough to debug and hold the delegated P2ABCE Java services (User, Verifier, . . .) of P2ABC with its 1GB of RAM, and with two network interfaces it's perfect to work as the gateway for the IoT devices to the Internet.

Only a microSD with enough space to burn the binary with the OS is needed to plug&play with the Raspberry Pi. We use Raspbian, a stable Debian based distro, recommended by the Raspberry Pi designers, and ready to use with the P2ABCE compiled *.jar* services.

CPU	ARMv8 64bit quad-core 1.2GHz
RAM	1GB
Storage	microSD
Firmware	Raspbian (Debian based distro)
Connectivity	Wifi n + Ethernet
Power	5V 2A

Table 2: Raspberry Pi 3 Specifications.

3.3.2 *Software*

The development is divided between the IoT device code and the P2ABCE services.

The P2ABCE is already written in Java, and few modifications will be done to the code in comparison to the existing project size, so we will continue using Java with the P2ABCE part.

All IoT devices, have a C cross-compiler, some even a C++ cross-compiler. The worst case scenario is that one must write assembly code, and that code will be specific of that target, so we won't consider them. If now we focus on the most constrained devices, we could find out that some can't compile C++, some may not have many common libraries, and that the memory limitations they face make practically impossible to use dynamic memory, if we want to avoid very possible execution malfunctions.

For that reason, the developed code for IoT devices must be written with standard C without using dynamic memory.

A project with thousands of lines of code can't be written in a single file. And to manage the compilation of multiple files, organized in various directories, we will use CMake.

CMake has many advantages over Makefiles:

- Cross-platform. It works in many systems, and more specifically, in Linux it generates Makefiles.
- Simpler syntax. Adding a library, files to compile, set definitions, etc. can be done with one CMake command, with rich documentation on the project's website.
- Cross-compilation. With only a CMAKE TOOLCHAIN file, CMake sets up automatically the cross-compilation with Makefiles and the C/C++ cross-compiler provided.

Although the ideal final code is pure C without external libraries or dynamic memory, the PoC uses three major libraries:

- OpenSSL: Provides reliable and tested AES and SHA256 implementations.
- LibGMP: Provides multiprecision integer modular arithmetic.
- cJSON: Provides a JSON parser to store and read the status in a human readable way.

These three libraries are used to implement different interfaces in the project, and C implementations of these interfaces should replace the external libraries in the future.

Finally, we use Docker to deploy the compilation environments:

P2ABCE ENVIRONMENT A container with OpenJDK 7 and Maven installed, with the Idemix maven plugins installed following the project instructions to use Idemix as the Engine for P2ABCE.

LEDE SDK ENVIRONMENT A container with CMake and the LEDE SDK [12] installed and configured for the Omega2 target.

The Dockerfiles can be found in the Appendix.

4

DRAFT

4.1 SMART CARD APDU

To communicate the smart cards and the reader an standardized protocol is specified in ISO/IEC 7816-4 [9].

The messages, also kown as Application Protocol Data Unit (APDU), are divided in APDU Commands and APDU Responses.

APDU Commands consist in 4 mandatory bytes (CLA, INS, P1, P2), and an optional payload.

- CLA byte: Instruction class. Denotes if the command is interindustry standard or proprietary.
- INS byte: Instruction code. Indicates the specific command.
- P1, P2 bytes: Instruction parameters.
- Lc, 0-3 bytes: Command data length.
- Command data: Lc bytes of data.
- Le, 0-3 bytes: Expected response data length.

This way, minimal number of bytes are needed to transmit commands to the smart card, allowing manufacturer's personalization of the smart card behavior and capabilities along with standard operations.

Figure 1: APDU Command

APDU Responses are generated inside the smart card, always as an answer to an APDU Command. They consist on an optional payload and two mandatory status bytes.

- Response data: At most Le bytes of data.
- SW1-SW2 bytes: Status bytes. Encode the exit status of the instruction.

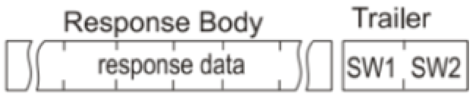


Figure 2: APDU Response

The transmission protocol varies between different types of readers and smart cards (e.g. chip, contact-less), but what is common between every smart card interaction, is the *APDU Command-Response Dialogue*. As long as the smart card has a power supply, it can maintain the dynamic memory in RAM between APDU Commands, what allows to do in two or more commmands complex operations, transmit more bytes than a single APDU can admit, etc.

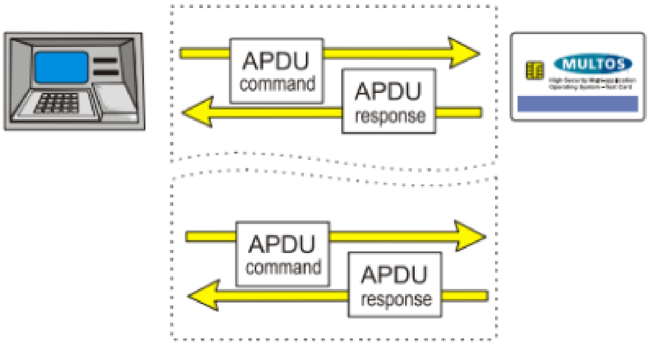


Figure 3: APDU Command-Response Dialogue

4.2 P2ABCE

In the P2ABCE repository [18] is available the project's code, divided in two solutions: a complete P2ABCE implementation in Java and a Multos Smartcard implementation as companion for the project.

The Java code is managed by a Maven project, structured using various known design patterns, but not of our interest. The structure we are actually interested in are the REST Services and their use of the Components classes, in which the smartcards are included.

P2ABCE project is based on the concept of smartcards to store the credentials, logical or physical. An interface is defined to communicate with these smartcards, and then different implementations allow to use either *Software Smartcards* or *Hardware Smartcards*.

The *SoftwareSmartcard* class implements the interface in Java, suitable for tests and self-stored smartcards that any application using P2ABCE may need.

The *HardwareSmartcard* class uses the standard APDU messages [TODO:ref] to interact with smartcards. P2ABCE defines for every method in the mentioned interface, the necessary APDU instructions, and currently relies on *javax.smartcardio* abstract classes (implemented by Oracle in their JRE) to communicate with the smartcard reader. This way, it doesn't matter what manufacturer issues the smartcard, or if it's an Android device, if they support the APDU API, P2ABCE will work with them.

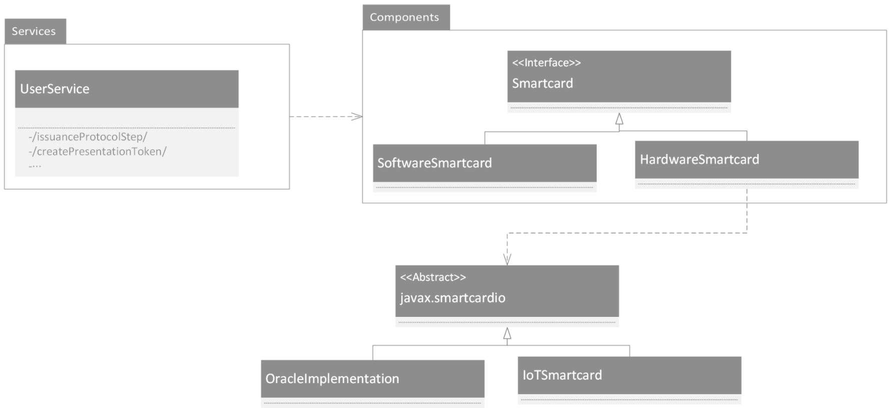


Figure 4: Basic P2ABCE structure

As a PoC the P2ABCE project includes the ABC4Trust Card Lite, an implementation for ML3-36K-R1 Multos Smartcards. The code is written in C, but is very dependent on the Multos framework, aside from numerous bugs and bad coding habits.

At this stage, we have two options to implement our IoT device compatible with P2ABCE:

- Implement in C the *Smartcard* interface used by P2ABCE architecture, and use some communication protocol to remotelly call the methods from the machine running the P2ABC Engine.
- Present the IoT device as a hardware smart card, using the APDU protocol (already defined, standard and with minimal overload). Providing a *javax.smartcardio* "IoT implementation" to communicate with the IoT device through a transmission protocol, the already existing *HardwareSmartcard* class can work with the new *IoTSmartcard* in the IoT device.

4.3 MULTOS

MULTOS is a multi-application smart card operative system, which provides a custom developing environment, with rich documentation [13]. MULTOS smart cards communicate like any other smart card following the standard, but internally offers a very specific architecture, affecting the way one must code applications for it.

In this section we will present the main characteristics of a MULTOS smart card that shaped the ABC4Trust Card Lite code and that we had to be aware of when adapting it to IoT devices.

MULTOS PROGRAMMING LANGUAGES A native assembly language called MEL, C and, to a lesser extent, Java, are the available languages to code for MULTOS. In our case, ABC4T Card Lite uses MEL and C.

MULTOS WORKFLOW Most of the transmission and communication process is done by MULTOS core, and it then selects, based on the CLA byte of the APDU, the application to load. This application is what most developers will only worry about, and is where their $\mathrm{main}()$ function will start.

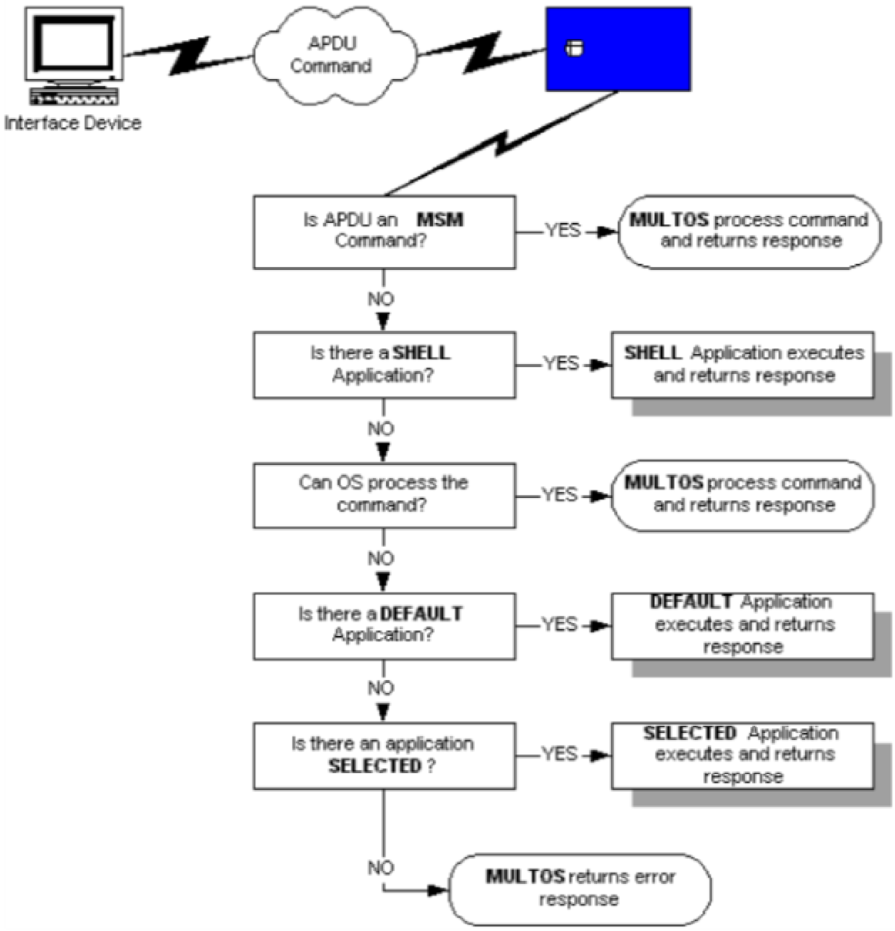


Figure 5: MULTOS workflow

The application uses then the *multos.h* file that declares multiple global variables already loaded with the needed data, including the APDU Command bytes.

Now the developer is in charge of checking what instruction was sent and if the APDU has the expected ISO Case. If everything is ok, code what needs to be run and write in specific data space the APDU Response bytes, call *multosExit()* and MULTOS will be in charge to send the APDU Response.

In summary, our application starts with all data loaded and exits without worrying how to send the answer. A very comfortable workflow that we must now implement for our IoT device if we would want ABC4T Card Lite code to work.

MULTOS MEMORY LAYOUT Each application in MULTOS has access to a specific memory layout, divided in different categories:

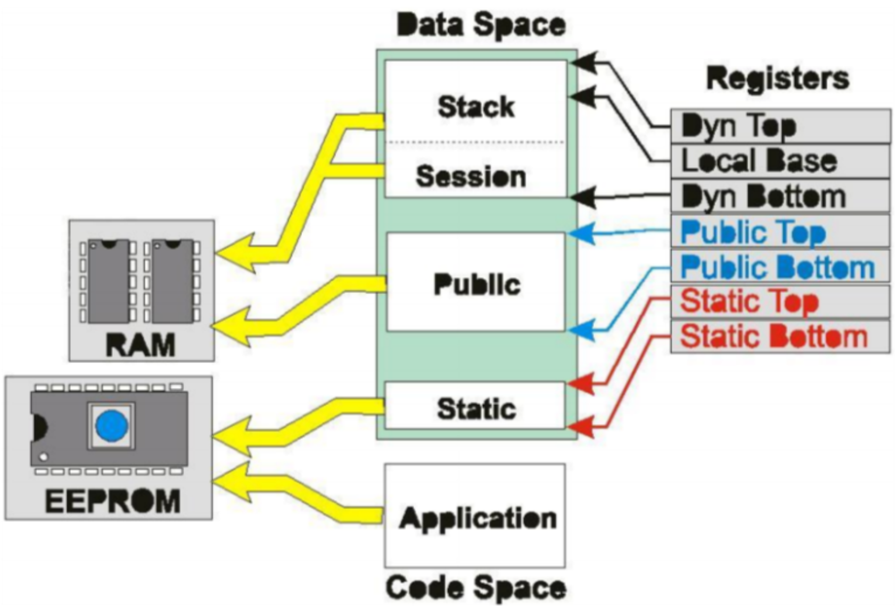


Figure 6: MULTOS Memory Layout

The Code Space is where the application code is stored. The Data Space is divided in Static memory, Public memory and Dynamic memory.

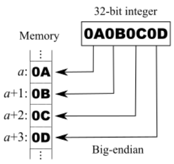
Static memory are the application variables declared after the specific *#pragma melstatic* compiler directive. These variables are stored in the non-volatile EEPROM, and any write is assured to be saved because they are not loaded into RAM.

Public memory can be seen as the input/output buffer for applications and MULTOS system. The APDU header appears at the top of Public, and command data at the bottom. The application writes then the APDU Response bytes in Public, at specific position (see Figure 7). To declare variables in this data space, the *#pragma melpublic* directive is available.

Dynamic memory works like usual program memory, with Session Data storing global variables and the Stack. The limited size of RAM in IoT devices and smart cards makes the use of dynamic memory not advisable. The compiler directive to use Session Data is *#pragma melsession*.

Address	Name	Description
PT[-1]	SW2	Byte 2 of the Status Word
PT[-2]	SW1	Byte 1 of the Status Word
PT[-4]	La	Actual length of response data
PT[-6]	Le	APDU expected length of response data
PT[-8]	Lc	APDU length of command data sent
PT[-9]	P3	If required, temporary buffer for 5th byte, if any, of APDU header
PT[-10]	P2	APDU Parameter byte 2
PT[-11]	P1	APDU Parameter byte 1
PT[-12]	INS	APDU Instruction byte
PT[-13]	CLA	APDU Class byte
PT[-14]	GetResponseSW1	Byte 1 of Status Word to be used in Get Response command
PT[-15]	GetResponseCLA	CLA to be used by Get Response command
PT[-16]	Protocol Type	Transport protocol type
PT[-17]	Protocol Flags	Bit flags indicating status of protocol values
PB[0]	Start of Data Area	Command data and response data start

Figure 7: MULTOS Public Memory Data Map



Big-Endian, Wikipedia

With regards to primitive types, to avoid confusion with their sizes, MULTOS defines and uses the following data types specified in Figure 8. It's important to notice that MULTOS is Big Endian and when storing structures there is no padding between defined variables, unlike modern compilers that perform data structure alignment [6] for performance.

Data Type	Definition
BOOL	boolean (byte)
BYTE	unsigned byte (byte)
SBYTE	signed byte (byte)
WORD	unsigned word (2 bytes)
SWORD	signed word (2 bytes)
DWORD	unsigned double word (4 bytes)
SDWORD	signed double word (4 bytes)

Figure 8: MULTOS Data Types

MULTOS STANDARD C-API A collection of more than a hundred functions are provided for arithmetic, cryptography, memory and smart card operations. The *multos.h* interface provides access to these functions, that ultimately call their respective primitive instructions in assembly code. The primitive instructions are but a system call with an operation code, loading data in the needed registers. Therefore, no implementation for these tools is available, nor in C, nor in assembly code.

Nevertheless, the C-API documentation [13] provides rich description for each function.

4.4 ABC4TRUST CARD LITE

P2ABCE provides a smart card reference implementation, ABC4Trust Card Lite [5]. It supports device-bound U-Prove and Idemix, and virtually any discrete logarithm based pABC system.

Version 1.2 is based on MULTOS ML3 cards, with approximately 64KB of EEPROM (non-volatile memory), 1KB of RAM and an Infineon SLE 78 microcontroller, a 16-bit based CPU aimed for chip cards.

The card stores the user's private key x and any Binary Large OBject (BLOB) that the P2ABCE may need (like user's credentials). Then P2ABCE delegates the cryptographic operations on the smart card, that operates with x.

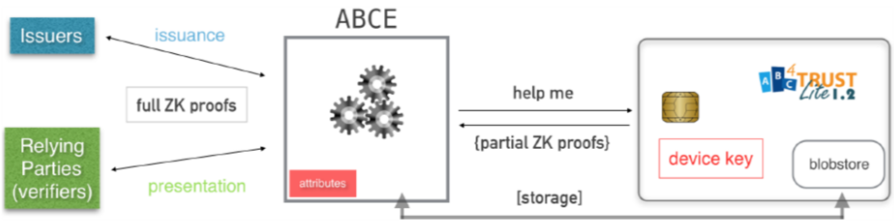


Figure 9: ABC4Trust Card Lite

The cryptographic operations performed by the smartcard are the modular exponentiation and addition that discrete logarithm ZKPs are based on.

The code is available from the P2ABCE project and has some good and bad points to have in count:

The best asset of this code is that it's written in C aiming to a very constrained device, similar in computational power to many IoT devices, and very limited memory.

Some *tricks* in the code include using *union* data types for variables that will be stored on the same data location, but at different moments (e.g. depending on APDU Command INS byte), minimizing this way the use of RAM and making code readability better; or strong use of pointers and *memcpy* calls to copy structures with multiple variables as arrays of bytes.

Among the many drawbacks, we could highlight the awful coding, the strong dependency on MULTOS framework and some bugs found.

The code is structured in two files, *main.h* and *main.c*, with 557 and 5157 lines of code respectively.

The file *main.h* is mostly a reimplementation in assembly MEL of some MULTOS functionality already offered with latest *multos.h*.

The *main.c* consists on near 600 lines of variables and data structures declarations, followed by the *main()* function, a 2635 lines long *switch-case* with practically no comments, and to conclude, the implementation of thirty functions called *Subroutines* at the end of the file.

This gives an idea of the problematic to maintain or even understand the code. But once one studies MULTOS framework in deep and applies many refactoring techniques to ABC4T Card's code, this becomes the best starting point for the IoT version.

4.5 IOT AND P2ABCE

In this section we will define how an IoT device will be integrated in the P2ABCE environment, being totally compatible with any other system using P2ABCE, addressing the power and memory constrains IoT devices face.

Our main goal is to make an IoT device capable to act as an User or Verifier in the P2ABCE architecture. For this, the device should manage complex XML schemas, perform cryptographic ZKP operations and communicate with the Verifier or Prover with which it's interacting.

The communication is already solved by the *Internet* capabilities of IoT devices.

Our concern are the data artifacts exchanged as XML and the cryptographic operations involving secret keys that must remain private to the IoT device.

Here is where we look at the P2ABCE architecture more closely, and the concept of smart cards shows a solution for the second issue. Even in the case we were to implement all P2ABCE inside an IoT device, we would have to implement support for software smart cards, to keep the secret inside the IoT device. We will start building the house from the ground, implementing the smart card operations inside the IoT device.

Now that in our design we have the smart card, we need to address the first point, XML squemas. We understand with *XML squemas* both managing the XML syntax and the whole process to generate a proper answer, that is, basically, the crypto engine that relies on Idemix and the smart card to hold the secret information.

Taking in consideration Idemix is currently provided in Java as a considerably big project, and version 3.0.36 still hasn't got official documentation, the task to port the Idemix crypto engine to IoT could be done in the future, if the chosen devices have enough storage and capacity. And even in that case, we would need to implement P2ABCE User and Verifier's architecture to completely free ourselves from an external P2ABCE machine.

The final port would be so big, many IoT devices would fall out of the requisites to run it, failing in our initial objective.

After this analysis of the P2ABCE, we conclude that the mandatory requisite for any IoT device that wants to work with this system and keep its private keys in it, is to implement the smart card functionality, and delegate the rest of the operations on a machine capable of running P2ABCE, until that functionality is implemented for the IoT device.

This architecture is not really such an original idea. For example, IPv6 involves managing 128 bits per address and large headers, and many use cases only need IoT devices to communicate inside a private network. That's why many of them use 6LoWPAN to compress packets or use smaller address sizes. To communicate a 6LoWPAN with the Internet, a proxy is needed to transform 6LoWPAN packets to IPv6.

Therefore, the IoT device now has a **duality** in its functions, because it is the User that starts any interaction with other systems, and it's also the smart card that P2ABCE delegates for crypto operations. It can also be seen as a **double delegation**. The IoT device delegates on the external P2ABCE server to manage the protocol, and the P2ABCE server delegates on the IoT, acting now as a smart card, for the cryptography.

We find here two challenges: how to delegate from the IoT device to the P2ABCE delegation server, and how to transmit them and the APDUs to the IoT device.

Currently P2ABCE offers various REST web services to run different roles in P2ABCE system: User Service, Issuer Service, Verification Service, etc. An application that integrates P2ABCE can make use of this services in the same machine or implement the functionality using the core components written in Java, the same ones the REST services use. Our PoC machine, the Omega2, can make REST calls easily, but other devices may use Constrained Application Protocol (CoAP), and in that case, the P2ABCE REST services should be rewritten to offer CoAP support. The commands needed to delegate to the P2ABCE delegation server will be the same to operate with the REST services. This way, the first issue is solved.

The transmission of the messages will depend on the specific use case, capabilities and resources available. If the delegation server is connected, for example, through RS-232 serial with the IoT device, and physically inaccessible, in the same way an IoT device on its own would be protected, the communication is simple, and not far away from the Arduino Yun idea of combining two devices, one more powerful but to use only when needed. But if the IoT device and the delegation server are apart, or more than one IoT device delegates to it, then the transmission must be secured. They could use 6LoWPAN to talk to each other (the delegation service could be deployed in the proxy) and then secure communications with existing solutions, like with pre-shared symmetric keys, certificates for authentication and authorization, etc., it depends on each particular deployment.

At the end of the day, this is all about usual security in IoT. Many other studies focus on this matter, so we will assume it can be done, and will focus on what's new, P2ABCE in IoT.

To sum up, our IoT device will act as User (Prover or Verifier) keeping its secrets in a software smart card. When it starts an interaction with other actor of the P2ABCE system (Issuer, Verifier, etc.), the IoT device will delegate with a remote call (using REST in our PoC) to a P2ABCE delegation server, attaching the XML file and the necessary information for the server to send the APDUs to the software smart card (in our PoC using TCP sockets, giving the IP and listening port).

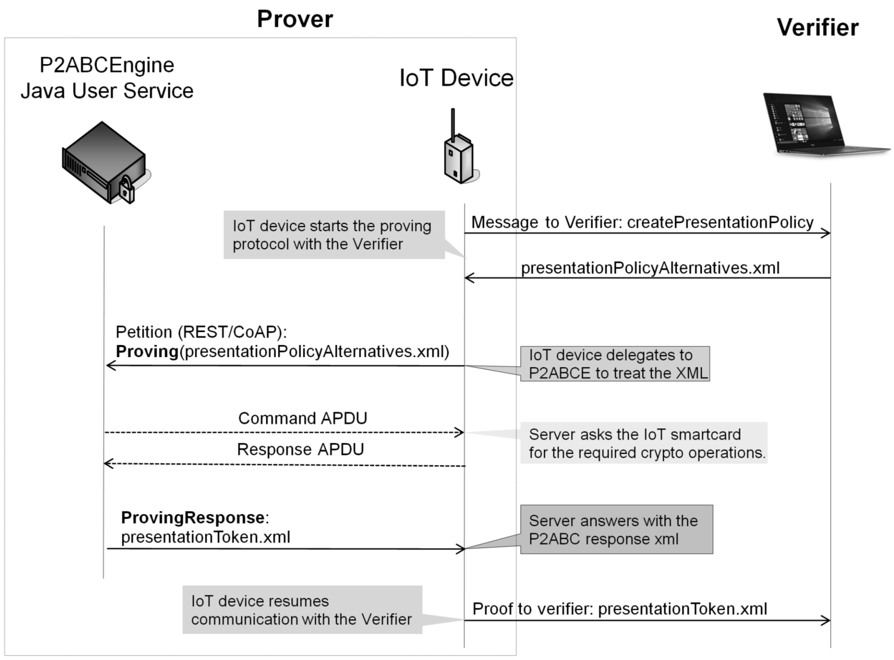


Figure 10: IoT Delegation in P2ABCE for Proving.

This simple design keeps the benefit of a 100% compatible P2ABCE deployment, and the integration of IoT devices to the P2ABCE ecosystem.

In the future, more functionality currently delegated in the P2ABCE server can be implemented in the IoT device, if its resources allow it. For example, in a M2M environment, where an IoT device can act as User and Verifier, the verification consists on sending a Presentation Policy, and verifying the Presentation Token, which implies less logic than generating it as the User. Therefore, the implementation of the

Verifier functionality would reduce significantly the need of a delegation server, but as we said, managing complex XML squemas is not something many IoT devices could do.

4.6 IOT SMART CARD

After many design decisions in the process to adapt the original ABC4T Card Lite code to pure C, working over a more usual architecture machine, in this section, we present the current PoC code, most important decisions, workflow execution, and future work.

First, let's define what a *more usual architecture* is. If we remember the MULTOS section, the framework gives an application a very specific memory layout and entry and output points of execution, that could be seen as a single process execution machine. Many IoT devices work like a computer, with multiple processes or threads, without pre-loaded data on startup (like the APDU MULTOS loads for the application), a non-volatile memory for data and code, maybe a basic file system in this memory, and RAM with the program's stack, heap, data and code.

Our PoC is tested on a Linux system, and we will give instructions on how to adapt each part to work with other typical IoT systems. For example, other IoT devices may work like MULTOS and let access variables in non-volatile memory during execution, and in that case, the port should be changed according to these particularities.

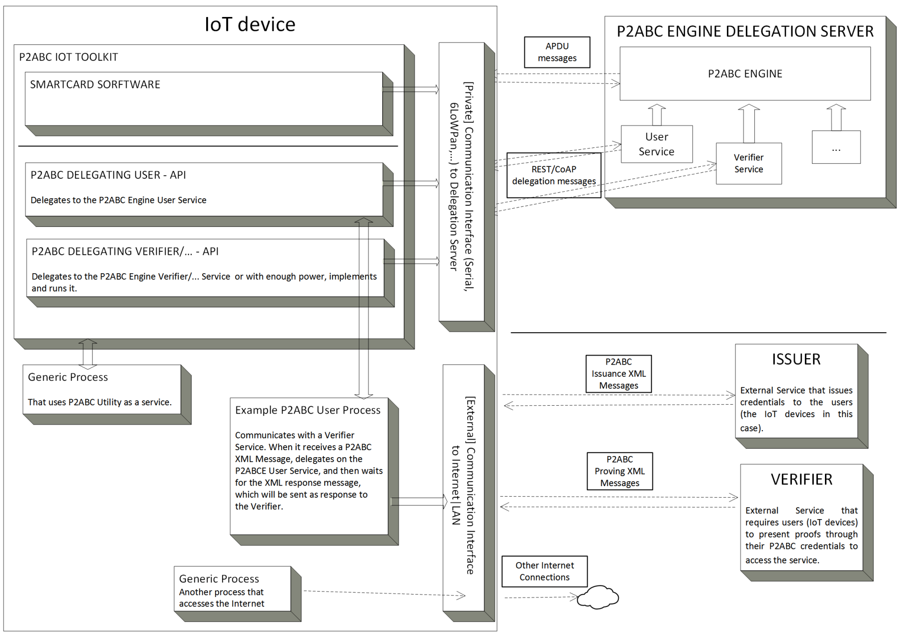


Figure 11: P2ABCE-IoT.

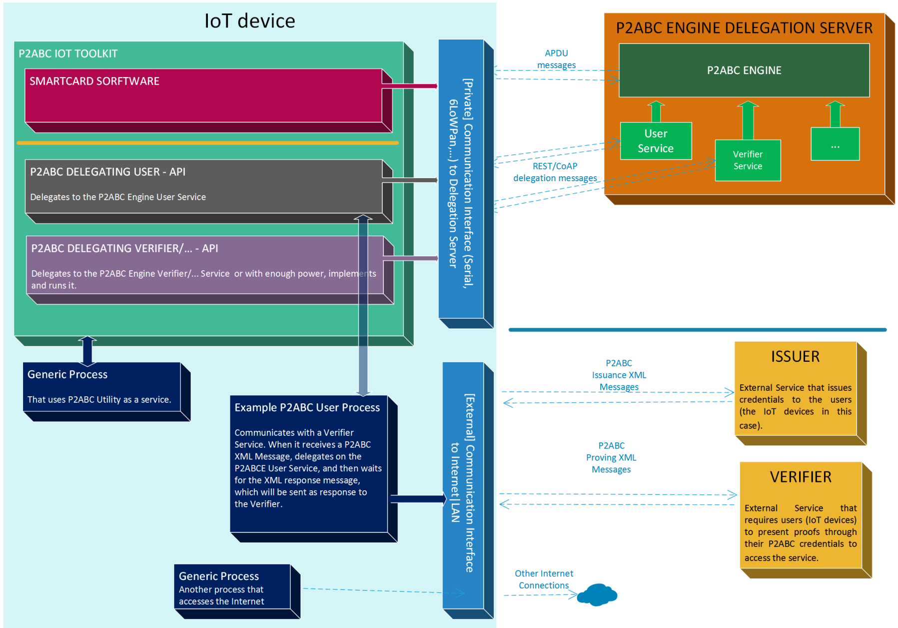


Figure 12: P2ABCE-IoT-color.

CODE STRUCTURE

We divide the project in three different sections with the objective of enhancing maintainability, improving future changes, ports, fixes, etc.

The first section is what could be called as the core of the smart card, the second one the interface for the tools the core need and may depend on the platform, and finally third party libraries, that in may be empty if the interfaces implementation doesn't need any.

In our PoC we used CMake to manage the project, due to the cross-compilation tools, integration with multiple IDEs and tests.

CORE SMART CARD The smart card logic lies in this section, the concepts of APDU Commands, what instructions are defined in P2ABCE smart cards and how to process them and generate proper APDU Responses.

Changes in the APDU protocol for P2ABCE must be done here, independently of the target platform.

After refactoring the original ABC4Trust Card's code, most of it fell in what we will call the core of the smart card.

All types and variable definitions and the APDU handling is done in this code. However, the ABC4Trust's code depended on the MULTOS C-API for the input/output of data, modular arithmetic, and even AES128 and SHA256 cryptography.

A characteristic of MULTOS C-API is that every function name starts with *multos*, but as we said, the *main.h* file implemented equiv-

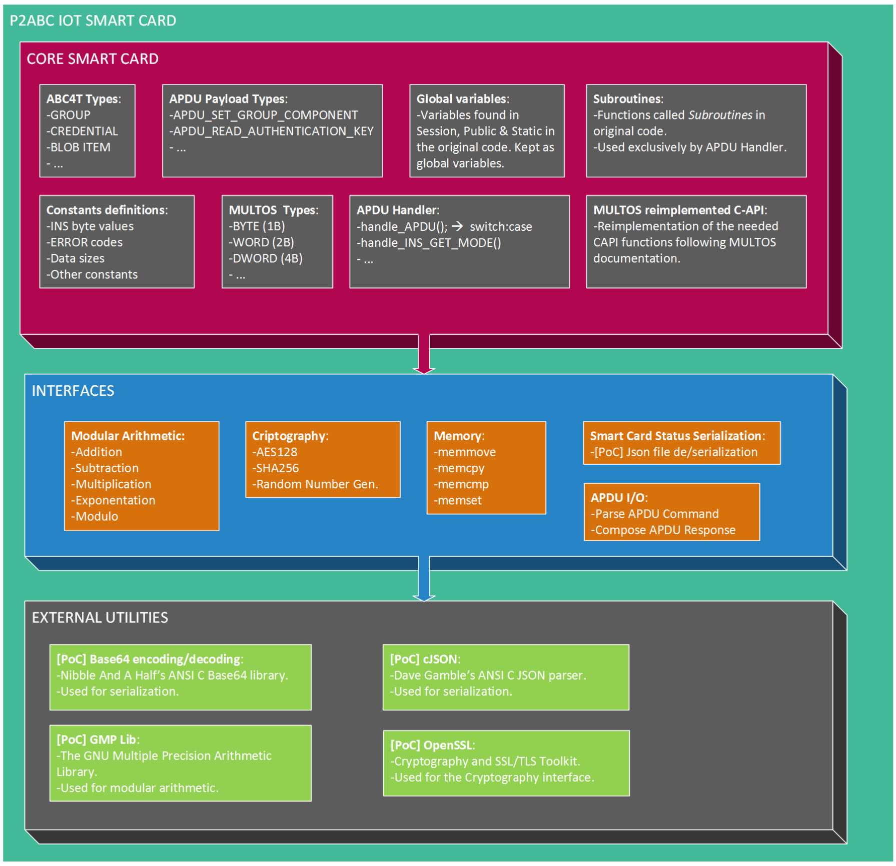


Figure 13: IoT Smart Card Code Structure.

alent functions to some available in *multos.h*. Our first step was to replace the *main.h* functions for the standard ones in the C-API. Then, we implemented, following the C-API documentation, the functions from *multos.h* (only the used ones) changing their names from *multosFoo()* to *mFoo()* for readability and emphasize that they were no longer from MULTOS.

Future changes in the code may refactor it so there's no longer need for the MULTOS framework functions.

INTERFACES To implement MULTOS functions, we needed to use some libraries, so we defined a facade to isolate the implementation of the core smart card from our different options, that could vary depending on the hardware or the system used by the IoT device.

The use of a facade lets us, for example, change the implementation of modular arithmetic with a hardware optimized version, or a future more lightweight library, or our very own software implementation using the same data types that the core uses, minimizing the data transformations needed.

Taking a step forward, we make the core smart card totally independent of any library, only on our interfaces. This means that typical

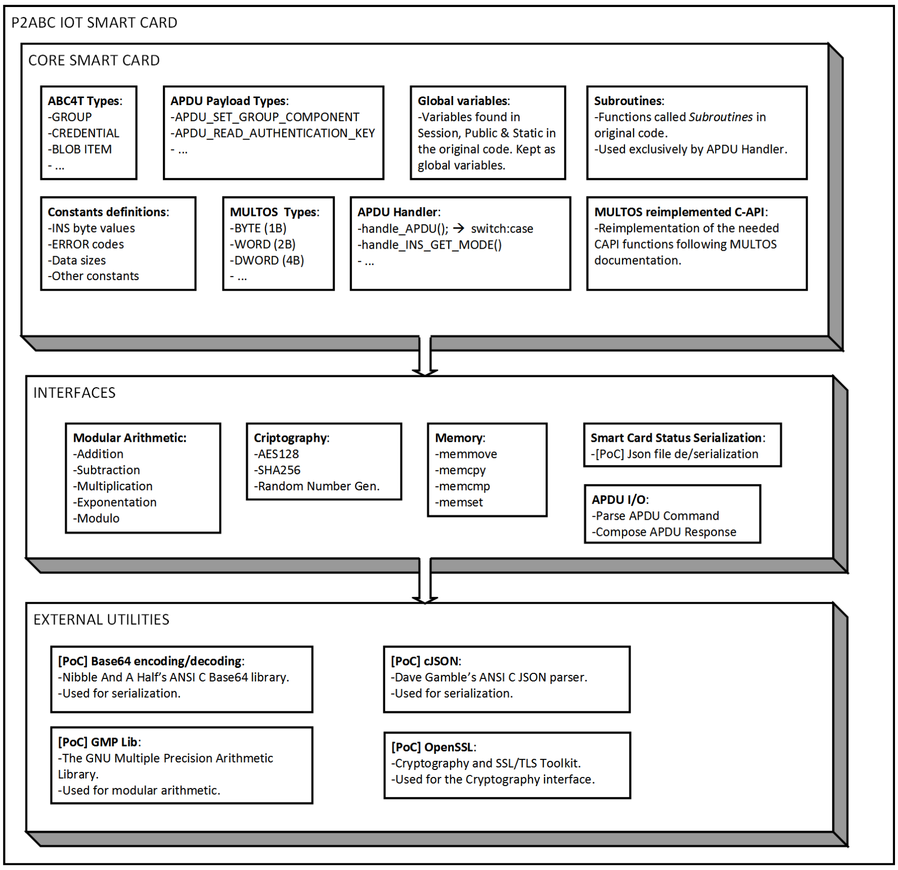
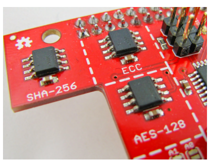


Figure 14: IoT Smart Card Code Structure.

C libraries, like the standard *stdlib.h*, or *string.h* are also behind the facade, in case some IoT system doesn't support them. The main goal we go after with this decision is that future developers adapting the code to a specific platform need to make no change to the *core smart card*'s code, only to the interfaces implementation.

EXTERNAL UTILITIES If the IoT system offers well tested libraries that could aid in the interfaces implementation, or we simply found a pure C implementation for the task, these third party libraries belong to this section.

In our PoC, we use two ANSI C libraries, for base64 and JSON, and two shared libraries available in as packages in LEDE, GMPLib and OpenSSL. The last two libraries offer more functionality than we need, hence, it's desired in a production code to implement *Modular Arithmetic* and *Cryptography* interfaces with more lightweight alternatives.



Atmel's cryptography chips.

For example, Atmel's ATAES132A [2] offers a serial chip for secure key storage, AES128 execution and random number generation. Another serial chip like ESP8266 offers WiFi connectivity, typically used with Arduino, and can also perform AES encryption. For random number generation, a technique used with Contiki devices is to read from sensors aleatory data and use it as seed. All these alternatives depend on the target device, but are all valid. The *interfaces* and *external utilities* sections allow for a clean and fast port of the code.

APPENDIX

A
APPENDIX TEST

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More dummy text.

A.1 APPENDIX SECTION TEST

Test: Table 3 (This reference should have a lowercase, small caps A if the option `floatperchapter` is activated, just as in the table itself → however, this does not work at the moment.)

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suscipit instructior	titulo	personas
quaestio philosophia	facto	demonstrated

Table 3: Autem usu id.

A.2 ANOTHER APPENDIX SECTION TEST

Equidem detraxit cu nam, vix eu delenit periculis. Eos ut vero constituto, no vidit propriae complectitur sea. Diceret nonummy in has, no qui eligendi recteque consetetur. Mel eu dictas suscipiantur, et sed placerat oporteat. At ipsum electram mei, ad aeque atomorum mea. There is also a useless Pascal listing below: Listing 1.

Listing 1: A floating example (`listings` manual)

```
for i:=maxint downto 0 do
begin
{ do nothing }
end;
```

[1] *2011 PlayStation Network outage*. https://en.wikipedia.org/wiki/2011_PlayStation_Network_outage.

[2] *ATAES132A 32K AES Serial EEPROM Datasheet*. http://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-8914-CryptoAuth-ATAES132A-Datasheet.pdf.

[3] *ATmega328 Datasheet*. http://www.atmel.com/Images/Atmel-42735-8-bit-AVR-Microcontroller-ATmega328-328P_Datasheet.pdf.

[4] Luigi Atzori, Antonio Iera, and Giacomo Morabito. "The Internet of Things: A survey." In: *Computer Networks* 54.15 (2010), pp. 2787 –2805. ISSN: 1389-1286. DOI: http://dx.doi.org/10.1016/j.comnet.2010.05.010. URL: http://www.sciencedirect.com/science/article/pii/S1389128610001568.

[5] Pascal Paillier CryptoExperts. *ABC4Trust on Smart Cards. Embedding Privacy-ABCs on Smart Cards*. Summit Event, Brussels, 2015.

[6] *Data structure alignment*. https://en.wikipedia.org/wiki/Data_structure_alignment.

[7] *Espressif ESP8266 Datasheet*. https://espressif.com/en/products/hardware/esp8266ex/resources.

[8] Tom Henriksson. "How 'strong anonymity' will finally fix the privacy problem." In: *VentureBeat* (2016). https://venturebeat.com/2016/10/08/how-strong-anonymity-will-finally-fix-the-privacy-problem/.

[9] *ISO/IEC 7816-4:2005 Identification cards – Integrated circuit cards – Part 4: Organization, security and commands for interchange*. https://www.iso.org/standard/36134.html.

[10] *Identity Mixer*. https://www.research.ibm.com/labs/zurich/idemix/.

[11] Donald E. Knuth. "Computer Programming as an Art." In: *Communications of the ACM* 17.12 (1974), pp. 667–673.

[12] *Linux Embedded Development Environment*. https://lede-project.org/.

[13] *MULTOS technical library*. http://www.multos.com/developer_centre/technical_library/.

[14] *MediaTek MT7688 Datasheet*. https://goo.gl/kqD2gF.

[15] R. Thandeeswaran N. Jeyanthi. *Security Breaches and Threat Prevention in the Internet of Things*. IGI Global, 2017.

[16] *OPKG Package Manager*. https://wiki.openwrt.org/doc/techref/opkg.

[17] *OpenWrt's build system*. https://wiki.openwrt.org/about/toolchain.

[18] *P2ABCEngine*. https://github.com/p2abcengine/p2abcengine.

[19] Mark Stanislav and Tod Beardsley. *HACKING IoT: A Case Study on Baby Monitor Exposures and Vulnerabilities*. Tech. rep. Rapid7, 2015.

[20] José Luis Cánovas Sánchez. "Pruebas de Conocimiento Cero y sus Aplicaciones."

[21] *THREADX OS Real-Time OS*. http://rtos.com/products/threadx/.

DECLARATION

Put your declaration here.

, Junio 2017

José Luis Cánovas Sánchez

COLOPHON

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