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Securing Multi-Application Smart Cards by Security-by-Contract

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Resumen

La tecnología de Java Card ha evolucionado hasta el punto de permitir la ejecución de servidores y clientes Web en una tarjeta inteligente. Sin embargo, desarrollos concretos de tarjetas inteligentes multiaplicación no son aún muy corrientes dado el modelo de negocio de descarga asíncrona y actualización de aplicaciones por diferentes partes que requiere que el control de las interacciones entre las aplicaciones sea hecho después de la expedición de la tarjeta. Los modelos y técnicas de seguridad actuales no soportan dicho tipo de evolución en la tartjeta.

Un enfoque prometedor para resolver este problema parece ser la idea de Seguridad-mediante-Contrato (S×C). S×C es un entorno en el que se hace obligatorio que cualquier modificación de una aplicación tras la expedición de la tarjeta traiga consigo una especificación de su comportamiento en lo que concierne a seguridad, llamado contrato. Este se debe ajustar a la política de seguridad de la tarjeta multiaplicación. A causa de los recursos limitados de estos dispositivos, el enfoque de S×C puede ser aplicado a diferentes niveles de abstracción, según un jerarquía de modelos la cual proporciona beneficios en términos de complejidad computacional o expresividad del lenguaje. El nivel de más detalle (mayor expresividad) requiere algoritmos demasiado complejos para ser ejecutados en la tarjeta, por lo que es necesario enviar datos de forma privada a una tercera parte de confianza que será la responsable de realizar la comparación del contrato y la política de la tarjeta (proceso llamado Comparación Contrato-Política) con objeto de decidir si la modificación se ajusta a la política de seguridad o no; es decir, si el cambio es aceptable según el comportamiento esperado por la tarjeta y expresado en su política.

El propósito del proyecto es desarrollar un sistema el cual resuelva el problema de externalizar el proceso de Comparación Contrato-Política a una entidad externa para tarjetas inteligentes multiaplicación de Java. Este sistema debe garantizar una comunicación segura entre la tarjeta y alguna tercera parte de confianza sobre un medio inseguro. La comunicación tiene que ser segura en términos de autenticación, integridad y confidencialidad. Lograr este objetivo requiere resolver problemas tales como la gestión de identidades y claves y el uso de funciones criptográficas para hacer segura la comunicación de datos privados almacenados en la tarjeta inteligente. Es por ello que los objetivos del proyecto son:

- Diseñar un sistema que resuelva el problema
- Implementar un prototipo que demuestre la validez del sistema
- Validar el prototipo y valorar su idoneidad en cuestión de espacio

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Capítulo 1

Introducción

La gran explosión de la comunicación digital ha producido en los últimos años que haya cambiado la forma de interaccionar entre la gente. De ahí que muchas organizaciones se esten moviendo hacía formas de comunicación en red debido a los requerimientos de que su información este disponible y segura al mismo tiempo. Muchas de ellas se han dado cuenta de la ventaja y beneficios que las tarjetas inteligentes ofrecen.

Una tarjeta inteligente es un dispositivo capaz de almacenar datos, llevar a cabo funciones por sí misma e interactuar de forma inteligente con un lector externo mediante un microprocesador empotrado en un tarjeta de plástico. Se ha expandido ampliamente gracias a su facilidad de uso, portabilidad y precio [27]. Son resistentes a la manipulación y proporcionan características de seguridad que les hace ser considerados dispositivos seguros y de confianza. Esto hace que sean usadas en aplicaciones donde se necesita alta seguridad y apropiadas para sistemas criptográficos y operaciones como autenticación.

Son especialmente interesantes las tarjetas inteligentes multiaplicación. No están muy extendidas debido al problema del control de las interacciones entres sus aplicaciones, especialmente cuando estas son añadidas después de la emisión de la tarjeta. Lo que falta es una forma rápida de realizar modificaciones sobre aplicaciones de manera asíncrona una vez que la tarjeta ha sido emitida. De esta forma, los emisores de las aplicaciones pueden confiar en que su aplicación no será accedida o modificada de forma inesperada.

El esquema de Seguridad-mediante-Contrato ($\mathsf{S}\times\mathsf{C}$) soluciona este problema mediante la comparación de un contrato que acompaña la aplicación con la política de la tarjeta. Pero dado que la tarjeta tiene recursos computacionales limitados, puede ser necesario llevar a cabo dicha comparación fuera de la tarjeta, en una tercera parte de confianza. Para ello, es necesario securizar la comunicación entre la tarjeta y esa parte. Esa es la base del problema a resolver.

Este proyecto se desarrolla en el marco de una Master Thesis de 30 ECTS en el departamento DTU Informatiks de la Technical University of Denmark (DTU), Lyngby (Copenhagen). Dicho proyecto, previamente a su depósito en el Centro Politécnico Superior (C.P.S.) de Zaragoza, ha sido entregado, presentado y evaluado en la DTU obteniendo la nota de 10.

1.1. Tarjetas inteligentes

Estos dispositivos están ampliamente extendidos por las características de seguridad que ofrecen a sus usuarios junto a la sencillez de su uso. Su hardware, tipos, aplicaciones, características físicas y de seguridad son descritas de forma más extensa en el Apéndice C. A continuación se destaca lo más importante.

Respecto al interfaz de comuniación que utilizan, pueden diferenciarse dos tipos de tarjetas. Los ataques que pueden ser llevados a cabo dependen de esta característica.

- Tarjetas inteligentes de contacto. Para encederse necesitan ser insertadas en un Disposito de Aceptación de Tarjetas (CAD, por sus siglas en inglés), que es el interfaz situado entre el host y la tarjeta. El área de contacto son ocho celdas que estan en contacto físico con el lector. Una desventaja de estas tarjetas es que pueden empezar a fallar como consecuencia del desgaste de sus celdas.
- Tarjetas inteligentes sin contacto. La comunicación, así como el suministro de energía, se lleva a cabo mediante el aire gracias a una antena situada dentro del cuerpo de plástico de la tarjeta. Utilizan un interfaz de radio frecuencia [27]. Dado que el chip está dentro del plástico, está más protegido y no sufre por el desgaste de sus contactos, luego tienen una vida más larga. Son tarjetas más fiables, pero más caras que las anteriores.

En lo concerniente al hardware, una tarjeta inteligente contiene:

Microprocesador Normalmente no construidos exclusivamente para tarjetas inteligentes por razones de dinero y seguridad. Los actuales estan basados en arquitecturas de 32-bit Reduced Instruction Set Computer (RISC) [27].

Memoria Dividida en tres partes: de acceso aleatorio (RAM), de solo lectura programable y borrable eléctricamente (EEPROM) y de solo lectura (ROM). Debido a que cada una de ellas ocupa una cantidad distinta de espacio por bit, se añaden siguiendo esta limitación: ROM donde sea posible, después EEPROM y finalmente RAM.

Coprocesadores Se trata de hardware suplementario para ayudar al microprocesador en tareas particulares. Los fabricantes son los que deciden cuales incluir debido a que incrementan el precio del chip considerablemente [27]. Los más importantes y normalmente añadidos son para algoritmos criptográficos y generación de números aleatorios.

Las principales aplicaciones se muestran a continuación [44][17], más información en Apéndice C.

Telecomunicación Las más conocidas son las tarjetas Subscriber Identity Model (SIM). Merece la pena también mencionar las casi extintas tarjetas prepago para llamar.

Banca Tarjetas de crédito, débito, etc.

Transporte Gran cantidad de tarjetas sin contacto han sido expedidas como las *Oyster Card* en Londres.

Control de acceso Se usan para restringir el acceso físico tanto a lugares como recursos.

Identificación Por ejemplo pasaportes electrónicos.

Otras aplicaciones Asistencia sanitaria, autenticación, tarjetas de fidelización, industria audiovisual, dinero para juegos, e-servicios, mallas de computación, etc.

Información sobre seguridad en tarjetas inteligentes se puede encontrar en el Apéndice C, sección 5.

1.2. Multiaplicación y Seguridad-mediante-Contrato

En lo que respecta a tarjetas inteligentes, las que despiertan mayor interés son las multiaplicación, y especialmente las tarjetas inteligentes multiaplicación abiertas. Su característica más importante es la oportunidad de permitir una carga dinámica de aplicaciones. Esto significa tener la posibilidad de añadir, actualizar o eliminar cualquier aplicación en la tarjeta en cualquier momento después de su emisión. Las tarjetas más conocidas de este tipo son MULTOS y Java Card. Asimismo, merece la pena destacar el estándar Global Platform. Todo esto se amplia en el Apéndice D.

El problema de este tipo de tarjetas es el control de las interacciones entre las aplicaciones almacenadas en ellas. Estas interacciones pueden llevar a comportamientos indeseados entre las aplicaciones. Por ejemplo, que una aplicación malintencionada consiga datos secretos de otra aplicación relacionada con temas bancarios. Aunque se han desarrollado herramientas como el cortafuegos y el interfaz de compartición de objetos (SIO, por sus siglas en inglés) de Java Card que intentan corregir estos problemas, ninguna lo hace de forma correcta ya que por ejemplo una aplicación puede utilizar el SIO para sus propios propósitos [34]. En definitiva, se pueden llegar a dar intercambios de información inesperados.

La idea de Seguridad-mediante-Contrato (*Security-by-Contract*,S×C) se ha desarrollado con objeto de resolver este problema. Este enfoque consiste en que cualquier aplicación debe venir acompañada de un contrato que especifique su comportamiento. Este contrato será comparado con la política de seguridad de la tarjeta; si cumple con lo esperado será aceptado y la aplicación instalada, en otro caso será rechazado. De esta forma, sólo se instalan aplicaciones que cumplan con el comportamiento deseado por la tarjeta.

1.3. Contexto del problema

Sin embargo, las tarjetas inteligentes son dispositivos limitados en recursos mientras que el algoritmo que realice la comparación anterior puede llegar a ser considerablemente complejo. Por ello, el esquema de S×C proporciona una jerarquía de modelos para la definición de contratos y políticas. Conforme aumenta el nivel de la escala, aumenta la complejidad de la definición por lo que se hace necesario mayor esfuerzo computacional. Se espera que en el nivel más alto, la tarjeta no pueda llevar a cabo la comparación por lo que sea necesario externalizar esa comparación a un dispositivo externo con mayor potencia computacional.

Dado que la información que se envia en la comunicación es la fundamental (contrato, política y resultado) del esquema propuesto, se debe asegurar dicha comunicación con objeto de que no pueda ser manipulada. Si pudiera llegar a ser modificada, el esquema completo sería inservible ya que la tarjeta no podría confiar en lo que el dispositivo externo le manda.

El proyecto que cubre este documento se enmarca en la construcción de un sistema que resuelva el problema anterior: asegurar la comunicación entre la tarjeta y un dispositivo externo para que la externalización del proceso de comparación entre el contrato y la política sea confiable.

1.4. Análisis de la solución

La solución al problema anterior se basa en la creación de un sistema criptográfico que asegure la comunicación proporcionando mutua autenticación, confidencialidad e integridad. Las identidades se manejan a través de certificados, lo que hace necesario el uso de un analizador sintáctico en la tarjeta para permitir que ella misma pueda verificar dichos certificados. Precisamente el uso de certificados junto con el almacentamiento de la política inicial de seguridad de la tarjeta provocan que sea necesario una fase de inicialización de la misma, durante la cual se generan sus certificados y se almacenan junto con la política. Esta fase debe llevarse a cabo de forma previa a la utilización de la tarjeta, ya que hasta ese momento su uso no es seguro. En esta solución, participan varias entidades con distintos roles: la tarjeta inteligente, un tercera parte de confianza sobre un entorno seguro que se encarga de realizar la inicialización de la tarjeta, otra tercera parte de confianza que realiza la comparación entre contrato y política y finalmente el emisor de la aplicación a añadir que debe almacenar el contrato en la tarjeta para poder llevarse a cabo la comparación previa. Cada entidad realiza comunicaciones de distinto tipo con la tarjeta con diferentes necesidades de seguridad.

El proyecto aporta el diseño presentado para resolver el problema de la externalización de la comparación entre contrato y política. Aunque diseños similares se han desarrollado para resolver problemas criptográficos, la contribución del proyecto es el diseño e implementación de la solución al problema en un dispositivo de recursos limitados con todo lo que ello implica: comunicación mediante Application Protocol Data Unit (APDU), restricciones de memoria, API limitada, requerimiento de un analizador léxico a construir en la tarjeta, etc. Particularmente, no solo proporciona dicho diseño para tarjetas inteligentes sino que se centra en resolver el problema para el esquema de S×C.

1.5. Objetivos y resultados

Los principales objetivos del proyecto, descritos de forma sintetizada, son los mostrados a continuación:

Diseño del sistema que resuelva el problema previamente explicado

Implementación de un prototipo

Validación del prototipo

Establecido esto, lo que se espera obtener del proyecto es el diseño de un sistema que proporcione una comunicación segura para poder confiar en la externalización de la comparación entre contrato y política para tarjetas multiaplicación. El sistema debe proporcionar mutua autenticación, confidencialidad e integridad. Todo ello se logra mediante una infraestructura de clave pública (PKI, por sus siglas en inglés). Dicho diseño debería ir acompañado de un prototipo construido que sirva como prueba de concepto para demostrar la validez del sistema previamente diseñado. Estas dos cosas, el diseño y el prototipo, son los resultado esperados del proyecto. Por último, la validación del prototipo debe ser realizada para asegurar la corrección de lo anterior. Asimismo, dado que las tarjetas inteligentes son dispositivos limitados en recursos especialmente de memoria, se espera que se realice algún tipo de memoria que permita analizar la idoneidad y viabilidad o no del sistema desarrollado en términos del espacio necesario en la tarjeta para llevar a cabo la idea de S×C. A este sentido, cabe destacar que del prototipo lo que se espera es obtener una implementación funcional y que signifique una acotación superior de sus necesidades de memoria. En otras palabras, no se espera obtener una versión optimizada de dicho prototipo.

1.6. Estructura de la memoria

La parte principal de esta memoria, excluyendo los apéndices, se estructura en cinco capítulos que siguen el siguiente orden:

1. Análisis del problema. Detalla el problema a resolver partiendo de un resumen del trabajo relacionado y el marco sobre el que se situa.
2. Diseño de la solución. Describe la arquitectura del sistema propuesto como solución al problema a resolver.
3. Implementación. En esta sección se aportan detalles de la implementación de la solución, incluyendo cambios necesarios en el diseño para la construcción del prototipo.
4. Evaluación. Presenta un ejemplo de utilización del sistema en forma de guía de usuario, así como un análisis de la memoria empleada por el sistema.
5. Conclusion. Contiene la conlusión, limitaciones y problemas encontrados, sugerencias de trabajo futuro y una valoración personal de lo que ha supuesto el desarrollo del proyecto.

Adicionalmente, con objeto de detallar el trabajo llevado a cabo se incluyen dos apéndices que contienen la gestión del tiempo y esfuerzo (Apéndice A) y la metodología de desarrollo (Apéndice B). Mediante la inclusión de ambos apéndices, se pretende que el lector tenga una idea más clara de las tareas realizadas, el esfuerzo invertido y la forma de llevarlas a cabo.

La memoria resultante del proyecto desarrollado en la Technical University of Denmark (DTU) ha sido añadida en forma de apéndices correspondiendo cada uno de ellos con los diferentes capítulos de dicho documento. Así pues, los anexos que van desde el Apéndice C hasta el H, contienen los capítulos de la memoria, mientras que los apéndices desde el I hasta el L contienen sus anexos. Todos estos anexos que corresponden a la memoria desarrollada y presentada en DTU, se encuentran en inglés. Dado que la memoria completa desarrollada para la universidad danesa es más detallada, en la presente, de menor longitud, se harán constantes referencias a los apéndices que contienen la primera con objeto de completar la información sobre el trabajo desarrollado.

Resultados preliminares del proyecto fueron aceptados y serán presentados en forma de publicación el próximo octubre en "The Fourth International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies (Ubicomm) 2010". Dicha publicación, cuya referencia se muestra a continuación, se puede encontrar en el Apéndice M.

[M] Nicola Dragoni, Eduardo Lostal, Davide Papini, and Javier Fabra. Securing Off-Card Contract-Policy Matching in Security-By-Contract for Multi-Application Smart Cards. *Ubicomm: The Fourth International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies*, 2010. Accepted for publication.

Por último, cabe destacar que a lo largo del presente documento (tanto en los capítulos como especialmente en los apéndices) se hace continuo uso de acrónimos, por lo que se aconseja al lector la lectura del correspondiente glosario (Apéndice N), tanto de su sección de castellano como de inglés.

Capítulo 2

Análisis del problema

Las tarjetas inteligentes multiaplicación permiten a los consumidores hacer una gestión (descarga y eliminación) dinámica de las aplicaciones durante el ciclo de vida de la tarjeta. La razón por la que ejemplos de estas tarjetas aún son raros es por la falta de solución al control de las interacciones entre las aplicaciones. De hecho el modelo de negocio de descarga y actualización asíncrona de aplicaciones por diferentes partes requiere el control de las interacciones entre las posibles aplicaciones trás la emisión de la tarjeta. La clave es asegurar a los emisores de las aplicaciones que estas no serán accedidas por otras indeseadas añadidas tras ellas, o al menos que sus aplicaciones sólo interaccionarán con otras de algunos socios de negocio.

El estado del arte de este problema se puede encontrar en el Apéndice E.

2.1. Seguridad-mediante-Contrato

Seguridad-mediante-Contrato es el esquema propuesto para prevenir el intercambio ilegal de información entre diversas aplicaciones, comprobando las interacciones en el momento de carga de la aplicación en la tarjeta. S×C resuelve también el problema de los cambios después de la emisión de la tarjeta, es decir carga, eliminación o actualización dinámica de aplicaciones durante el ciclo de vida de la tarjeta. En otras palabras, la evolución dinámica del contenido de la tarjeta inteligente.

El enfoque de S×C se construye sobre la idea de Código Conteniendo el Modelo (MCC por sus siglas inglesas) y ha sido apropiadamente desarrollado para entornos de código móvil ([33]), intentando adaptarse a la tecnología de tarjetas inteligentes. En términos generales, consiste en la idea de contrato que especifica el comportamiento de la aplicación, de política que especifica la política de seguridad de la tarjeta y el algoritmo de comparación que comprueba si el contrato se ajusta a la política. El objetivo es hacer esta comprobación cuando se carga la aplicación en la tarjeta ahorrando costosas monitarizaciones en tiempo de ejecución. Los problemas que este esquema pretende resolver se pueden resumir como lo hace [35] en:

1. Una nueva aplicación no debería interaccionar con aplicaciones prohibidas ya almacenadas

2. Un cambio dinámico no debería afectar al funcionamiento correcto de applicaciones ya almacenadas. Estos cambios pueden ser:

   - Adición de una nueva aplicación
   - Actualización de una aplicación
   - Cambios en la política de la tarjeta
   - Eliminación de una aplicación

Un contrato es una especificación completa, correcta y formal del comportamiento de una aplicación en lo que respecta a acciones de seguridad relevantes y particularmente con problemas de intercambio de datos sensibles. No solo almacena el comportamiento de la aplicación sino el deseable para otras aplicaciones en relación a communicaciones directas o indirectas con ellas [34]. El objetivo es que una nueva aplicación sea capaz de expresar su deseo de interactuar con otras aún no presentes en la tarjeta, por ejemplo. El contrato es proporcionado por el emisor de la aplicación quien es el responsable de adjuntarlo a la aplicación a ser instalada.

Una política es una especificación formal y completa del comportamiento aceptable para las aplicaciones que esperan ser ejecutadas en la tarjeta en lo que respecta a sus acciones relevantes de seguridad (ambas definiciones obtenidas de [33]). La política inicial debe ser creada por el emisor de la tarjeta. Es el responsable de preparar los requerimientos de la tarjeta.

2.1.1. Esquema de trabajo de la Seguridad-mediante-Contrato

En lo que respecta a S×C para código móvil, la plataforma objetivo (i.e., tarjetas inteligentes) sigue un esquema similar al mostrado en la Figura E.1 en tiempo de carga de la aplicación. Primero, comprueba que la evidencia es correcta. Tal evidencia puede ser una firma digital. Como alternativa a la evidencia puede usarse cualquier tipo de prueba confirmando que el código satisface el contrato (i.e., [15] para tarjetas inteligentes).

Una vez que se tiene la evidencia de que el contrato es digno de confianza, la plataforma comprueba que este se ajusta a la política de la plataforma objetivo. Este proceso es la Comparación Contrato-Política. Si se ajusta, la aplicación se puede lanzar. La comparación garantiza que las interacciones resultantes son correctas. Esto resulta en un ahorro considerable sobre el uso de monitores de referencia en ejecución [32].

Volviendo a las tarjetas inteligentes, el algoritmo de comparación debería dar un resultado positivo sólo en el caso que cada petición del contrato sea conforme a todos los requerimientos de seguridad que la tarjeta requiere. Particularmente, ambos debería coincidir si no dan lugar a ninguna fuga o intercambio ilegal de información entre la nueva aplicación y otra existente en la tarjeta.

2.1.2. Jerarquía de modelos de contrato/política

Se considera más seguro realizar la comprobación previa en la misma tarjeta, ya que supone no tener que confiar en entidades externas. Su característica de resistencia a la manipulación de los contenidos hace que las operaciones en la tarjeta sean más confiables. Sin embargo, dados sus recursos limitados puede llegar a ser neceario que algunas operaciones se lleven a cabo fuera de la tarjeta [25].

Es precisamente por dichas limitaciones computacionales por las que S×C propone una jerarquía de modelos para contratos y políticas. Éstos tienen diferentes características en cada nivel de la jerarquía especificando el comportamiento de la aplicación con diferente profundidad en función de la capacidad computacional esperada para ese nivel. En otras palabras, cada nivel trabaja sobre diferentes capacidades computacionales y tiene diferentes limitaciones de expresividad acorde a ellas. Por ejemplo, el nivel más bajo tiene los mayores beneficios en términos computacionales, pero sus contenidos pierden en expresividad; es decir, son menos concretos. Por otra parte, el nivel más alto necesita de muchos recursos del procesador, pero permite una completa especificación de contratos y políticas.

Los niveles propuestos son [34]:

L0: Aplicación como servicio. En este nivel las aplicaciones son definidas como una lista de servicios disponibles y requeridos, similares a la configuración de *Global Platform*. Este es el nivel que necesita menos esfuerzo computacional y presumiblemente puede ser llevado a cabo en la propia tarjeta.

L1: Flujo de control permitido. Este nivel construye un grafo representando la aplicación donde los vértices son los estados de esta y las aristas la invocación de diferentes servicios. Permite realizar un control de la información más detallado. Los niveles más abstractos se basan en él, añadiendo otras características.

L2: Flujo de control deseado y permitido. Añade estados correctos y de error al grafo previo. El objetivo es proporcionar una forma de comprobar que cualquier cambio en la política o la eliminación de una aplicación no evite el correcto funcionamiento del resto.

L3: Flujo completo de información. En este nivel, el grafo es mejorado añadiendo el flujo de información entre las variables. Requiere el esfuerzo computacional más alto.

2.1.2.1. Limitación del nivel 0

El problema del nivel 0 es que sólo captura el posible intercambio de información entre las aplicaciones en lugar del real; lo que significa que no puede especificar el comportamiento de una aplicación. Como [35] refleja, no es posible distinguir entre servicios que una aplicación puede necesitar de los que realmente requiere. Por ejemplo, supongamos que una aplicación A en la tarjeta, la cual se quiere eliminar, proporciona un método que otra aplicación B puede requerir. Lo que el nivel 0 no puede comprobar es si la aplicación B seguirá trabajando apropiadamente tras quitar la aplicación A. Para hacerlo necesita otro nivel de abstracción. Tampoco puede capturar las comunicaciones indirectas entre las aplicaciones.

Esa es la razón por la que para un nivel de seguridad más alto es apropiado usar algún otro nivel. El problema radica en la capacidad computacional limitada para realizar la Comparación Contrato-Política en la tarjeta para niveles más altos. Por ello, cuando dicha tarea requiere un gran esfuerzo es posible externalizar esa fase a una Tercera Parte de Confianza (TPC). Esto se llama Externalización de la Comparación Contrato-Política.

2.1.3. Problema: Securizando la externalización de la Comparación Contrato-Política

La idea de la externalización de la Comparación Contrato-Política se muestra en la Figura E.2. Se lleva a cabo cuando la fase de comparación es demasiado pesada (computacionalmente hablando) para realizarla en la tarjeta. En ese caso, es necesario hacer uso de una TPC que proporcione sus capacidades computacionales para correr el algoritmo de comparación. La TPC puede proporcionar una prueba de la conformidad a la tarjeta inteligente, la cual debe verificarla. La política de la tarjeta inteligente (TI) se actualiza según el resultado de la comparación recibida de TPC: si la comprobación ha sido exitosa, la política se actualiza con el nuevo contrato y la aplicación puede ser ejecutada. De otra forma, la aplicación se rechaza. En caso de que TPC incluya una prueba de la comparación en la respuesta, ésta debe ser verificada como se muestra en la Figura E.2.

Dado que la comunicación entre TI y TPC se lleva a cabo sobre un entorno inseguro, tiene que ser securizada. El sistema debe asegurar autenticación, confidencialidad e integridad de los datos enviados durante toda la comunicación. Para garantizar la autenticación e integridad, las dos partes (TI y TPC) tienen que cifrar y firmar sus mensajes por medio de sus parejas de claves. Deberían mantener su clave privada secreta y enviar sus claves públicas a la otra entidad. Por tanto, es necesario algún tipo de intercambio de claves al inicio.

Pero este no es tan fácil ya que algún intruso puede intentar interceptar dichas claves como sucede en un ataque muy común: Hombre en el medio. Este ataque consiste en que un intruso se coloca entre la entidad externa y la tarjeta y lanza conexiones independientes a estas partes haciéndoles creer que se comunican entre ellas cuando en realidad todos los mensajes llegan al intruso. Un ataque de este tipo puede llevarse a cabo durante el intercambio de claves, haciendo inútil el sistema de clave pública, ya que el intruso consigue todos los mensajes en claro. Se realizaría de la siguiente forma. TPC envía la clave pública a la tarjeta, pero el intruso intercepta el mensaje sustituyendo la clave por otra que sólo el conoce. La tarjeta recibe esta clave del intruso y responde con la suya. El intruso intercepta de nuevo el mensaje sustituyendo la clave por otra nueva que le manda a TPC. Tras esto, el intruso puede interceptar y conseguir el texto en claro del resto de los mensajes sin que las otras partes se den cuenta de ello.

Este problema se resuelve usando certificados que hayan sido emitidos por una Autoridad de Certificación (AC) en la que ambas partes confíen. Los certificados identifican a su dueño inequívocamente y no pueden ser falsificados por ser firmados con la clave privada de la AC. Sin embargo, los certificados de TI no se pueden enviar a través de un medio inseguro para que sean instalados ahí, ya que podrían ser víctimas del ataque previamente descrito. Deben ser almacenados a través de un medio seguro y sólo una vez durante la inicialización de la tarjeta. Esto es por lo que una fase de inicialización es necesaria. Se realiza a través de un medio seguro gracias a un Lector Seguro (LS) el cuál está situado entre la tarjeta y la AC. Es el responsable de enviar las peticiones de certificación (CSR por sus siglas en inglés) a la AC y almacenar los certificados en la tarjeta. La tarjeta no puede ser usada hasta que la fase de inicialización haya terminado. En otro caso, no se logran los requerimientos de seguridad y las verificaciones no pueden realizarse. Cualquier cambio sobre cualquier aplicación debería ser rechazado hasta finalizar la inicialización. Una vez que todo ha sido almacenado, la tarjeta esta lista para trabajar.

En definitiva, el proyecto se centra en resolver el problema de securizar la comunicación entre TI y TPC durante la externalización de la fase de Comparación Contrato-Política. El objetivo es hacer segura y digna de confianza la comunicación a través de un medio inseguro satisfaciendo los requerimientos de mutua autenticación, confidencialidad e integridad. Para lograrlo, se hace uso de una infraestructura de clave pública la cual necesita certificados para gestionar las identidades.

Capítulo 3

Diseño de la solución

El problema cuya solución se desarrolla en este capítulo es la securización de la comunicación entre TI y TPC para poder realizar de forma segura la externalización del proceso Comparación Contrato-Política a TPC sobre un medio inseguro en términos de mutua autenticación, confidencialidad e integridad. La solución se basa en un sistema de clave pública con identidades manejadas por certificados, lo que hace necesaria una fase de inicialización (distinta de la fase de instalación). El sistema se basa en la suposición de que TPC es un dispositivo seguro, de forma que TI pueda confiar en el resultado de la comparación hecha en él. Es por ello que lo que debe ser asegurado es la comunicación. Con objeto de ayudar a la comprensión del sistema, cabe destacar que la tarjeta trabaja como un servidor, de forma que siempre es la entidad externa la que debe comenzar la comunicación. Es por ello que a lo largo de este capítulo el término *Comando* se utilizará para referirse a los mensajes enviados desde cualquier entidad externa a la tarjeta, mientras que el término *Respuesta* se referirá a los mensajes de la tarjeta al exterior.

En la solución propuesta, cada una de las entidades que participan en la fase de comparación (TI y TPC) posee dos parejas de claves: una para cifrar y otra para firmar. Aunque es posible realizar ambas cosas con una sola pareja de claves, es más seguro hacerlo con dos. Ya que se consideran dos funciones criptográficas diferentes, en el improbable caso de que una de las dos fuera comprometida, la otra no. Por lo que proporcionan más seguridad. No obstante, para remarcar el hecho de que es opcional, en las figuras del capítulo aparece como tal.

3.1. Confidencialidad y Nonce

Dado que en el sistema lo realmente necesario es que ambas partes esten seguras quién es el remitente de los mensajes y que no hayan sido modificados; en otras palabras, autenticación e integridad, se puede plantear la pregunta de por qué confidencialidad es otro requerimiento. Las razones por las que el sistema proporciona también confidencialidad son para evitar ataques de sniffing sobre la información y que algún intruso fuera capaz de conseguir información sobre el comportamiento de la aplicación o la política con objetivo de intentar llevar a cabo ataques contra la tarjeta. Además, se debe tener en cuenta que algunos desarrolladores de aplicaciones pueden demandar esta característica, rechazando instalar su aplicación en la tarjeta si no se cumple. Por ejemplo, aplicaciones bancarias. La confidencialidad es normalmente recomendada si los recursos lo permiten, dado que sus beneficios son mucho mayores que sus desventajas.

En lo que respecta al Número usado una sola vez (Nonce por sus siglas en inglés) es necesario para prevenir a la tarjeta de ataques de repetición, en la que el mismo mensaje se reenvía en diferentes sesiones con el objeto de ser aceptado. El Nonce es algo parecido a una marca de tiempo que identifica cada sesión. Debe ser aleatorio para evitar su predictibilidad. Esta discusión se realiza en profundidad en la primera primera sección del Apéndice F.

3.2. Arquitectura del sistema

Esta sección describe las fases del sistema diseñado como solución. Aparecen en el orden que deberían ser ejecutadas.

3.2.1. Fase de instalación

Las aplicaciones en las tarjetas inteligentes deben ser instaladas para poder ser usadas. La instalación se realiza posteriormente al despliegue del bytecode en la tarjeta. Durante esta fase las claves son generadas y almacenadas en la tarjeta. Este hecho es el que hace el diseño del sistema tan seguro. Dado que las claves son generadas en la tarjeta, la clave privada nunca la abandona (no hay razón para ello). Esto hace casi imposible que un intruso pueda hacerse con ella, lo que significa que le será extremadamente díficil romper el sistema de clave pública.

3.2.2. Fase de inicialización

Esta fase se encarga de crear y almacenar los certificados de TI, de AC (necesario para verificar los certificados de TPC) y la política de la tarjeta. El proceso entero esta compuesto de tres etapas: Construcción de las peticiones de certificado (CSR), emisión de certificados y finalmente el almacenamiento de la política. El Lector Seguro (LS) es la entidad externa que se encarga de este trabajo.

Se debe llevar a cabo sobre un entorno considerado seguro. LS se encarga de almacenar los certificados y la política, por lo que la seguridad de la tarjeta depende de él. Si el almacenamiento es comprometido, y por tanto lo almacenado en la tarjeta, también lo es el resto del sistema. Es por ello, que este entorno debe ser seguro.

Merece la pena mencionar que esta fase solo puede realizarse una vez, o mejor dicho, que cada almacenamiento puede ser realizado una sola vez. Así se evita que cualquiera pueda almacenar lo que desee en la tarjeta.

3.2.2.1. Construcción de peticiones de certificados

En esta etapa los CSRs se generan y almacenan en el LS para ser enviados a la AC.

Una petición de certificado está compuesta de un nombre distinguido, una clave pública y, opcionalmente, un conjunto de atributos. Todo esto es firmado por medio de la entidad que pide el certificado. Una AC recibe el CSR y si es correcto (información y firma), crea un certificado de clave pública conteniendo la información del CSR. La firma se usa como evidencia de que la entidad que esta pidiendo el certificado es la dueña de la clave pública. Normalmente, AC puede requerir otros medios no-electrónicos para asegurarse de la identidad de la entidad que solicita el certificado.

LS tiene que crear dos CSRs, uno para cada par de claves. El CSR para cifrar se crea en primer lugar, luego el usado para firmar. Para hacerlo necesita las claves públicas almacenadas en la tarjeta. Esto es por lo que para construir el CSR, el primer *Comando* enviado desde LS a TI, solicita la clave pública para cifrar (TICPuCif) y no contiene ningún dato. TI recibe la petición y contesta con una *Respuesta* incluyendo TICPuCif.

LS por medio de TICPuCif crea el CSR para cifrar (TICifCSR) añadiendo la pertinente información. Sin embargo, la tarjeta tiene que firmar el CSR dado que es la dueña de la clave privada. De forma que en este momento LS tiene que enviar TICifCSR a la tarjeta y ser firmado ahí con la clave privada para cifrar (TICPrCif). De ese forma, AC puede verificar que la firma es correcta, y consecuentemente, que la clave pública coincide con la privada del solicitante. En otras palabras, la firma es lo que la AC necesita para asegurarse que TICPuCif pertenece a quien esta enviando el TICifCSR, porque es el único que puede firmar con la clave privada que corresponde a la pública del CSR. Una vez esta firmado, la tarjeta envía una *Respuesta* conteniendo el TICifCSR firmado ($\mathrm{Fir}_{TICPrCif}$(TICifCSR)) en los datos. Este proceso se muestra en la Figura 3.1.

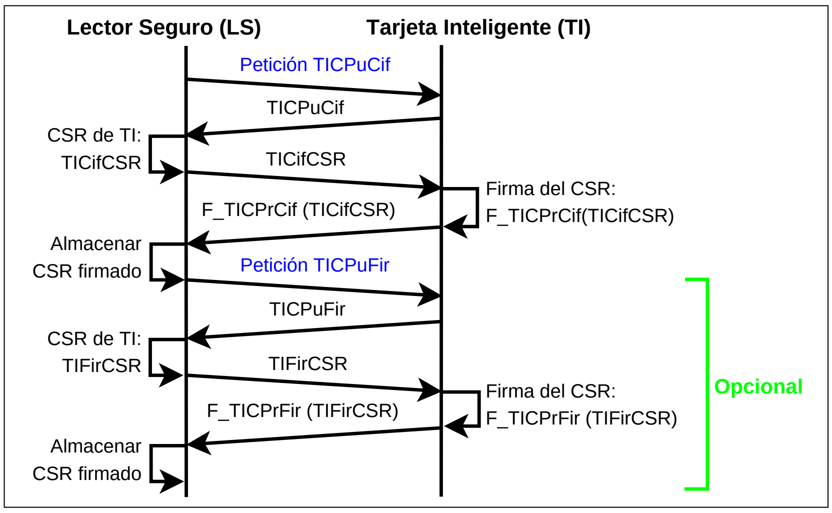


Figura 3.1: Fase de inicialización: Digrama de construcción de los CSRs

Como notación cabe destacar que en la Figura 3.1 y siguientes, los mensajes que aparecen en azul son mensajes que no contienen datos, mientras que los que estan en negro sí.

En definitiva, el flujo de mensajes para la construcción del primer CSR es:

1. *Comando* 1: No contiene datos, solicita TICPuCif
2. *Respuesta* 1: TICPuCif
3. *Comando* 2: TICifCSR
4. *Respuesta* 2: CSR firmado, esto es $\mathrm{Fir}_{TICPrCif}$(TICifCSR)

LS almacena $\mathrm{Fir}_{TICPrCif}$(TICifCSR) y, tras esto, construye el CSR para firmar (TIFirCSR) de la misma forma: solicita la clave pública para firmar a la tarjeta (TICPuFir), construye TIFirCSR y lo envia a la tarjeta para que se firmado con la clave privada para firmar (TICPrFir). Por lo tanto, los mensajes para la construcción del segundo CSR contendrán:

1. *Comando* 1: Sin datos, solicita TICPuFir
2. *Respuesta* 1: TICPuFir
3. *Comando* 2: TIFirCSR
4. *Respuesta* 2: CSR firmado, esto es $\mathrm{Fir}_{TICPrFir}$(TIFirCSR)

3.2.2.2. Emisión de certificados

Una vez los CSRs han sido construidos y firmados, LS tiene que enviarlos a una AC para conseguir los correspondientes certificados. Este proceso se muestra en la Figura 3.2. En esta fase LS pasa a ser LS-Gestor de certifidos ya que no es cuestión de la etapa de diseño decidir como se realizará esta parte, sino que se trata de detalles de implementación.

El contenido de los mensajes intercambiados entre el LS-Gestor de certificados y la AC son los siguientes:

1. *Comando* 1: $\text{Fir}_{TICPrCif}$(TICifCSR)
2. *Respuesta* 1: TICertCifr, certificado de TI para cifrar
3. *Comando* 2: $\text{Fir}_{TICPrFir}$(TIFirCSR)
4. *Respuesta* 2: TICertFirm, certificado de TI para firmar

Cada certificado contiene (entre otras cosas) información sobre el dueño de la clave, la clave pública y la firma. Por ejemplo, los certificados anteriores deberían contener:

- Información que identifique al dueño: ID_{TI}
- Clave pública a ser identificada por el certificado: TICPuCif/TICPuFir
- Firma del certificado: Fir_{CPrAC} (TICifInfo/TIFirInfo)

Una vez que los certificados han sido emitidos por la AC, enviados y recibidos, LS los almacena hasta que puedan ser enviados y almacenados en TI.

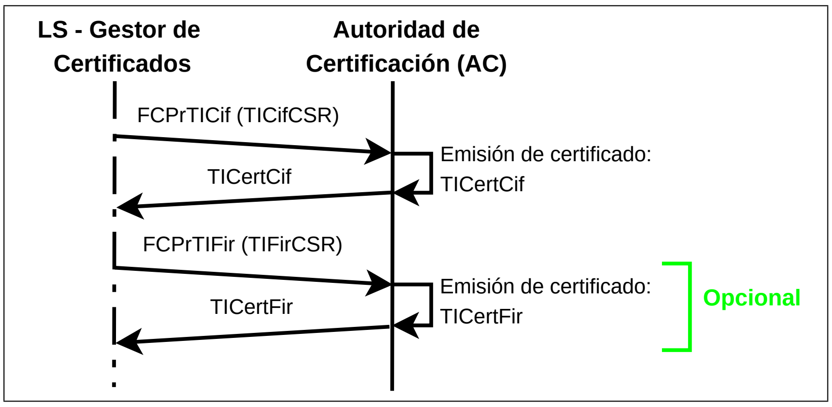

LS - Gestor de Certificados
Autoridad de Certificación (AC)
FCPrTICif (TICifCSR)
Emisión de certificado: TICertCif
TICertCif
FCPrTIFir (TIFirCSR)
Emisión de certificado: TICertFir
TICertFir
Opcional

Figura 3.2: Fase de inicialización: Diagrama de emisión de certificados

3.2.2.3. Almacenamiento de certificados y política

La última etapa de la fase de inicialización es el almacenamiento de todo lo necesario en la tarjeta. LS tiene que enviar los certificados tanto de TI como de CA y la política de seguridad inicial de la tarjeta. Cada una de las cosas a ser almacenadas deben enviarse por separado en un *Comando* diferente. La tarjeta siempre responde con una confirmación sin datos. Esta etapa puede observarse en la Figura 3.3. Como se ha puntualizado antes, estos mensajes pueden ser enviados una sola vez, es decir, cada uno de estos objetos solo puede ser almacenado en la tarjeta una vez.

Los datos enviados dentro de los *Comando* de LS son los siguientes (el orden no es importante):

- *Comando* 1: Certificado de AC
- *Comando* 2: TICertCifr
- *Comando* 3: TICertFirm
- *Comando* 4: Política inicial de seguridad de la tarjeta

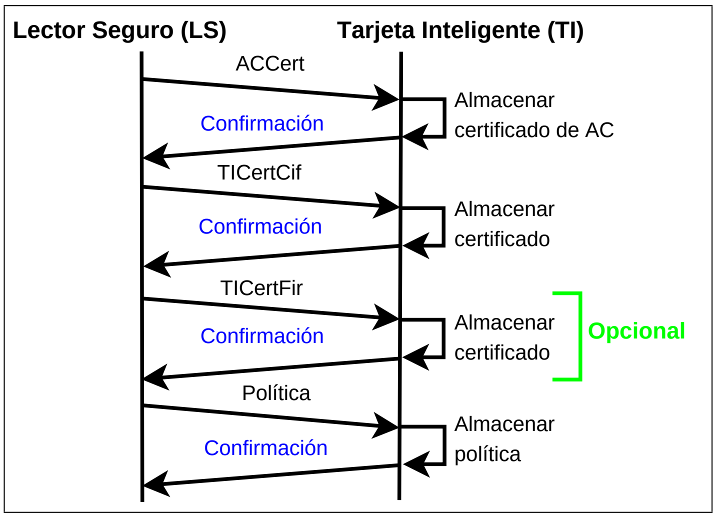


Figura 3.3: Fase de inicialización: Diagrama de almacenamiento de certificados y política

Después de que TI haya sido inicializada, está lista para ser usada para realizar de forma segura su actividad. En este momento, la tarjeta es capaz de verificar la identidad de TPC (verificar sus certificados), autenticar y autorizar sus peticiones.

3.2.3. Fase de almacenamiento del contrato

En esta fase el contrato de la aplicación que se desea instalar debe ser almacenado en la tarjeta. Debe llevarse acabo de forma previa a la Comparación Contrato-Política, ya que esta fase hace uso de dicho contrato. El esquema es el siguiente. El Emisor de la Aplicación (EA) envía el contrato a TI. TI lo almacena y le manda una confirmación de su llegada. El proceso se muestra en la Figura F.5. En ella EA se denomina AI por sus siglas en inglés.

3.2.4. Fase de Comparación Contrato-Política

La Comparación Contrato-Política es la fase clave del esquema de S×C. Tiene que correr el algoritmo de comparación por medio de los datos proporcionados a través de una comunicación segura entre TPC y TI. De forma más concreta, el contrato y la política almacenados en la tarjeta se envían cifrados desde la tarjeta a algún TPC que ejecutará el algoritmo de comparación devolviendo el resultado a la tarjeta. Esta fase se llevará a cabo cada vez que un cambio sea necesario sobre las aplicaciones de la tarjeta, ya sea adición, actualización, eliminación de aplicaciones o cambios en la política. Esta fase se ejecuta posteriormente a la de almacenamiento del contrato.

La fase de Comparación Contrato-Política tiene tres etapas:

1. Intercambio de certificados
2. Envío de contrato y política
3. Envío del resultado de la comparación

El proceso entero se puede observar en la Figura 3.4.

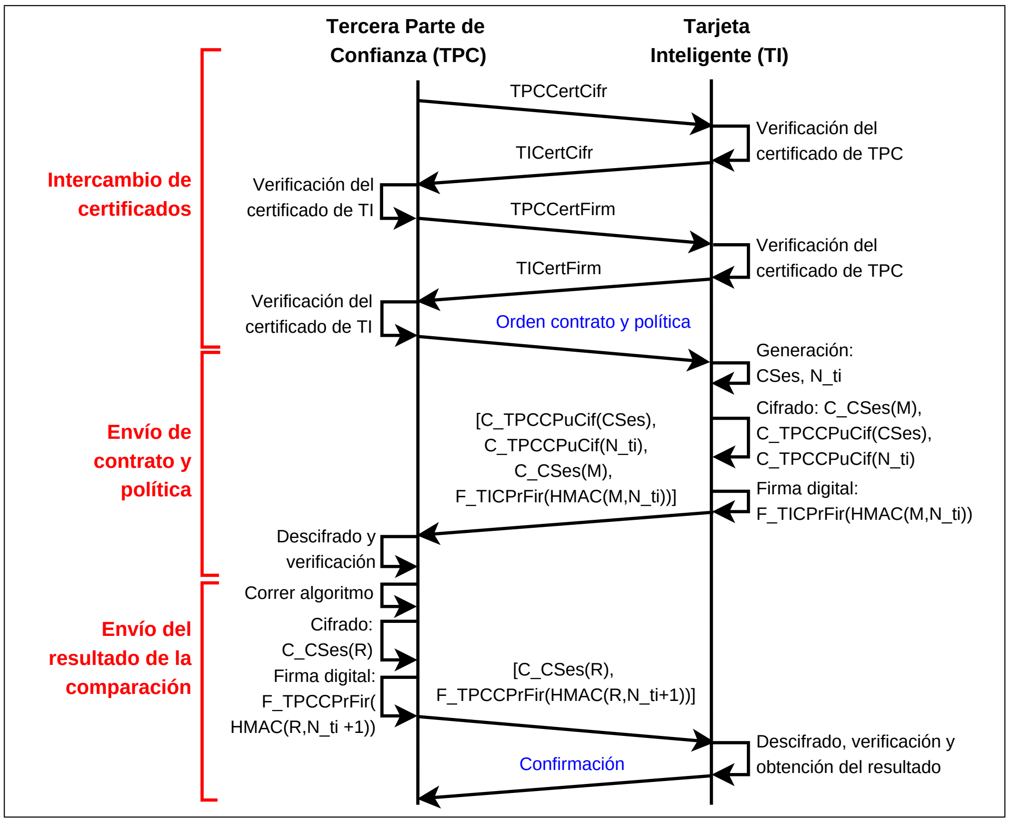

Tercera Parte de Confianza (TPC)
Tarjeta Inteligente (TI)
Intercambio de certificados
Envío de contrato y política
Envío del resultado de la comparación
TPCCertCifr
Verificación del certificado de TPC
TICertCifr
Verificación del certificado de TI
TPCCertFirm
Verificación del certificado de TPC
TICertFirm
Verificación del certificado de TI
Orden contrato y política
Generación: CSes, N_ti
Cifrado: C_CSes(M), C_TPCCPuCif(CSes), C_TPCCPuCif(N_ti)
[C_TPCCPuCif(CSes), C_TPCCPuCif(N_ti), C_CSes(M), F_TICPrFir(HMAC(M,N_ti))]
Firma digital: F_TICPrFir(HMAC(M,N_ti))
Descifrado y verificación
Correr algoritmo
Cifrado: C_CSes(R)
Firma digital: F_TPCCPrFir(HMAC(R,N_ti +1))
[C_CSes(R), F_TPCCPrFir(HMAC(R,N_ti+1))]
Descifrado, verificación y obtención del resultado
Confirmación

Figura 3.4: Diagrama de la fase de Comparación Contrato-Política

3.2.4.1. Intercambio de certificados

El intercambio de los certificados entre la tarjeta y el TPC se lleva a cabo por medio de mensajes que incluyen los correspondientes certificados. Cada parte tiene que intercambiar dos certificados con la otra parte: una para cifrar y otro para firmar. Lo que significa que cuatro mensajes son necesarios para completar el intercambio donde dos son de TPC y otros dos de TI.

TPC comienza la comunicación enviando su certificado en un *Comando*. El analizador en TI debería verificar el certificado con el de la AC almacenado. El analizador también obtiene la clave pública de TPC para cifrar. Si la verificación es positiva (el certificado es válido), TI responde con una *Respuesta* incluyendo su certificado para cifrar. TPC verifica este certificado y obtiene la clave pública correspondiente. Este proceso se repite para intercambiar los certificados para firmar. Se puede observar en la Figura 3.4. Los datos enviados durante esta etapa son:

- *Comando* 1: TPCCertCifr, certificado de TPC para cifrar
- *Respuesta*: TICertCifr
- *Comando* 2: TTPCertFirm, certificado de TPC para firmar
- *Respuesta* 2: TICertFirm

3.2.4.2. Envío de contrato y política

Cuando el intercambio de certificados ha terminado, TPC tiene que pedir el contrato y la política que se encuentran en la tarjeta. Así pues, envía un *Comando* sin datos para realizar la petición. Tanto el contrato como la política se envían dentro del mismo mensaje con objeto de reducir la cantidad de mensajes a intercambiar, esto es: TIContratoPolítica (las siglas TI se añaden para diferenciar los datos entre los enviados y los recuperados en la verificación TPCContratoPolítica, que se utilizará más adelante).

Contrato y política tienen que estar cifrados y firmados por la tarjeta antes de ser enviados para asegurar los requerimientos del sistema (autenticación, confidencialidad e integridad). El cifrado se realiza a través de criptografía simétrica en bloque. La razón de usar este tipo de cifrado en lugar de criptografía asimétrica (basada en PKI) es que la segunda es más lenta cuando se realiza sobre una cantidad considerable de datos, mientras que el cifrado simétrico proporciona una velocidad de cifra más alta (también de descifrado ya que es la misma operación). Además, la criptografía simétrica proveerá alta seguridad debido a su falta de linealidad (clave aleatoria y diferente en cada sesión) y que normalmente sólo ataques de fuerza bruta suelen funcionar (aunque depende del algoritmo ya que por ejemplo DES puede ser roto por criptoanálisis [8]). En definitiva, un cifrador en bloque es apropidado para ser usado sobre una cantidad de datos grande.

Usar criptografía simétrica implica que ambas partes deben conocer la clave. Así que la tarjeta, que es la genera la clave, tiene que enviar la clave compartida a TPC. Pero dicha clave no puede enviarse en texto plano ya que un intruso podría interceptar el mensaje y descifrar su contenido (no tiene sentido enviar el mensaje cifrado junto con la clave en plano con la que descifrar el mensaje). Es por eso que se cifra esta clave por medio de la clave pública de TPC, asegurando que éste será el único capaz de descifrarla. El cifrado se hace esta vez por medio de criptrogafía asimétrica ya que se trata sólo de unos pocos cientos de bits como máximo. La clave para criptografía simétrica cambiará en cada sesión para asegurar un nivel más alto de seguridad asegurando su frescura y aleatoriedad.

La secuencia de acciones a realizar por la tarjeta para securizar la *Respuesta* a TPC conteniendo el contrato y la política es la siguiente:

1. Generar una clave de sesión que será usada para criptografía simétrica: C_{ses}
2. Generar el Nonce: N_{TI}
3. Cifrar la clave de sesión a través de la clave pública de TPC para cifrar: $\text{Cif}_{TPCCPuCif}(C_{ses})$
4. Cifrar el Nonce a través de la clave pública de TPC para cifrar: $\text{Cif}_{TPCCPuCif}(N_{TI})$

5. Cifrar el mensaje con la clave de sesión:
   $\text{Cif}_{C_{ses}}(\text{TIContratoPolítica})$

6. Calcular el HMAC (un hash mezclado con un *salt*) del contenido:
   $\text{HMAC}(\text{TIContratoPolítica}, N_{TI})$

7. Firmar el HMAC anterior con la clave para firmar:
   $\text{Fir}_{TICPrFir}(\text{HMAC}(\text{TIContratoPolítica}, N_{TI}))$

Se usa una función Hash-based Message Authentication Code (HMAC)para crear la firma en lugar de una función de Hash normal como Secure Hash Algorithm (SHA), ya que HMAC añade una clave compartida (llamada *salt*) que asegura la frescura del resumen: cada HMAC construido con difererente *salt* dará lugar un resumen diferente. Además, garantiza que sólo las partes de la comunicación que conozcan esta clave compartida podrán generar el resumen y comprobar por tanto su integridad. Para construir este tipo de resumen, es necesario un número aleatorio renovado en cada sesión. Dado que el Nonce se ajusta perfectamente a estas características, es el usado.

Finalmente, la *Respuesta* segura construida para contestar a la petición del TPC es la siguiente:

- *Respuesta*: [$\text{Cif}_{TPCCPuCif}(C_{ses})$, $\text{Cif}_{TPCCPuCif}(N_{TI})$,
  $\text{Cif}_{C_{ses}}(\text{TIContratoPolítica})$,
  $\text{Fir}_{TICPrFir}(\text{HMAC}(\text{TIContratoPolítica}, N_{TI}))$], que contiene:
  - Clave de sesión cifrada: $\text{Cif}_{TPCCPuCif}(C_{ses})$
  - Nonce cifrado: $\text{Cif}_{TPCCPuCif}(N_{TI})$
  - Contrato y política cifrados: $\text{Cif}_{C_{ses}}(\text{TIContratoPolítica})$
  - Firma: $\text{Fir}_{TICPrFir}(\text{HMAC}(\text{TIContratoPolítica}, N_{TI}))$

TPC recibe la *Respuesta*, la cual tiene que descifrar y verificar. Para comprobar la integridad y autenticidad construye un HMAC del contenido que acaba de descifrar y lo compara con el HMAC que ha obtenido del descifrado de la firma. Si ambos HMAC coinciden, la autenticidad ha sido probada ya que sólo la tarjeta puede firmar con su clave privada. La integridad por su parte, también habrá sido comprobada ya que si ambos HMAC coinciden significa que los datos sobre los que el HMAC se ha realizado, coinciden con los descifrados, es decir, que nadie ha podido modificar el contenido. Obviamente, dado que dichos datos estaban cifrados, la confidencialidad también se ha cumplido.

La secuencia de acciones necesarias para llevar a cabo la verificación son las siguientes:

1. Descifrar la clave de sesión:
   $\text{Des}_{TPCCPrCif}(\text{Cif}_{TPCCPuCif}(C_{ses})) = C_{ses}$

2. Descifrar el Nonce: $\text{Des}_{TPCCPrCif}(\text{Cif}_{TPCCPuCif}(N_{TI})) = N_{TI}$

3. Obtener el contrato y política descifrando con la clave de sesión:
   $\text{Des}_{C_{ses}}(\text{Cif}_{C_{ses}}(\text{TPCContratoPolítica})) = \text{TPCContratoPolítica}$

4. Calcular el HMAC del contrato y la política descifrados:
   $\text{HMAC}(\text{TPCContratoPolítica}, N_{TI})$

5. Descifrar la firma a través de la clave pública para firmar de la tarjeta:
   $\text{Des}_{TICPuFir}(\text{Fir}_{TICPrFir}(\text{HMAC(TIContratoPolítica, } N_{TI}))) =$
   $\text{HMAC(TIContratoPolítica, } N_{TI})$

6. Si el HMAC calculado en el TPC a través del contenido descifrado del mensaje coincide con el HMAC obtenido de la firma del mensaje, los requerimientos de autenticidad, confidencialidad e integridad han sido cumplidos; de otra forma, no. Esto es:

   If (HMAC(TIContratoPolítica, N_{TI}) == HMAC(TPCContratoPolítica, N_{TI}))
   $\rightarrow$ Mensaje OK
   else $\rightarrow$ Requerimientos no cumplidos

Si la verificación es correcta, TPC ha obtenido el contrato y la política de una forma segura.

3.2.4.3. Envío del resultado de la comparación

Una vez el contrato y la política estan en posesión de TPC, éste puede ejecutar el algoritmo de comparación obteniendo el resultado correspondiente. Tras esto, tiene que construir un *Comando* seguro que lo contenga para ser enviado a la tarjeta de una forma similar ha como ha sido realizado antes el envío del contrato y la política. La clave usada para cifrar es la misma clave recibida antes y usada para descifrar previamente el mensaje (contrato y política). Así que en primer lugar se cifra el resultado con esta clave. La firma se realiza como antes con la diferencia que el HMAC usa como *salt* en este caso el valor N_{TI+1} en lugar del anterior. Este cambio se hace para asegurar que TPC ha podido leer, almacenar y modificar el Nonce. Además, supone una medida contra ataques dado que incrementa la aleatoriedad de la clave. Gracias a ello, la función HMAC cambia ya que la clave usada para la operación de cifrado es diferente; por tanto, incrementa el esfuerzo de un atacante que intente falsificar el HMAC.

La secuencia de acciones que tiene que seguir TPC para construir el *Comando* a la tarjeta es la siguiente:

1. Cifrar el resultado del algoritmo con la clave de sesión: $\text{Cif}_{C_{ses}}$(TPCResultado)

2. Calcular el HMAC del contenido: HMAC(TPCResultado, N_{TI+1})

3. Firmar el HMAC anterior con la clave para firmar:
   $\text{Fir}_{TPCCPrFir}(\text{HMAC(TPCResultado, } N_{TI+1}))$

Finalmente, el *Comando* construido para enviar a la tarjeta conteniendo el resultado es:

- *Comando*: [$\text{Cif}_{C_{ses}}$(TPCResultado),
  $\text{Fir}_{TPCCPrFir}(\text{HMAC(TPCResultado, } N_{TI+1}))$], que contiene:
  - Resultado cifrado: $\text{Cif}_{C_{ses}}$(TPCResultado)
  - Firma:
    $\text{Fir}_{TPCCPrFir}(\text{HMAC(TPCResultado, } N_{TI+1}))$

De la misma forma que TPC ha verificado el mensaje anterior, la tarjeta tiene que hacerlo en este momento. La secuencia de acciones a llevar a cabo es la siguiente:

1. Obtener el resultado descifrando con la clave de sesión:
   $\text{Des}_{C_{ses}}(\text{Cif}_{C_{ses}}(\text{TIResultado})) = \text{TIResultado}$

2. Calcular el HMAC del resultado descifrado: HMAC(TIResultado, N_{TI+1})

3. Descifrar la firma a través de la clave pública para firmar de TPC:
   $\text{Des}_{TPCCPuFir}(\text{Fir}_{TPCCPrFir}(\text{HMAC}(\text{TPCResultado}, N_{TI+1}))) =$
   HMAC(TPCResultado, N_{TI+1})

4. Si el HMAC calculado en TI a través del contenido descifrado del mensaje coincide con el HMAC obtenido de la firma incluida en el mensaje, entonces los requerimientos de autenticación, confidencialidad e integridad han sido cumplidos; de otra forma no. Esto es:

   If (HMAC(TPCResultado, N_{TI+1}) == HMAC(TIResultado, N_{TI+1}))
   $\rightarrow$ Mensaje OK
   else $\rightarrow$ Requerimientos no cumplidos

Si el *Comando* es correcto, la tarjeta puede obtener el resultado y enviar una confirmación a TTP en una *Respuesta*. Con el resultado, la tarjeta puede decidir si la aplicación debería ser instalada en la tarjeta o no.

Capítulo 4
Implementación

Con el objetivo de validar el diseño previo del sistema para resolver el problema de la externalización de la Comparación Contrato-Política se construyó un prototipo. Este prototipo debe interpretarse como una prueba de concepto en el sentido que lo que se pretende con su construcción es obtener una prueba funcional que demuestre que el sistema diseñado es viable. Esto significa que no es necesario su funcionamiento en una tarjeta real, ni se espera obtener una versión optimizada de su código. Con estas premisas, se construye el prototipo para ser usado sobre un simulador cuyas limitaciones provocan la necesidad de realizar diversos cambios sobre el diseño previo. Cabe destacar que las especificaciones de los dominios de seguridad de Global Platform no han sido tenidos en cuenta por limitaciones de tiempo. Esta es una de las mejoras propuestas como trabajo futuro.

Durante el capítulo se tratarán las herramientas utilizadas durante esta fase, así como todo lo relacionado con certificados y funciones criptográficas. Algunos comentarios que no encajan en ninguna de estas secciones se pueden encontrar en la última parte del Apéndice G. De hecho, este capítulo se halla considerablemente más detallado en el citado apéndice.

4.1. Herramientas

En esta sección se detallan las herramientas utilizadas en la etapa de implementación; es decir, lenguajes de programación, entorno, simuladores, etc.

Los lenguajes de programación utilizados han sido dos dependiendo de la plataforma de cada entidad. Así pues, para EA, LS y TPC se ha utilizado Java con la versión del Java Development Kit (JDK) 1.6.0.18. Cabe destacar que se ha hecho uso de los paquetes sun.*; que no pertenecen a la API de Java, pero sí están disponibles dentro del Software Development Kit (SDK) incorporado en el JDK. No es recomendable su uso dado que al no ser parte de la API, Sun no se compromete a mantenerlos en las diferentes versiones del JDK. Es por ello, que se puede garantizar que el prototipo funciona para el JDK especificado, pero no en otro diferente. Este tema se trata en profundidad en el Apéndice G y el reemplazo de dichos paquetes se propone como trabajo futuro. Por su parte para TI se ha utilizado Java Card en su versión 2.2.2. Por qué no se ha utilizado la versión 3 de este lenguaje se explica en la correspondiente sección del Apéndice G. Las razones por las que se usan y más características de estos lenguajes se explican en el apartado "Programming Languages" de dicho apéndice.

El entorno de programación utilizado ha sido *Eclipse SK* 3.5.2. Sobre él se lanzaban las entidades externas a la tarjeta. Mientras que para simular la tarjeta esta se lanzaba directamente por línea de comandos sobre el simulador. Los simuladores que se han utilizado han sido dos, dependiendo de la etapa de la implementación:

- Java Card platform Workstation Development Environment tool (JCWDE) para la primera parte que no almacenaba el estado de la tarjeta
- C-language Java Card Runtime Environment (CREF) para la segunda cuando era necesario que la tarjeta recordara su estado de una simulación a otra

Así pues, JCWDE se utilizó para la primera parte de la implementación cuando se trabajó en la generación y almacenamiento de certificados, ya que la tarjeta no necesitaba recordar su estado tras la última simulación. CREF fue utilizado en el resto del desarrollo cuando era necesario hacer uso de memoria persistente. Este simulador crea una imagen de la memoria de la tarjeta que permite recuperar su estado cuando se vuelve a realizar una simulación. Ambos simuladores tienen el mismo problema y es que no soportan todas las clases de la API de Java Card 2.2.2. Esto ha provocado que el prototipo sea construido con limitaciones en las longitudes de clave y, dada la falta de algunos algoritmos necesarios para la implementación realizada, con cambios en el diseño del sistema para poder obtener el prototipo trabajando. Estos cambios son asumibles dado el objetivo del prototipo, pero no lo serían para una implementación en una tarjeta real. Es por ello, que durante esta etapa se construyeron dos códigos fuente distintos que son el del prototipo y una implementación preparada para su uso en una tarjeta real que soporte los algoritmos necesarios. Dichas implementaciones se pueden encontrar en los apéndices J (prototipo) y K (real). Se ofrece una explicación más detallada de entorno de programación, simuladores y sus limitaciones en el Apéndice G.

4.2. Certificados

En esta sección se examina todo lo referente a los certificados: generación, gestión, análisis, etc. Se han utilizado los tipos de certificados X.509. Para familiarizarse y trabajar con ellos, es necesario tener conocimientos sobre Abstract Syntax Notation One (ASN.1) y las codificaciones Basic Encoding Rules (BER) y Distinguished Encoding Rules (DER). En el Apéndice G, se detallan las referencias donde poder buscar información de estas especificaciones y codificaciones. Asimismo, las especificaciones de ASN.1 para los CSRs y los certificados se encuentran en el Apéndice I.

4.2.1. CSRs y generación de certificados

La implementación de la generación de certificados se ha realizado por medio de *OpenSSL*. Primero se genero un certificado autofirmado para la AC. Con él, *OpenSSL* era capaz de construir los certificados a partir de los CSRs y firmarlos con esta AC.

La construcción de los CSRs se realiza en el LS por medio de clases incluidas en paquetes sun.*, cuya conveniencia se ha comentado anteriormente. Estos paquetes facilitan clases para trabajar tanto con DER como con Base64, lo cual es necesario para la generación de los CSRs. El proceso más complicado fue la generación de la firma del certificado, la cual debe ser enviada a TI para ser firmada. Es decir, se prepara la estructura a firmar en el LS y se envía a TI, el cual la devuelve firmada. Dicha estructura tiene la siguiente forma: 00 || 01 || PS || 00 || T, donde:

- T es la codificación DER de la estructura digestInfo (consultar especificación de ASN.1 en Código I.6)
- PS es una cadena de octetos de longitud k-3-||T|| con valor FF. Su longitud debe ser de al menos 8 octetos
- k es el tamaño de módulo del algoritmo de Rivest, Shamir and Adleman (RSA)

Esto debe ser enviado a la tarjeta para ser cifrado con la clave privada de TI. Pero surge un problema y es que dado que la estructura previa se construye según el esquema de PKCS#1 v1.5 (Public-Key Cryptography Standard), el relleno (padding) ya ha sido añadido, por lo que es necesario una implementación de RSA que no añada ningún relleno al realizar el cifrado (i.e., ALG_NO_PAD). Pero el simulador no soporta esta implementación, por lo que la decisión tomada fue modificar el diseño, enviando la clave privada de la tarjeta para que fuera LS el que cifrara la estructura consiguiendo la firma. Esto se muestra en la Figura 4.1. Este cambio sólo es aceptable dado el objetivo del prototipo, pero no para una tarjeta real. Más detalle en la correspondiente sección del Apéndice G.

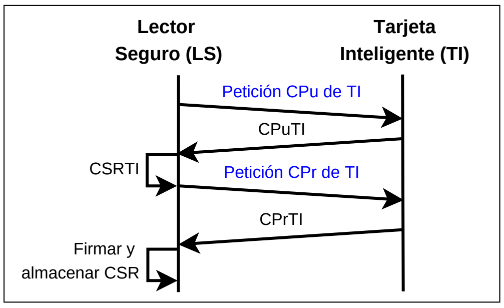


Figura 4.1: Construcción de los CSRs en el prototipo

4.2.2. Certificados en las entidades externas

Sus certificados se almacenan en ficheros de extension Privacy-Enhanced Electronic Mail (PEM) y codificados en Base64. Cuando esas entidades se ejecutan los certificados se almacenan en estructuras de datos de tipo X509Certificate. Más información en la sección “Off-Card Certificates”del Apéndice G.

4.2.3. Certificados en la tarjeta

Los certificados en la tarjeta se almacenan en vectores de bytes y codificados con DER. Cabe destacar la diferencia entre los certificados de TI y AC que se conservan desde la inicialización durante el resto de tiempo de vida de la aplicación, de los certificados de TPC los cuales se almacenan momentáneamente mientras son analizados y se extrae la clave. Más detalle en la sección “On-Card Certificates”del Apéndice G.

4.2.4. Analizador sintáctico en la tarjeta

Dadas las características de las tarjetas inteligentes, no es posible comprobar todos los contenidos del certificado, por lo que el analizador construido lo que se encarga es de comprobar lo siguiente:

- Conformidad del certificado con codificación DER y especificación ASN.1
- Algoritmos de clave y firma esperados, así como la longitud de clave
- Validez de la firma

De la misma forma que con la firma del CSR, al intentar descifrarla es necesario usar la implementación del algoritmo de RSA sin relleno. Dado que no está disponible, la solución elegida fue que cuando el analizador llegue a la firma, se devuelva ésta a la entidad externa con la que se esta comunicando. La entidad externa descifrará la firma y le enviará la estructura descifrada para que la tarjeta pueda realizar la comprobación de la validez de la firma. Esto se muestra en la Figura 4.2. El analizador con mayor detalle se describe en la sección "Parser On-Card"del Apéndice G.

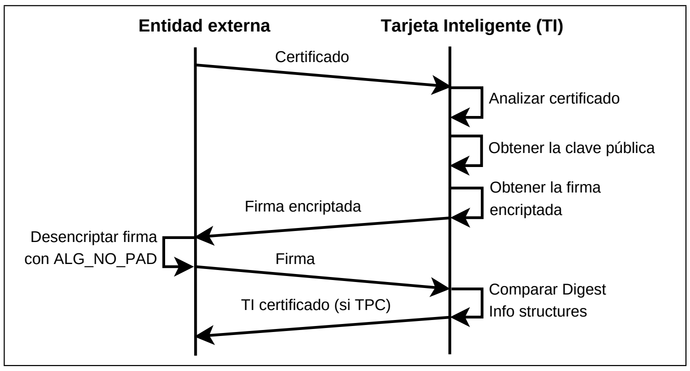


Figura 4.2: Verificación de la firma de los certificados en el prototipo

4.3. Funciones criptográficas

Esta sección describe la implementación de las funciones criptográficas de la segunda parte de la fase de Comparación Contrato-Política, tras el intercambio de certificados. En esta parte, se puede distinguir entre criptografía simétrica y asimétrica, pero es de forma conjunta como el sistema tiene sentido.

El algoritmo de criptografía en bloque simétrica utilizado ha sido AES con una longitud de clave de 128 bits (la única proporcionada por el simulador) con un tamaño de bloque de 16 bits y con el modo *Cipher Block Chaining* (CBC). Como vector de inicialización (necesario para el modo CBC) se ha utilizado el Nonce por ser aleatorio y renovado en cada nueva sesión. El por qué del uso de este algoritmo en lugar de otros (p.ej., DES) así como el uso del modo u otras posibilidades para el vector de inicialización se detallan en la sección "Cryptographic Functions" del Apéndice G.

Por otra parte, el cifrado por RSA se ha llevado a cabo a través de una longitud de clave de 512 bits, ya que era la única longitud proporcionada por el simulador. Para el proceso de Comparación Contrato-Política no hay problema con el simulador ya que no importa cual sea la implementación de RSA utilizada, mientras se use la misma en las dos partes de la comunicación. Así pues se usa la única implementación proporcionada por el simulador: un cifrador RSA acorde con el esquema de PKCS#1 (v1.5).

Un problema relevante de seguridad es el uso del algoritmo de generación pseudo aleatoria de números para la implementación del prototipo. De nuevo, se ha tenido que implementar así por la limitación del simulador. Se debería usar el generador seguro de números aleatorios, dado que éste método esta preparado para tratar con requerimientos criptográficos como [49] especifica. Más detalle sobre este problema en "Cryptographic Functions" del Apéndice G.

Como comentario final de esta sección, cabe destacar que en la implementación para una tarjeta real se recomienda incrementar la longitud de las claves de RSA. Se espera que se usen durante un largo tiempo, pero su longitud es muy corta. Así que se sugiere aumentarla hasta 2048 bits para la implementación real. Los cambios entre ambas implementaciones se especifican en el Apéndice K.

Capítulo 5

Evaluación

Durante este capítulo se muestra en primer lugar un caso de uso de forma que además sirva de guía de usuario para que el lector se familiarize con el uso del prototipo desarrollado. Tras esto, se realiza un análisis de dicho prototipo respecto a sus prestaciones en términos de memoria, dada los recursos limitados en este sentido de las tarjetas inteligentes.

En este momento cabe destacar la metodología de pruebas seguida. Se ha probado toda la casuística posible, conforme las distintas partes del sistema se iban implementando. Dicha casuística se basa en la posibilidad de errores en la firma, cifrado, longitud inesperada del mensaje, certificado incorrecto en cuanto a formato, firma del certificado no válida, etc. Toda esta casuística, se ha probado en el momento de la implementación de la parte encargada de trabajar con la posibilidad de fallo. Es decir, se realizó una separación modular del sistema para llevar a cabo las pruebas. Por ejemplo, en el caso de certificados, tras la implementación de la parte que verificaba la firma se ha probado que sucedía si se cambiaba un byte de la firma recibida (evidentemente fallaba).

5.1. Caso de uso

Dada la limitación de espacio del presente documento, esta parte se encuentra perfectamente desarrollada en la primera parte del Apéndice H.

5.2. Evaluación de los resultados

La importancia del siguiente análisis radica en las limitaciones de memoria de las tarjetas inteligentes, ya que si la idea teórica del esquema de S×C necesita gran parte de la memoria disponible para llevarse a cabo, se puede concluir que no es la apropiada. El análisis se ha llevado a cabo mediante una opción del simulador CREF, para más información de su funcionamiento consultar el capítulo 10 de [2]. En el Apéndice L, se pueden observar las capturas de pantallas con toda la información suministrada por el simulador, correspondiendo cada imagen con una de las fases del sistema. La información importante se muestra en bytes resumida en la Tabla 5.1.

En dicha tabla se muestran solo resultados de la EEPROM. La razón es que es la única interesante para el desarrollador de tarjetas inteligentes. Se trata de la memoria persistente donde se almacenan las aplicaciones. Además, también se encuentran los datos que deben ser almacenados cuando la fuente de energía cesa de suministrar a la tarjeta; p.ej., cuando la tarjeta se retira del lector. Los resultados tanto de la ROM como de la RAM, son triviales en este sentido, ya que la primera es inicializada por el fabricante y no se puede modificar; mientras que la segunda es la memoria volátil que se borra cada vez que la tarjeta deja de recibir energía. La estructura de la memoria persistente se puede observar en la Figura H.12 del Apéndice H.

CREF proporciona una memoria de 64 KB (i.e., 65536 bytes), aunque las tarjetas reales suelen

Etapa	**Figura**	**Consumido antes**	**Consumido después**	**Disponible antes**	**Disponible después**
Descarga	L.1	6994	12837	58510	52667
Instalación	L.2	12837	14322	52667	51182
Inicialización	L.3	14322	17919	51182	47585
Communicación	L.4	18298	18135	47206	47369

Tabla 5.1: Análisis de las estadísticas de memoria en bytes

ser de al menos 128 KB. Las etapas elegidas para la toma de datos se corresponden con los momentos más importantes del ciclo de vida de la aplicación en la tarjeta:

- Descarga: Almacenamiento del bytecode en la tarjeta
- Instalación: Instalación y llamada al método *Register*
- Inicialización: Fase de inicialización
- Communicación: Fase de Comparación Contrato-Política

Como se puede ver en la tabla, la tarjeta reserva casi 7 KB para sus necesidades antes de almacenar nada. La descarga del applet necesita casi 6 KB, mientras que la instalación uno más. En este momento, las instancias de métodos y variables ya han sido creadas. La inicialización disminuye la memoria disponible en 3 KB. Los certificados y la política (se utiliza una de 518 bytes de tamaño, pero este dependerá de las necesidades de la tarjeta) han sido ahora almacenados. El consumo de correr el algoritmo de comparación necesita unos pocos cientos de bytes. En resumem, se necesita alrededor de 11 KB. Este resultado debe entenderse como un límite superior a las necesidades de espacio de la aplicación, dado que su optimización no era un objetivo. Se deben considerar los siguientes puntos antes de realizar la valoración:

- Lo que más espacio necesita es la descarga de la aplicación que consiste en el bytecode generado a partir del código fuente. Ésta es bastante más pesada que las aplicaciones testeadas que necesitan alrededor de 4.5 KB. Suponiendo esa media aún podrían almacenarse en la tarjeta 11 aplicaciones más; número que crece si se consideran aplicaciones más pequeñas, lo que es de esperar.
- El análisis se ha realizado sobre el prototipo, el cual fue modificado añadiendo métodos por las limitaciones del simulador. En una aplicación real, estos son eliminados reduciendo el bytecode a cargar en la tarjeta.
- Se debe tener en cuenta que el hardware esta en continua evolución, por lo que se puede esperar que las capacidades de memoria crezcan, mientras que las necesidades seguirán siendo las mismas para la aplicación.
- En el trabajo futuro se propone la optimización de la implementación realizada, lo que reduciría su peso.

Aunque debería realizarse una optimización sobre el código, se considera el análisis satisfactorio y el sistema apropiado para la perspectiva multiaplicación. La aplicación necesita más espacio que las normales dado que lleva a cabo más operaciones, pero no reduce considerablemente el espacio, permitiendo almacenar un buen número de aplicaciones de forma segura.

Capítulo 6

Conclusión y trabajo futuro

Durante este capítulo se presentan las conclusiones extraidas del proyecto. Junto a ellas un resumen tanto de las limitaciones y problemas surgidas durante su desarrollo como del trabajo futuro propuesto. Finalmente se presenta una valoración de lo que su realización ha supuesto a nivel personal.

6.1. Conclusión

La tecnología de tarjetas inteligentes ha evolucionado y expandido muy rápidamente durante la última década. La razón de este desarrollo ha sido sus características de seguridad y resistencia a la manipulación del chip lo que permite al usuario mantener los contenidos de su tarjeta físicamente seguros. Las tarjetas inteligentes han progresado hasta el punto de permitir la ejecución de varias aplicaciones en la tarjeta inteligente y la carga, eliminación y actualización dinámica de aplicaciones durante la vida activa de la tarjeta. Estas tarjetas reciben el nombre de tarjetas inteligentes multi-aplicación. Sin embargo, su difusión no ha sido significativamente grande debido a los problemas de seguridad inherentes y relacionados a la posibilidad de modificación de las tarjetas posteriormente a su expedición. Este problema concierne principalmente a la falta de control de las interacciones entre aplicaciones (es posible que el dueño de una aplicación desee que su aplicación no sea accedida por otras de origen inesperado). La descarga y actualización asíncrona de aplicaciones de distinto origen require el control de las interacciones después de que la tarjeta haya sido expedida.

El esquema de Seguridad-mediante-Contrato (S×C) se propone como una medida para resolver este problema abierto. Consiste en la idea de contrato. Un contrato especifica el comportamiento de una aplicación en lo que refiere a seguridad. Cualquier modificación que se pretenda realizar en la tarjeta debe venir acompañada de un contrato para ser comparada con la política de la tarjeta, la cual define el comportamiento de seguridad esperado, o mejor dicho, el requerido por la tarjeta. El proceso de comprobar si el contrato se ajusta a la política o no se llama Comparación Contrato-Política y es la fase clave del esquema. Dados los recursos limitados de las tarjetas inteligentes, una jerarquía de modelos de contratos y políticas se ha desarrollado. En ella, los modelos dependen del nivel de detalle requerido. Esta jerarquía de modelos aporta diversos beneficios en términos de complejidad computacional o expresividad. El nivel de expresividad más alto requiere demasiado esfuerzo computacional para poder llevarse a cabo en la tarjeta. Por ello, es necesario realizar la fase de comprobación de la conformidad fuera de la tarjeta. Esto implica la necesidad de una comunicación segura para los datos enviados entre la tarjeta y la entidad responsable de ejecutar dicha fase.

El proyecto desarrollado resuelve el problema de la comunicación en la externalización de la Comparación Contrato-Política de S×C a una tercera parte de confianza. La contribución del proyecto es triple. Provee un diseño para conseguir una comunicación segura, la implementación de un prototipo como prueba de concepto y resultados de pruebas que muestran la viabilidad e idoneidad del prototipo definiendo un límite superior para sus necesidades de memoria. La solución provee mutua autenticación, confidencialidad e integridad. Esto es logrado mediante una infraestructura de clave pública donde las identidades son manejadas por medio de certificados. Además, cabe destacar que dada la necesidad de verificar dichos certificados en la tarjeta, un analizador sintáctico ha sido implementado en ella.

6.2. Limitaciones y problemas encontrados

Han sido varios los problemas encontrados durante el desarrollo del proyecto, así como limitaciones, en su mayoría relacionadas con el simulador utilizado. En esta sección se resume lo más importante de todo esto.

El primer problema fue la bibliografía. La mayoría de la información suministrada era anticuada e innecesaria. Esto hizó que el estudio previo fuera excesivamente lento inicialmente. Gran parte de dicha bibliografía no introducía apropiadamente el tema siendo en algunos casos demasiado básica, genérica o desfasada. Así que tras la primera parte del estudio previo fue necesario buscar nueva bibliografía. En lo que respecta información sobre tarjetas inteligentes fue fácil encontrar referencias adecuadas, pero no lo fue tanto para la parte de seguridad. De forma similar, el inicio de la etapa de implementación fue especialmente complicado debido a la falta de ejemplos de implementación en Java Card. El conocimento de la plataforma era nulo y la escasez de ejemplos útiles para comenzar a trabajar con ella hizó que el inicio de esta etapa fuera díficil. Además, los mensajes de error que mostraba el simulador sobre la tarjeta eran extremadamente genéricos y no ayudaban a localizar los errores, sin más que a prueba y error hasta encontrar donde estaba el fallo. Finalmente, aunque el uso de certificados en tarjetas inteligentes no es nuevo, es llevado a cabo por empresas que no hacen público su trabajo, de forma que no había ningún ejemplo de como trabajar con ellos, tanto de la generación como la verificación o gestión.

La limitación más importante del proyecto fue la generada por el simulador utilizado. Este asunto se discute de forma más extendida en el Apéndice G, sección G.2. En resumen, el simulador utilizado no proporciona todas las funciones criptográficas necesarias para una implementación correcta del diseño preparado. Ello propició que el prototipo sufriera cambios importantes (p.ej., exportación de la clave privada). Dado que el objetivo del prototipo es probar la validez del diseño, es decir, obtener un prototipo funcional que demuestre que el diseño funciona como se espera; los cambio se llevaron a cabo. Para una implementación real, esos cambios serían inaceptables ya que suponen graves riesgos de seguridad. Ésto dió lugar a la creación de dos implementaciones diferentes: la del prototipo (Apéndice J) testeada en el simulador y la real (K) sin testear. Asimismo, esto conlleva otro problema y es que la segunda implementación no ha podido ser probada. Sin embargo, se espera su correcto funcionamiento, o en cualquier caso, que sirva como punto de partida para conseguir una implementación para una tarjeta real.

En lo que respecta al analizador sintáctico construido para verificar los certificados en la tarjeta, cabe destacar que por las limitaciones de la tarjeta en cuanto a la falta de un reloj de donde obtener el tiempo, así como, de la imposibilidad de realizar conexiones a Internet, los certificados no pueden ser completamente verificados ya que no se puede comprobar su revocación ni su período de validez. Soluciones a estos problemas se sugieren como trabajo futuro.

Otra limitación encontrada fue la falta de soporte para la generación de peticiones de certificado, tanto en la API de Java Card como en Java. Esa es la razón de que la generación de estas peticioens se realice en una entidad externa a la tarjeta haciendo uso de paquetes de Sun que aunque estan incluidos dentro del kit de desarrollo, no lo están dentro de la API de Java. No se recomienda su uso, ya que Sun no se compremente a mantenerlos de una versión a otra, lo que provoca la generación de una prototipo inestable entre la sucesivas versiones de Java. Esto se explica más detalladamente en la sección G.1.2.3.

Finalmente, cabe destacar que la API de Java Card es reducida, lo que provoca que se eche en falta muchas de las características usuales que proporcionan los lenguajes de programación como la creación de nuevas estructuras de datos, vectores multidimensionales, cadenas, etc. Esto supuso una limitación en cuanto a que la programación fue realizada a más bajo nivel y de forma más tediosa que si dichas características hubieran estado presentes.

6.3. Trabajo futuro

Esta sección establece posibles direcciones del trabajo futuro. Propone tanto mejoras del sistema como soluciones a temas dejados a un lado o ignorados durante el desarollo del proyecto debido a la limitación temporal que éste conlleva.

Durante la etapa de implementación, los recursos limitados de la tarjeta en términos de memoria fueron tomados en cuenta, pero no como una prioridad. Por encima de ello, se encontraba el conseguir un código fuente fácil de comprender dado que este código supone un punto de partida para posteriores trabajos. Además tanto el trabajo con APDU como con funciones criptógraficas no es trivial para quién no este familiarizado con ello. Esto añadido a un código complejo con variables que se reutilizan (como ejemplo de optimización), puede provocar que empezar a trabajar con dicho código sea considerablemente díficil. Precisamente dicho propósito de claridad en el código es lo que hace que un estudio exhaustivo del código permitiera obtener una versión optimizada en términos de memoria. El estudio debería cubrir el uso del recolector de basura, creación de nuevas instancias, reutilización de variables, extender el uso de variables globales, etc.

Otro aspecto a mejorar de la implementación es la generación de CSR con el objetivo de usar únicamente la API de Java evitando los paquetes de sun.*, y por tanto, obteniendo una versión más estable independiente de las actualizaciones de estos paquetes. La forma de implementar esto sería construir las clases que trabajan con la codificación DER y que permitirían generar CSRs *a mano* y conformes con el estándar. Debería tenerse en cuenta que no todas las características son necesarias ya que no serán usadas en la tarjeta (p.ej., las extensiones pueden omitirse). Dado que la implementación de estas clases no necesita nada que no proporcione la API de Java Card, esta generación podría hacerse incluso en la propia tarjeta. De esa forma, la fase de inicialización sería menos complicada y más rápida dado que la generación se haría en la propia tarjeta y se realizarían menos comunicaciones. Aunque por otra parte, sería necesario usar más espacio en la tarjeta.

El uso de diferentes AC fue otro tema dejado a un lado. Para simplificar la tarea se decidió usar una única AC. Sin embargo, en el mundo real la tarjeta debería almacenar certificados de varias AC con objeto de poder comprobar certificados firmados por diversas ACs. Esto implica tener en cuenta la forma de almacenar dichos certificados en las tarjetas (dispositivos con recursos limitados de memoria). Por ejemplo, podría no ser necesario almacenar el certificado entero, sino las partes necesarias. Además, sería ineficiente parsear el certificado entero cada vez, por lo que debería pensarse en formas rápidas de acceder a las partes necesarias (se debe tener en cuenta que no se pueden crear nuevas estructuras de datos en Java Card). Algunos de estos punto son discutidos en [37].

Otra línea de trabajo puede ser mejorar el analizador implementado. Por considerarse fuera del ámbito del proyecto, se han dejado a un lado interesantes temas como son la verificación del período de validez y la revocación de certificados en la tarjeta. El problema de la validez radica en la falta de un reloj en la tarjeta (dado la falta de suministro ininterrumpido de energía); de forma que no es posible conocer el tiempo actual. Dado que el tiempo es necesario para conocer si TPC es confiable, la tarjeta no puede confiar en él para el suministro del tiempo. De ahí, que la solución que se propone es el uso de un servidor, conocido y confiado por la tarjeta y accesible desde la TPC, el cual proveerá el tiempo actual a la tarjeta. En esta comunicación, TPC se comporta como una puerta de salida entre la tarjeta y el servidor. Este esquema esta representado en la Figura 6.1. El sistema empezaría como respuesta a la llegada del primer certificado de la TPC, ya que la tarjeta no puedo empezar la comunicación. TI envía el certificado a TPC junto con un NONCE. Esta debería reenviar el mensaje al Servidor (S). Este obtiene los datos y responde con la fecha y el NONCE incrementado, ambos encriptados y firmados. La razón de usar encriptación, firma y NONCE es la misma que en el resto del proyecto. TPC reenvia el mensaje de S a TI, la cual obtiene la fecha y puede verificar el período de validez.

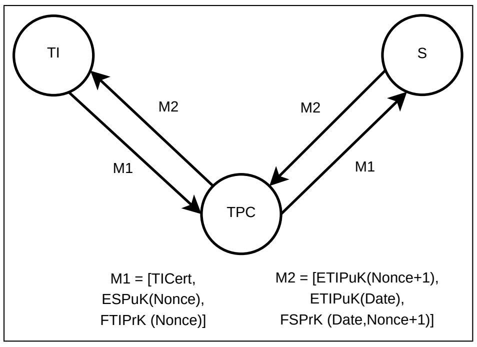

TI
S
M2
M2
M1
M1
TPC
M1 = [TICert, ESPuK(Nonce), FTIPrK (Nonce)]
M2 = [ETIPuK(Nonce+1), ETIPuK(Date), FSPrK (Date,Nonce+1)]

Figura 6.1: Diagrama de la solución para el problema del período de validez

La solución propuesta para el problema de la revocación es similar. La diferencia radica en la información que contienen los mensajes. Este problema se trata en [25]. Como distinción en contraste a [25] donde se discute lo que el servidor tiene que hacer; cabe destacar que dado que la idea es confiar en el servidor para resolver el problema, no importa como lo haga ya sea con protocolos de validación del certificado o mediante Listas de Revocación de Certificados (CRL, por sus siglas en inglés). El trabajo consiste en diseñar la comunicación entre TI, TPC y S.

En lo que respecta a certificados hay un tema interesante dejado a un lado: su renovación en la tarjeta. Se ha considerado fuera del propósito del proyecto, pero es algo a tener en cuenta, ya que al expirar su período de validez, la tarjeta queda inservible. El problema radica en que dado que la tarjeta trabaja como un servidor no sabe quién es el que le envía la petición en cada momento. Esto significa que p.ej., el emisor de una aplicación podría instalar una nueva política que aceptará su aplicación no válida, sin ser un LS. La solución en el prototipo fue permitir al LS almacenar una sóla vez las cosas necesarias; i.e., los certificados de TI y AC y la política sólo pueden ser instalados una vez. De esta forma, cualquier ataque que intente sustituir algún componente fallará. El problema subyaciente es que el certificado no puede ser renovado. La idea propuesta para su solución es almacenar el certificado del LS en la tarjeta. Así, LS puede renovar lo necesario gracias a su firma digital (TI puede verificar su identidad). El envío de una renovación de certificado vendría firmado lo que identifica unívocamente a su remitente: si es LS se acepta, en otro caso se rechaza. La solución implica cambios en el diseño y añadir una nueva etapa para la renovación (Figuras **??** y **??**). Si se quisiera que otro LS fuera capaz de realizar la renovación, su certificado debería ser almacenado también; volviendo al tema de multi-AC ya discutido.

Finalmente, otra parte que no ha sido tenido en cuenta por razones de tiempo han sido los dominios de seguridad de Global Platform. Se usan para permitir a las aplicaciones compartir espacio en una tarjeta sin comprometer la seguridad de sus emisores. Se debería extender el proyecto con los SD relacionados a la instalación de aplicaciones.

6.4. Valoración personal

La sensación que me queda a nivel personal tras la elaboración de este proyecto es muy satisfactoria, especialmente por las condiciones en las que se ha desarrollado y los conocimientos que me ha aportado, no sólo a nivel técnico sino también en la forma de trabajo.

En primer lugar el hecho de llevarlo a cabo en un país extranjero ha implicado que su realización a todos los niveles haya sido completamente en inglés. A todos los niveles significa: búsqueda de información, referencias, reuniones, comunicación con el tutor, redacción, presentación y defensa, etc. Me alegra mucho que se haya terminado de forma exitosa incluida su defensa durante alrededor de una hora y media frente a un examinador externo obteniendo la calificación de 10.

Por otra parte, el ambiente y forma de trabajar que he disfrutado en la *DTU* ha sido inmejorable. Me ha permitido conocer perfectamente la labor de investigación. A lo largo del desarrollo del proyecto he tenido la oportunidad de dialogar sobre mi proyecto tanto con mi supervisor como con expertos criptógrafos que dieron lugar a sugerencias y modificaciones sobre el diseño. Incluso tuve la oportunidad de presentar y discutir el diseño con Lawrie Brown (creador del *LOKI*). Todo este ambiente me ha iniciado en la labor investigadora y me ha enseñado como trabajar en ella, especialmente en lo que se refiere a colaborar con otras personas.

Asimismo el hecho de trabajar en este proyecto de la *DTU* me ha dado la posibilidad de realizar una publicación que será presentada en una conferencia en octubre mostrando resultados previos del trabajo que he desarrollado. Esto supone una gran satisfacción ya que implica un reconocimiento del trabajo realizado. Asimismo, me abre puertas a trabajar como investigador puesto que la mayoría de puestos de este tipo valoran (sino exigen) este hecho.

En cuanto, a nivel ténico he aprendido e interiorizado conocimientos sobre criptografía y seguridad, temas de vital importancia en la tecnología actual. Dado que durante el proyecto se ha diseñado e implementado un sistema criptográfico, lo primero que fue necesario fue realizar un estudio exhaustivo de criptografía. Durante todo el proyecto, este conocimiento se ha profundizado mediante la bibliografía consultada sobre seguridad, certificados, etc. En lo que se refiere también a nivel técnico, cabe destacar todo lo aprendido sobre la tecnología de tarjetas inteligentes. Al inicio del proyecto, comence con un conocimiento nulo sobre dicha tecnología, mientras que tras su finalización estoy completamente familiarizado con ella. Para ello, fue necesario consultar bibliografía sobre hardware, seguridad física, tarjetas multiaplicación, S×C etc. Junto con la tecnología sobre tarjetas inteligentes fue necesario familiarizarse con la plataforma sobre la que se trabajaba: Java Card. Aunque tiene gran similitud a Java como lenguaje de programación, no así algunas de sus características de seguridad, forma de trabajar con vectores, y sobre todo la forma en la que se realiza la comunicación (i.e., APDU). En definitiva, el proyecto me ha aportado un profundo conocimiento tanto de tarjetas inteligentes como de la plataforma sobre la que he trabajado, es decir, Java Card. Además, he aprendido a como enfrentarme a una tecnología nueva y empezar a trabajar con ella hasta llegar a controlarla, lo cual es muy importante para mi futura profesión.

Organización, responsabilidad, constancia, ser minucioso y cuidar los detalles para obtener un buen resultado son algunos de los valores que el proyecto me ha aportado. El hecho de no haber trabajado antes en un proyecto de tales dimensiones ha hecho que desde el principio haya puesto especial interés en lo que se refiere a la organización, ya que la documentación generada, así como la bibliografía era bastante considerable. Asimismo, la duración del proyecto hace que se tenga que tener cuidado con los detalles e intentar dejar todo lo más claro posible, ya que sino se hace díficil retomar trabajo hecho dos semanas antes. Dicha duración también implica el desarrollo de una constancia en el trabajo y ser responsable con él, puesto que se prolonga por un tiempo considerable.

En definitiva, el proyecto me ha aportado muchas conocimientos tanto a nivel técnico como personal, así como me ha hecho desarrollar valores que serán importantes en mi futura profesión. Por otra parte, el trabajo llevado a cabo servirá como un punto de partida firme sobre el que se podrán establecer futuros desarrollos.

Apéndice A
Gestión del tiempo y esfuerzo

En este apéndice se da una idea de la gestión del tiempo realizada, así como del esfuerzo invertido en la realización del proyecto. Para ello, se ha separado el trabajo en grupos de tareas a realizar cuyo significado se explica en la primera parte del apéndice. En la segunda, se procede dividir dichas tareas en otras más pequeñas detallando de forma estimativa las horas invertidas en ellas. Al final del apéndice se pueden encontrar tanto un diagrama de Gantt como uno de sectores circulares, ambos construidos a partir de los datos anteriores.

A.1. Grupos de tareas

Los grupos de tareas que se han construido de forma general han sido los siguientes:

Estudio previo Este grupo engloba toda la consulta, lectura y búsqueda de bibliografía sobre criptografía, tarjetas inteligentes, su seguridad, información sobre Java Card, estado del arte sobre el problema, Seguridad-mediante-Contrato y estándares y especificaciones de los certificados y sus peticiones.

Diseño Esto incluye el diseño de la arquitectura del sistema, definiendo las diferentes etapas y entidades que participan en ella, además del estudio de los ataques que podían ser llevados a cabo. Como resultado de esta parte, el tiempo de estas tareas incluye el de la documentación que generan.

Familiarización con el entorno Este grupo de tareas fue el llevado a cabo de forma previa al inicio de la implementación cuando la plataforma, entorno y simuladores eran desconocidos. Incluye la prueba, uso y posterior decisión sobre el IDE y simuladores a utilizar. Asimismo, incluye el desarrollo de aplicaciones sencillas y seguimiento de tutoriales para conseguir la conexión entre la tarjeta y un dispositivo externo.

Implementación Este grupo de tareas se divide en el esfuerzo de implementación por separado de cada uno de los hitos del sistema.

Evaluación Incluye las pruebas realizadas sobre el prototipo para validar su funcionamiento y el análisis de memoria realizado a dicho prototipo.

Documentación Engloba la generación de documentación del proyecto en todas sus fases (excepto diseño): diagramas, memorias tanto para Dinamarca como España y la publicación.

Copias de seguridad Este grupo de tareas tiene en cuenta el sistema de copias de seguridad seguido, diferenciando las tareas según los disintos tipos de copia.

Reuniones Esta tarea única tiene en cuenta las reuniones con el tutor, el ponente (vía Skype) y discusiones con expertos sobre el sistema.

A.2. Tareas realizadas

En esta sección se realiza la división de tareas dentro de los grupos previamente descritos con la estimación del tiempo empleado.

A.2.1. Estudio previo

Para resumir solo se muestra el tema sobre el que trata la consulta, lectura y búsqueda de bibliografía.

- Criptografía: 30 h
- Tarjetas inteligentes: 40 h
- Seguridad en tarjetas inteligentes: 30 h
- Java Card (incluyendo consulta de su API): 60 h
- Estado del arte: 10 h
- Seguridad-mediante-Contrato: 30 h
- Estándares y especificaciones de certificados y sus peticiones: 50 h

Estimación total de horas de estudio previo: 250 h

A.2.2. Diseño

- Diseño de la fase de inicialización: 20 h
- Diseño de la fase de almacenamiento del contrato: 2 h
- Diseño de la fase de comparación entre contrato y política: 60 h
- Estudio de los ataques que se pueden llevar a cabo: 30 h

Estimación total de horas de diseño: 112 h

A.2.3. Familiarización con el entorno

- Instalación, tutoriales y pruebas con NetBeans y lo necesario para Java Card: 40 h
- Instalación, tutoriales y pruebas con Eclipse y lo necesario para Java Card: 10 h
- Instalación y pruebas con OpenSSL: 5 h
- Familiarización, pruebas y consulta de bibliografía de $\LaTeX$: 10 h

Estimación total de horas de familiarización con el entorno: 65 h

A.2.4. Implementación

En lugar de estimar el tiempo de las partes por separado, se han detallado los hitos de la implementación del proyecto. Esto se ha hecho así ya que no tendría sentido describir el tiempo necesario para construir las entidades puesto que en cada una de las fases participan distintas entidades. Por ello, la estimación es más precisa si lo que se tiene en cuenta es lo que cada parte del sistema ha necesitado.

- Estructura básica de los códigos fuentes de las entidades y comunicación: 30 h
- Envíos y recepciones por APDU (también longitud extendida): 25 h
- Generación de las peticiones y posteriores certificados: 60 h
- Funciones criptográficas: 50 h
- Analizador sintáctico en la tarjeta: 65 h
- Almacenamiento del contrato: 5 h

Estimación total de horas de implementación: 235 h

A.2.5. Evaluación

- Pruebas realizadas durante la implementación: 20 h
- Análisis de las prestaciones: 5 h

Estimación total de horas de evaluación: 25 h

A.2.6. Documentación

- Documentos de/para reuniones y organización: 10 h
- Diagramas: 10 h
- Memoria para Dinamarca: 180 h
- Memoria para España: 80 h
- Redacción de la publicación (Apéndice M): 35 h

Estimación total de horas de documentación: 315 h

A.2.7. Copias de seguridad

Para asegurar la ausencia de pérdida de información, se estableción una política de copias de seguridad que se basa en cuatro sistemas de copias con diferente periodicidad. Diariamente, se realizaban dos copias de seguridad al terminar de trabajar: una a un USB Pen Drive que consistía en la copia integra del directorio del proyecto incluyendo bibliografía, documentos de diseño, proyectos de la implementación, memoria, etc.; y otra enviada al correo electrónico que contenía comprimidos los proyectos de la implementación y el directorio que contenía el proyecto de LaTeXde la memoria. Semanalmente se realizaba una copia del directorio del proyecto a un disco duro externo. El repositorio de Subversion (SVN) fue utilizado para almacenar el estado del proyecto en los hitos de la implementación.

- Copia diaria del directorio a USB Pen Drive: 15 h
- Copia diaria de memoria e implementación al correo: 7 h
- Copia de seguridad semanal a disco duro externo: 3 h
- Copias de seguridad mediante un repositorio de SVN: 1h

Estimación total de horas de copias de seguridad: 26 h

A.2.8. Reuniones

La estimación total de horas de reuniones es: 20 h

A.3. Diagramas

A continuación se encuentran dos diagramas obtenidos a partir de los datos anteriores. Con ellos se pretende que presentar de forma gráfica la distribución de los esfuerzos. Se han eligido un diagrama de Gantt (Figura A.1) y una gráfica de sectores circulares (Figura A.2).

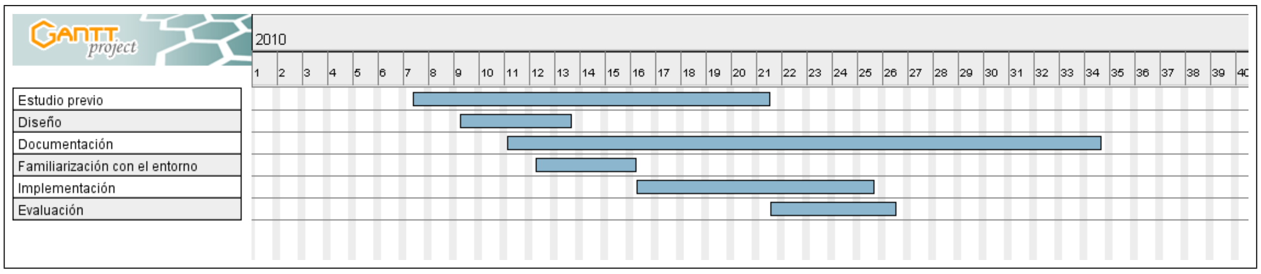


Figura A.1: Diagrama de Gantt con la distribución del esfuerzo en el tiempo

El diagrama de Gantt muestra como se ha distribuido el esfuerzo en el tiempo, pero en este caso, no es muy esclarecedor dado que los diversos grupos de tareas se superponen entre ellos. De esta forma, no se puede apreciar un avance claro entre las distintas etapas del proyecto. Realmente este diagrama no implica que esas tareas se lleven a cabo ininterrumpidamente durante toda su duración, sino que empiezan y terminan en el espacio de tiempo que muestra. Por ejemplo, la documentación se ha hecho por partes. En dicho diagrama se han omitido las barras temporales correspondientes a las reuniones y copias de seguridad, ya que son tareas que se alargan durante toda la duración del proyecto. El diagrama de sectores por su parte, muestra la cantidad de esfuerzo invertido en cada una de los grupos de tareas. La estimación aproximada del número total de horas invertidas en el proyecto es alrededor de 1048. La mayor parte del esfuerzo se dedicó a la documentación, aspecto que parece normal ya que esa documentación (de por sí tarea costosa en tiempo) ha generado dos memorias distintas y una publicación. La otra parte que necesitó más tiempo fue el estudio previo, dado que se partía de un conocimiento nulo sobre la tecnología y que los problemas encontrados en la generación de las peticiones de certificados provocaron un estudio exhaustivo de especificaciones y formatos. La implementación necesitó también de una buena parte del tiempo. De hecho, su principio no fue fácil al tratarse de una tecnología nueva con errores en la tarjeta no fácilmente identificables a priori. El resto de tareas han necesitado de menos tiempo al tratarse de cosas más puntuales o de duración más corta.

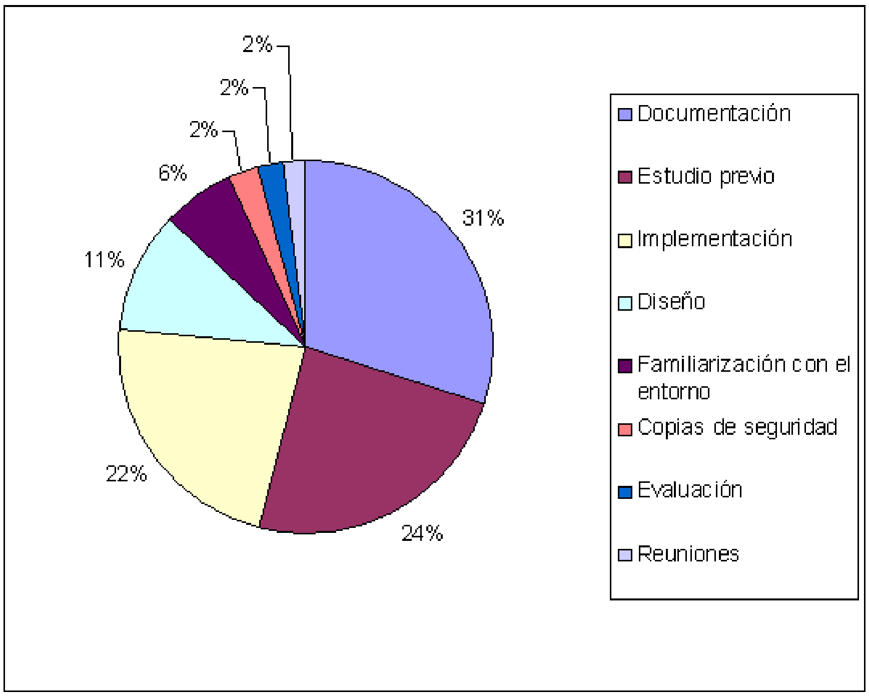


Figura A.2: Diagrama de sectores circulares con la distribución del esfuerzo

Apéndice B

Metodología de desarrollo

La metodología de desarrollo seguida para la construcción del prototipo ha sido en cascada, pero con una pequeña variación, y es que la retroalimentación no se reduce sólo desde la última etapa a las anteriores, sino también desde la etapa de implementación hasta la de diseño. Esto se puede observar en la Figura B.1.

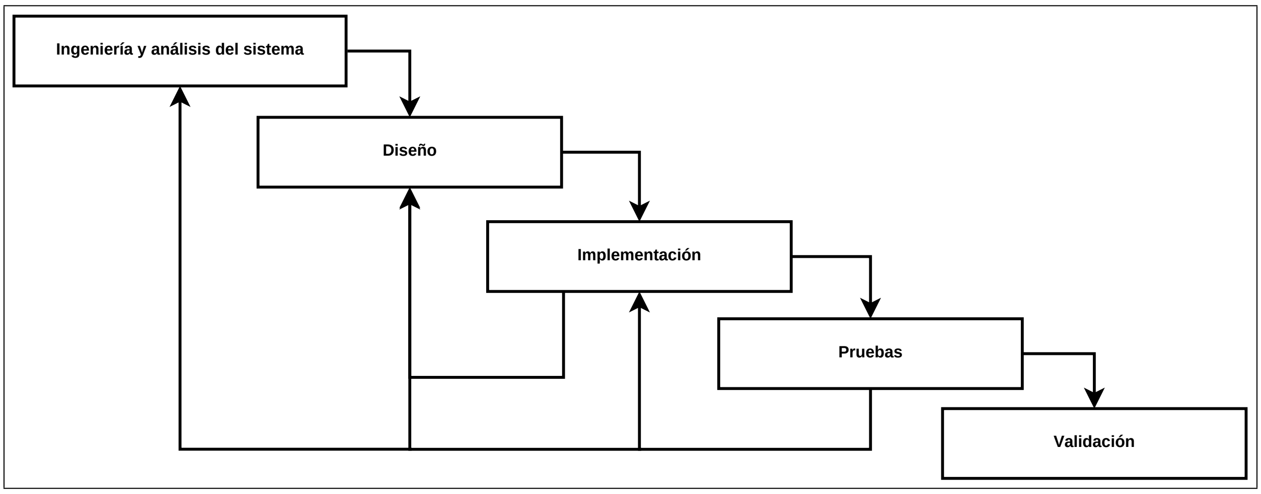


Figura B.1: Diagrama que muestra la metodología de desarrollo utilizada

La razón para este cambio fue el desconocimiento previo de la plataforma y simuladores utilizados para la implementación. Dada las limitaciones de estos, la etapa de implementación provocó cambios sobre el diseño para que el prototipo fuera funcional. Asimismo dado que no hay posibilidad de manutención del software ya que a la finalización del proyecto, se entregan los deliverables y no tiene continuidad en un futuro próximo, no es necesario que exista una fase de mantenimiento. En su lugar, aparece la fase de validación la cual supone la finalización del proyecto y no tiene ningún tipo de realimentación.

Así pues, la metodología está compuesta de las siguientes partes:

Ingeniería y análisis del sistema Esta es la etapa donde se estudian las necesidades para preparar los requisitos del sistema.

Diseño Se prepara el diseño del sistema como solución al problema y satisfaciendo los requisitos obtenidos en la etapa anterior. Como resultado se obtiene la arquitectura del sistema, normalmente en forma de diagramas que detallan su funcionamiento.

Implementación En esta etapa se deciden las herramientas a utilizar en cuanto a entorno de programación, lenguajes, simuladores. Una vez que dichas herramientas son conocidas se llevan a cabo la codificación del diseño, es decir la construcción del código fuente del prototipo.

Pruebas El objetivo de esta parte es comprobar la validez e idoneidad de la implementación. Es decir, que las pruebas pueden estar orientadas a buscar errores en la implementación o validar ésta en cuestiones de rendimiento o uso de recursos.

Validación Finalmente, iteraciones de las etapas anteriores dan lugar al sistema final el cual se valida en esta fase, considerandose finalizado.

El proyecto comenzó con la fase de análisis del sistema, donde tras un estudio del problema a resolver se procedió a definir las necesidades del sistema para solucionar el problema. Una vez que esas necesidades estaban claras, se pasó a la etapa de diseño donde se prepara la arquitectura del sistema. Como resultado de esta etapa, surgen los distintos diagramas que rigen el funcionamiento del sistema. Tras el refinamiento de estos diagramas, se llega a la etapa de implementación.

Durante esta etapa se produce la primera realimentación. Las limitaciones del simulador provocan que cambios en el diseño sean necesarios. Dichos cambios se han detallado en el capítulo de implementación.

Una vez superados estos cambios, en la fase de pruebas durante el análisis de memoria se observan las estadísticas sobre el espacio necesario en memoria de la aplicación. Su análisis da lugar a un refinamiento y optimización de algunas de las partes del código fuente de la tarjeta inteligente.

En lo que respecta a las pruebas de validación del sistema, se realizó una separación modular de forma que en lugar de hacer las pruebas sobre todo el sistema como se espera en la metodología en cascada; dichas pruebas se hicieron sobre cada una de las partes del sistema conforme se desarrollaban. La validación de todas las partes por separado, es lo que permite la validación total del sistema. Para confirmar esto último, se realizaron algunas pruebas más sobre el prototipo ya terminado para comprobar su correcto funcionamiento.

Apéndice C

Smart Card Technology

The big explosion of the digital communication produced in the last years has done that the way to interact among the people had changed. That is why organizations are moving towards network communications ways because of the requirements for their information was available and secure at the same time. Many of them have realized of the advantages and benefits that smart cards are offering.

A smart card is a device able to store data, carry out functions on itself and interact in an intelligent way with an external reader by means of a microprocessor embedded in the plastic card. It is a widespread device thanks to its easiness of use, portability and cheap price [27]. Smart cards are tamper-resistant and provide security features what makes them to be considered as a secure and trusted device. These features allow smart card to be used in fields where high-security is needed and suitable to cryptographic systems and operations like authentication and authorization.

Its origins are dated back to plastic cards which were started to deploy in US in the early 1950s for payment applications. At the beginning, they were made of paper moving later to PVC to get a longer lifetime. VISA and Mastercard appeared at this moment. Magnetic stripe cards were introduced afterwards, mainly because of the fraud. They were able to store digital data. Nevertheless, magnetic stripes had an important weakness: everyone with the right equipment could read, modify or delete the data, or even make a copy of the card bit by bit (technique called Card Skimming). Thus, sensitive data could not be stored on the card. To check them consisted in accessing online to a server or host with confidential data. This is as smart cards appeared. Two German invertors applied for its patent in 1968, a Japanese in 1970 and a French in 1974. In 1984 in France, telephone cards were distributed as a trial and the first bank card, which incorporated safety cryptographic keys and algorithms, was introduced [39]. Some authors argue that development of smart cards was slow at the beginning because of all information about smart cards was tried to keep withheld to avoid becoming an unsecure device [17].

At the beginning, development process was very long and complex. After choosing the chip (first step), code was written. This code was a mix between C and assembly in order to optimize. Developers had to manage for themselves memory pages. Once compiled, binary code was added to Operating System (OS) binary code and test on an emulator. In fact, OS was a few low level primitives used to managed the chip. Next step was to send it to Integrated Circuit Chip (ICC) manufacturer. After that, no change or update could be done, due to it was considered a possible weakness to attack. Masking process built Read-Only-Memory (ROM) on the wafer. Since process was very slow, manufacturers proposed generic soft masks which included a limited OS with some functionalities. Developer left OS issue aside and used Application Programming Interfaces (APIs). That made the process easier and faster: application was compiled and its binary was added to the soft mask to be sent to ICC manufacturer. BasicCard apparition was the key point for the subsequent growth in the mid of 90s. It allows developer to program a smart card without knowing anything of low level and architecture. It was compiled in P-codes which were interpreted on the card in run-time. Tools and libraries (questioned about their security features) were available to developers and price per card was very cheap [44]. After that, Java Card birth opened a new perspective of possibilities for developing smart card applications, including multi-application smart card. From the last years to date, smart card technology has still not stopped of growing.

Smart card, to ensure their worldwide functionality, must be compliant with the international standards, particularly with ISO/IEC 7816 (International Organization for Standardization/International Electrotechnical Commission), indeed an extension from ISO 7810, which defines physical characteristics, dimensions and location of the contacts, electrical interface and transmission protocols, robustness of the card and functionality among other aspects for smart cards. This standard has been updated adding some other specifications like Cryptographic information application. More information could be found in [13].

C.1. Types

Several types of smart cards exist whose suitability depends on which was the application field. They are sorted by increasing cost. Features are better as higher as the cost is [22].

C.1.1. Memory Cards

These cards have some security features and logic to control the access to the memory (p.ej., usually Personal Identification Number (PIN) code is required to access data). They are very common and cheap, but also less functional. The memory is made up of Electrically Erasable Programmable Read-Only-Memory (EEPROM), or Flash memory in some cases, and ROM. That allows card issuer to be able to implement more complex applications and modify and update data stored if necessary. Due to its simplicity, usage is suitable to simple task like pre paid cards (p.ej., transport, phone).

Depending on the literature, cards described at this section are distinguished in two types: with logic, which have been detailed at the previous paragraph; and without it. Latter are the simplest and cheapest cards, and usually, useless after being used. For instance, pre-paid phone cards (not rechargeable).

C.1.2. Microprocessor Cards

The main distinct feature of these cards is that they have incorporated a microprocessor which allows them to carry out more complicated operations and functions. In contrast to memory cards, they have also included a Random Access Memory (RAM) which provides volatile memory. To take advantage of the microprocessor, these cards have their own OS. It has to handle file manipulation and data transmission and to manage the memory. Microprocessor card's security features have been improved from memory cards and allow multi-application. These cards are used in high-security required applications; that is why they will be the study object of the current thesis.

C.2. Different Types of Smart Card Communication Interfaces

Different attacks might be tried against the card according to the communication interface. That is why the following classification is done according to this feature.

C.2.1. Contact Smart Cards

These cards need to be inserted into the Card Acceptance Device (CAD) in order to be powered on. CAD is the interface placed between the host (off-card side) and the card. Contact cards have several gold-plated pads in the contact area, which are in physical contact with the reader when the card is inserted in. At Figure C.1, common smart card contacts show up.

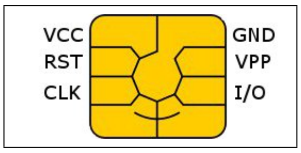


Figura C.1: Contacts of a common contact smart card

The aim of every contact is the following [27], [39]:

- VCC: Supply voltage.
- RST: Reset input. Used itself or in combination with an internal reset.
- CLK: Clock signal input. It should be external, since the card is only powered on when it is put into a CAD.
- GND: Ground.
- VPP: External programming voltage input (depreciated, no longer used).
- I/O: Input/output for serial data communications.

Two remaining contacts are reserved to the manufacturer or card issuer; they are auxiliary contacts and will be used according future application's needs. Thereby, some manufacturers build cards with the six useful contacts, instead of the eight.

VPP contact was used in 1960s to supply voltage to program and erase EEPROM, but since 1990s this voltage is supplied by a charge pump that exists on the chip. This contact cannot be used to a distinct goal because it would be not compliant with the ISO standard.

A drawback is that contacts might start to fail because of being worn out. That might be caused by electrostatic discharges, card tearing because user pulls out the card earlier, etc.

C.2.2. Contactless Smart Cards

In contrast to contact smart cards, communication is done over-the-air thanks to an antenna glued inside the plastic body of the card, as Figure C.2 shows. The antenna communicates with the reader through a Radio Frequency interface. When the card is placed into a card reader's electromagnetic field, both power supply and communication are carrying out [27].

They are used in applications which need to make quick and secure transactions.

Two types can be distinguished [22]; vicinity cards, which offer a maximum read distance between 1 and 1.5 meters, and proximity cards, with a range around ten centimeters. Both standards can be checked at [13].

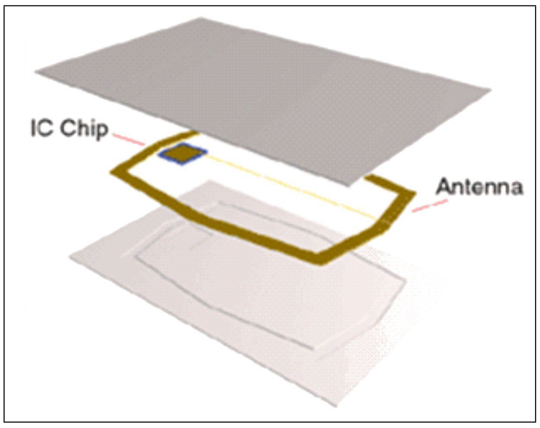


Figura C.2: Contactless smart card

Contactless smart cards are not inserted in any reader. Therefore, their contacts are not worn out with usage; i.e., they have a longer life. In addition, as the chip is within the plastic body, it is more protected. Thus, they are more reliable than contact smart cards, but more expensive.

An advantage of these cards from card issuer's business point, it is that microprocessor is not visible (there is no contact area to insert into the reader) which allows card issuer to print whatever it want on the card [39], for instance the company logo.

C.2.3. Dual Interface Cards

They are cards whose communication can be established either contact or contactless mechanism what allows using the card in both ways. These cards are designed to work in more than one application.

C.3. Hardware

The appearance of a common smart card chip is as the shown in Figure C.3. The main parts (microprocessor, memories and coprocessors) can be distinguished easily.

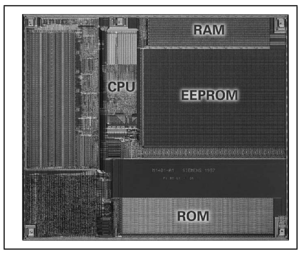


Figura C.3: Physical view of a smart card chip

C.3.1. Microprocessor

It is the most important part of the card. Usually they are not specially built with the aim of being used in a smart card. The main reasons are money and security. Money because to develop a new processor is expensive. Security because smart cards need to be reliable; a well-known processor which has been in the market for a long time and correctly tested is more trustworthy than a new processor.

Traditional processors in smart card were based on 8-bit Complex Instruction Set Computer (CISC) architecture built on Motorola 6805 or Intel 8051 core, with an extension to the instruction set. As the smart card evolved, embedded processors started to be based on 32-bit Reduced Instruction Set Computer (RISC) architectures in order to be able to support new needs like Java Card requires, for instance [27].

C.3.2. Memory

Memory is divided in three parts: RAM, EEPROM and ROM.

RAM is used to hold temporary values, i.e., volatile memory, due to their content is erased every time that the card is powered off. EEPROM holds data which can be modified during the lifetime of the card, but which is stored across the card restart events: mainly cardholder data such as keys or passwords. ROM is used to hold the programs which run on the card. ROM's contents cannot be modified and they are stored for the whole lifetime of the card. Both EEPROM and ROM are non-volatile (or persistent) memory.

Because of every type of memory uses a different amount of space per bit, they are added according to this constraint, trying to use ROM wherever was possible, later EEPROM and finally RAM.

C.3.3. Coprocessors

Processors used in smart cards are not very powerful; that is why some supplementary hardware is added to the chip to carry out particular tasks which cannot be satisfied easily by software. They are called coprocessors. This is true for 8-bit architectures, but in 32-bit architectures is no longer necessary, because as coprocessors are added as the price of the chip increases [27]. Consequently, manufacturers are who decide which coprocessors have to be added according to their needs. Particularly, two common and important coprocessors related to cryptography are added:

Coprocessor for cryptographic algorithms calculate each respective algorithm by hardware. For instance, since Data Encryption Standard (DES) and Advanced Encryption Standard (AES), which are algorithms which make bitwise and bitshift operations, are usually used in financial systems, both of them are available as coprocessors. In fact, DES processor is specially fast and small. In order to facilitate the running of Public Key Infrastructure (PKI), coprocessors working with large number exponentiation and modulo operations are also built. For instance, to Rivest, Shamir and Adleman (RSA) or elliptic curves algorithms.

Random-number generator is currently added in the most of smart cards to help PKI [27], since significant importance of the randomness in current cryptographic systems. A weak random key might cause a key was compromised, that is why their correct operation is critical. Although it can be enhanced by software (and it is usually done), coprocessor must generate enough randomness.

C.4. Smart Card's Applications

Thanks to its security features a lot of companies have chosen to use a smart card as trusted part to give to their customer, that is the reason why smart card have been widespread in different fields. The most common fields [44][17] can be looked at Figure C.4 (including some of the most remarkable examples) and they are briefly summarized at the following; however, it may expect that they will be deployed in more kind of applications in a future.

Telecommunication The most known are the Subscriber Identity Model (SIM) cards which almost everybody has in their mobile phone. These cards are being improved with a lot of new features; even Hypertext Transfer Protocol (HTTP) requests are already allowed. It is also worth mentioning the almost extinct pre-charge cards for phoning.

Banking Nowadays, credit and debit card are widespread. Some well-known examples are Mastercard or Visa cards.

Health care The most well-known example is Sesam Vitale, a system deployed in France to pass from paper-based payments to reimburse money to electronic transactions. Some features were added afterwards like storing medical records and prescriptions [4]. Also, Versichertenkarte in Germany is known.

Audiovisual industry Some pay per view channels and digital TV need a smart card to work as a decoder.

Transport A big amount of contactless smart card have been deployed in public transport industry used to pay (fast ticketing). Some examples are Oyster Card in London and T-money in South Korea.

Access control Smart cards are used to restrict physical access to only authorized staff in a lot of companies and buildings which need to limit the access inside them. For instance, in the university, it is used to control who is able to go to the library, departments, etc. It has not to be only for physical access, but also for some resources of a company.

Identification The best examples are electronic passports and national ID cards. Usage of smart cards in this field is very useful, if it is taken in account the possibility to keep safe either secret keys or certificates on the card. At this way, to forge these kind of documents is much harder and the authentication of the cardholder is ensured.

Authentication Since smart card is considered a safe token, it can be used in some applications as an authentication way on the web, for example.

Loyalty applications For instance, it is used in programs in which customer is earning points for using a service and receive a reward later (e.g. petrol station or mobile phone bill loyalty strategies).

Pocket-gamming An example is smart cards used in some casinos to be able to have cashless machines, with the according benefits for the casino [45].

E-services With the new smart cards which support TCP/IP, a new perspective is opened to smart card industry. Internet is suitable to be used in smart cards due to their capabilities to store and work with cryptographic keys. The most important e-services are e-commerce, remote banking and working.

Grid computing Some researchers have used smart cards as secure computing nodes.

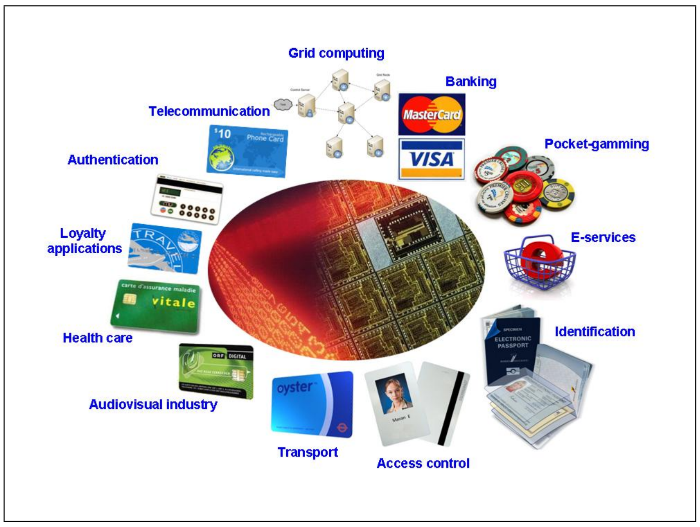


Figura C.4: Some applications of smart cards

C.5. Security in Smart Cards

One of the highlights which have made smart cards so widespread are their security features. Very often a smart card is used as a security solution with the aim of providing tamper-resistant functionality, in systems which provide some kind of security duties. At this point, it is worth mentioning that a smart card can be used as a secure token, but it does not guarantee the system where card was added was a secure system. One of the principles of the security says the following: "Security of a system consists in the security of its weakest part", what, in this case, means that to use a smart card not ensures the security of the whole system, as it is exposed at [22].

Smart cards solve security problems like secure cryptographic keys storage and distribution, authentication implementation or data confidentiality. They seem to provide a portable and flexible computing platform due to the use of a limited interface which does not allow attackers to access protected information [5]. As far as PKI systems concern, smart cards are particularly suitable. This is why if private key never leaves the card, to compromise it from a card reader or a PC is very difficult. Consequently, some services which PKI provides like secure email access, encrypted files, or digitally signatures, fit very well to be used through smart cards systems. Also, private keys which the card stores are protected within a security perimeter of hardware token which avoid card from being used by someone who does not know the PIN [39]. In other words, they provide hardware non repudiation, due to it is unlikely that someone was able to access to the private key and pass for the cardholder.

This section gives a brief overview of the types of attacks against smart cards following a similar structure than [27]. As it has been pointed out in a previous section, this structure is done partially according to the interface which the card used.

C.5.1. Physical Attacks against Contact Smart Cards

These kinds of attacks are carrying out over the hardware either gaining physical access to the microprocessor or through observation of the token. Theoretically, both of them can reach the target of getting information about the card and their functionalities and compromising their security measures. This topic is widely explained at [5] by means of introducing some examples, and mainly at [23] and [52].

C.5.1.1. Invasive Attacks

Executing these attacks means to get physical access to the microprocessor, or in other words remove it from the smart card, in order to inspect and try to tamper it. The whole process requires expensive equipment to remove the microprocessor and work within it, a high ability and long time to reach results. That is the reason why they are not very common except among the manufacturers companies, laboratories and perhaps some researchers. These attacks are focused in attacks to bus lines, EEPROM, RAM and ROM and reverse engineering.

It is possible to place a probe on bus lines between blocks of a chip and by means of an oscilloscope seeing the values sent on aforesaid lines. To avoid buses being through probed, they are usually placed in the lower layers of the device and scrambled in a specific way.

Either scrambling non-volatile memory cells is a way to prevent similar attacks against EEPROM. By hardware, is easy, efficient in space and very hard to break by an attacker. By software, it is harder to program but it can be made chip-specific and dynamic [27].

In what RAM´s concerned, its content can be held in the memory if their cells are cooled to a temperature of -60 °C or if the content is not changed for a long time. Hence, on one hand, secret keys should not be kept in the memory for more than the elapsed time. On the other hand, RAM can be protected with a metal layer, which elimination leads to useless memory cells.

On one hand, EEPROM and RAM data are encrypted in real-time (even by using memory address, that is, cipher text is distinct for the same plaintext and different address) in order to be protected. This feature is available in newest microcontroller. On the other hand, smart card manufacturers use ion-implanted ROM to prevent this memory from being read bit by bit using an optical microscope.

One of the most important invasive attacks is the reverse engineering. The goal is get to know how a chip works in order to be able to copy the design with the corresponding losses to the owner. Also weaknesses on the chip can be found. These attacks are usually carrying out by people inside to the smart card industry who can access the necessary equipment to make the attack and are the most interested in getting information about the competitors to have competitive advantage. Consequently, several countermeasures are usually implemented on the chips. The most important are glue logic, obfuscated logic and adding another metal layer. One known example of reverse engineering which got their goal was MIFARE. The proprietary cryptographic algorithm was broken by reverse engineering compromising the MIFARE chips which used this algorithm [24].

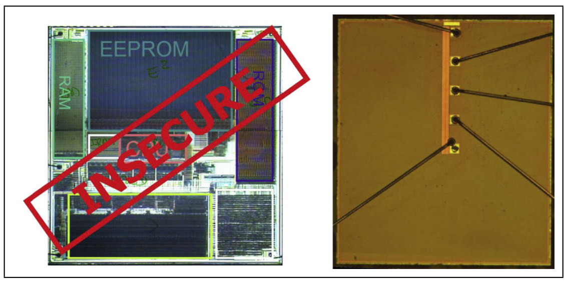


Figura C.5: Physical view for two chips; both insecure (left) and secure (rigth)

As it can be seen at Figure C.5 (got from [27]), a secure chip looks like the right one. It implements several of the countermeasures aforementioned to prevent the physical attacks against the chip. Some of them are glue logic and a new metal layer which makes access to the chip difficult.

C.5.1.2. Side-Channel Attacks

They work observing the changes in a smart card when it processes different information and deals with unexpected effects. The main techniques are timing, power and electromagnetic analysis and fault induction attacks.

Timing analysis, as its name suggests, consists in checking the time of operations to get conclusions and make inferences from it. To avoid attacks over:

- PIN code, the whole bytes are compared
- Cryptographic keys, current cards use noise-free cryptographic algorithms

Power analysis is the technique which observes the power consumption over the time (for instance adding a resistor in series with card and checking the voltage change) and gives information about which operation is carrying out the microprocessor. There is two ways to do it: Simple (SPA) and Differential (DPA). Simple looks for several patterns in the consumption. For example, the rounds in AES cipher or square and multiply algorithms in RSA. If power consumption can change because of the value of the keys used, an attacker might get these keys [22]. DPA analyzes statically the samples. It is one of the most important attacks due to carrying it out is relatively cheap and the consumption is yet dependent to the data and the microprocessor. Some countermeasures include either to add a voltage regulator or artificial noise generator, use random delays or an on-chip random generator which varies the frequency of the clock. It is also possible to use machine instructions with similar consumption or have prepared different algorithms to solve the same problem. Patented countermeasures can be read at Cryptography Research, Inc. [42].

An electromagnetic analysis can be carried out by means of the electromagnetic radiation of the chip. It is hard to get success with it because it is necessary chip has to be close enough to get a properly signal. To prevent chips from this attack, a metal shields can be added or some layers stacked on top of it. Because of this attack is related to power analysis attack, their countermeasures help to protect against this one also.

Fault induction attacks try to produce some effect, which attackers can take advantage from, after injecting a fault. Some of them are focused in the movement of the silicon atoms which might provoke resetting data, data randomization or modification of operation codes. Shielding and scrambling wires on the chip help to make difficult to access the important parts.

C.5.2. Security of Contactless Smart Cards

Any possible attack to a contact smart card, it is possible to be carried out in a contactless smart card, and therefore, the attacks and their countermeasures explained in the previous sections are valid for these kind of cards too. One contactless smart card drawback is that as they communicate over the air, everyone who wants to carry out an attack, only needs a radio device (ready to work at a short range) to try it against a card placed some meters far from the device. Some attacks are the following.

Due to communication is over the air, it is easy to try an eavesdropping attack without the cardholder realized that someone is accessing to its card. It is difficult to get private data, but all the communications should make encrypted to avoid problems. In fact, in order to avoid a man-in-the-middle attack which would be able to altering the data transmitted, data should not be only encrypted, but with certain randomness. That assures data integrity [27].

Denial of service is one of the hardest attacks to fight against because any countermeasure works properly for contactless smart card.

Finally, other important attack is radio frequency analysis, which is made up of a power and electromagnetic analysis. It is not necessary to have physical access because data is taken from radio field emitted. This attack is easier to carry out and harder to detect. It may prevent by means of a current stabilizer and message and exponents randomization.

C.5.3. Anomaly Monitors

Some parts of the smart card might be affected by changes in their environment when they do the conditions go too extreme [27]. That is the reason why some anomaly monitors are added. They expect the card works in a range of acceptable conditions. When these conditions change and go to an unacceptable value, they (monitors) notice it and the chip stops running up to conditions come back to be suitable. They need space on the chip, so usually not all of the following monitors are implemented on the same card; it depends on what is the task for.

Voltage monitor is used in the most of current cards because it can avoid some attacks to get information as secret keys by Differential Fault Analysis (to know more [9]). When it detects that the voltage is working over the upper or down the lower limit, it informs the smart card in order to stop running. To avoid monitor from being disabled by an attacker, they are protected in such a way that its manipulation stops the card. Another monitor always placed on the chip is a power on detector which leads the chip to an initial state when it detects a power on condition.

The clock signal is provided by an external clock (because of the lack of power supply). The frequency does not depend on the card then, but on the supplier. Hence, a frequency monitoring may be added. It orders the card to stop when under or over frequency values appear.

As far as temperature concerns it is a controversial topic because; on one hand, it may change out of the specifications without being an attack. On the other hand, an attack modifying the temperature can lead to manipulate the random-number generator ([27]). That is why temperature sensors are discussed by the experts, and also, because of deactivating the chip when it is working in a temperature out of the specifications can increase failure rate.

C.5.4. Software Attacks

In addition to the normal bugs which can be found in any software development, it is worth mentioning the following aspects.

To do the verification of the bytecode is a task too expensive to run on the card, so it is not possible to perform it over the microprocessor of chip. Therefore, malicious applications built over illegal bytecode instructions is a problem to be solved. Otherwise, these kind of constructions can allow an attacker to get the total control of the card in the worst case.

It should be taken into account the parties which participate in the communication between the smart card and the host. Moreover the smart card, either the link layer or the host can be attacked. That is why the design of the system and a correct use of the cryptography are necessary to develop a trusted system. An example of how the communication may be compromised by a man-in-the-middle attack could be read at [6]. More information about software attacks in [12].

Apéndice D

Multi-Application Smart Cards

As its name suggest, a multi-application smart card is a smart card which can host several applications. After the huge development in 90's, a lot of companies chose to use smart cards as a security solution and normal people used to go with several of these cards everyday. The idea is to be able to use the same card for the whole needs of the user instead of one card for each need; that is, ro reduce the number of cards in the user's wallet. Nevertheless, the most important reason to work in that topic is the needs of the issuer card companies of being able to offer more services in the same card. The best example is a SIM card which currently has been improved up to provide to end-user new services. It was necessary to improve the cards to get the flexibility and the security to make the market's needs possible.

The most interesting issue in multi-application is the chance to allow the dynamic application load. That means to be able to add new, update or remove the already loaded applications on the card whenever the user wanted. For instance, if a customer wishes to change their bank account from one bank to other, the customer would be able to remove the application of the old bank and install application from the newer. All process may be done quickly, instead of canceling the old credit card and ordering a new one to the current bank. Another example about update operation is the following. Let's suppose a worker who uses a smart card as an access control card in his job. Some day, he is promoted, and then, has access to a new laboratory with a stronger security measures. Application in the smart card needs to update itself to adapt to the new algorithm to check the identity and permissions or update the previous content.

The architecture of a multi-application smart card is shown at Figure D.1. As it can be seen, applications run over the OS which interprets the instructions to do them irrespective from the hardware. This independence is achieved through a virtual machine, for instance Java Card uses Java Card Virtual Machine (the acronym JVCM will be used in the remain) which is similar to the Java Virtual Machine.

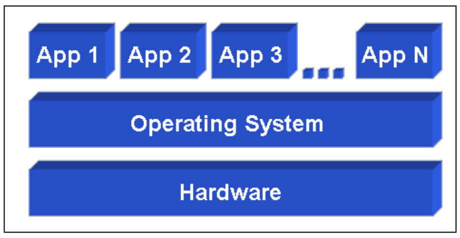


Figura D.1: Architecture for multi-application smart cards

D.1. Main Standards

The two main standards are MULTOS and Java Card which are explained below. Some more are Smartcard.NET (to support .Net framework, freedom for the developer to choose the language to work), Multiapplication BasicCard (evolution from BasicCard, file system similar to File Allocation Table (FAT) by means of the data is sharing) or Windows for Smart Cards (WfSC, authentication oriented, real FAT file system). A brief summary of all of them can be read at [44]. In the following, Java Card will be described deeper than MULTOS for two reasons: it is the most important standard for multi-application smart cards and it is which will be used in the implementation. Also, Global Platform will be slightly presented.

D.1.1. MULTOS

This operating system is considered the main competitor to Java Card. It was created emphasizing on interoperability and security. Its architecture is made up of a virtual machine and a security scheme from Secure Trusted Environment Provisioning (STEP) technology to protect smart card, application code and data [30]. It is possible to program for MULTOS in several high-level languages, thanks to the amount of available compilers, like Modula-2, Basic, etc. although the most common are Java and C. It is also possible to program in low-level assembly language. Applications are compiled into MEL bytecodes. MEL is an optimized language which is based on Pascal P-codes. Then they are executed by the virtual machine which checks every bytecode and the address accessed. Data sharing is not allowed among applications, thus any application can access to the data of the others [30]. The main drawback from MULTOS respect Java is that manufacturers of the first one are not allowed to add their own API, so to be able to use the functions everywhere they have to be replicated.

D.1.2. Java Card

Java Card is a technology which allows developer to build applications using Java Card programming language to run them in smart cards. It defines a subset of the Java Programming language and a Java Card API. As it happens with Java, it provides object oriented programming, a secure programming platform, interoperability and hardware independence (portability). Although its speed is limited because of the card's hardware and the byte code run-time's interpretation, Java Cards are not slower thanks to the usage of crypto-coprocessors which help them to make cryptographic operations much faster.

However, the key point of this technology is the chance to develop multi-application smart cards and manage (addition, removal and update) them dynamically, that is, post-issuance card application management. Since this dynamism may generate several security problems; a context isolation mechanism was added to the Java Card Runtime Environment (JCRE). It provides isolation among applications at context level, as explain [50], what means that applets (applications on-card) cannot access applets from other context. This granularity is appreciated at Figure D.2 (from [17]), where "Packageïs used instead of çontext".

Context isolation is enforced by an application firewall which checks every access; and if someone is not allowed, it throws an exception. But, some applets may need to call methods from others. This is possible by means of Shared Interface Objects (SIO). It is an interface which stores the accessible methods. Thus, an applet accesses to data or methods from some distinct applet accessing SIO mechanisms through the firewall.

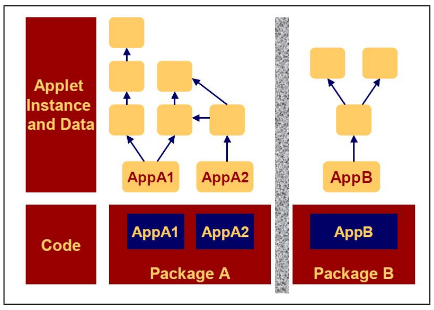


Figura D.2: Firewall containment

D.1.2.1. Previous Versions to Java Card 3.0

In previous versions to Java Card 3, the card always works as a server; it gets a request, processes it and sends response back to the client, but it never takes the initiative. Communications are made by Application Protocol Data Unit (APDU) commands, specified at ISO 7816 standard. Garbage collection works on demand, that is, developer is the responsible for the memory management. If it is neglected, execution might run out the memory resources of the card, and consequently, make it useless.

The most representative of these versions is the split virtual machine architecture, which it shows at Figure D.3 (got from [17]). Owing to the constrained resources of traditional smart cards; it is not possible to do bytecode generation on-card. That is why it is carrying out on the PC. Thereby, loading, linking, optimization and bytecode verification are done off-card by a tool, the converter, whose output is a Converted Applet (CAP) file. This file is loaded on the card and ready to be interpreted by the JCVM [50]. To sum up, bytecode execution and security enforcement are done on-card and previous work off-card.

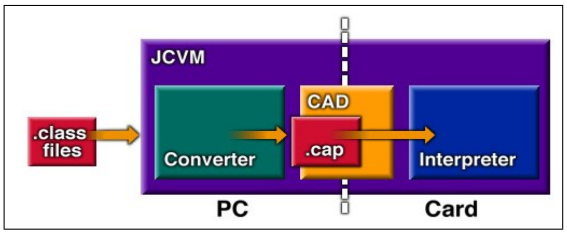


Figura D.3: Split Java Card Virtual Machine

D.1.2.2. Java Card 3.0

Java Card 3.0 provides two editions, both of them backward compatible:

Classic is an evolution from the version 2.2.2, oriented to constrained resource cards, using the split-virtual machine and working as a server.

Connected is network oriented to high-end cards with improved connectivity; that is why HTTP(s) is added as communication protocol using high speed interfaces like USB [3]. Card can work as a client and a Web server is incorporated giving rise to a new kind of applets: servlets.

A relevant feature of this edition is the on-card bytecode verification which supposes the change in the architecture: JCVM is not split but it is completely integrated on the card.

Necessaries protocols and layers are shown in Figure D.4. The protocols which are bordered by the black line are exclusive from Connected Edition, whilst the rest are available for Classic Edition too. New logical protocols were developed to replace APDU because it spent too much time with ISO (APDU) command. Connections were not enough fast and a high-speed protocol was needed for new applications [10]; p.ej., for mobile applications.

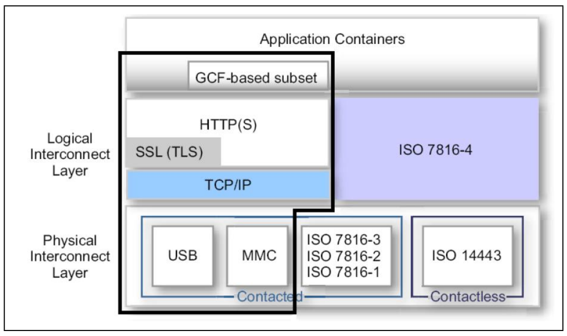


Figura D.4: Physical and logical layers of Java Card 3 Connected Edition

D.1.2.3. Application Protocol Data Unit

APDU is the protocol used by Java Card to establish communication. As it has been described previously, the card always (Classic Edition and previous versions) works as a server following a master-slave model between the card and the CAD, which is the responsible for supplying power to the card. Communication consists of two types of messages:

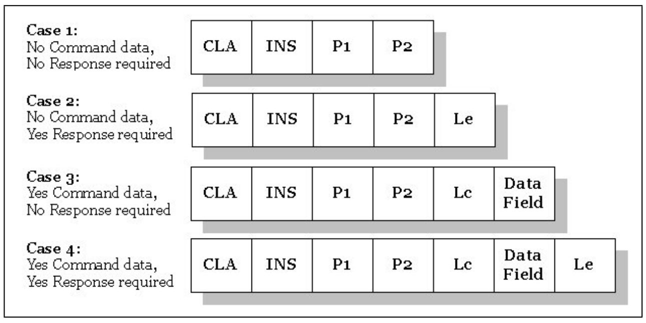
- Command APDU, which are the messages sent from the CAD to the card
- Response APDU, which are the messages sent from the card to the CAD

Every response is sent as a reply to a command and every command receives a response. Both types of messages are transmitted by Transmission Protocol Data Units [20]. The most common protocols are: byte-oriented, block-oriented and contactless.

A command APDU is merely made up of two parts: Header (mandatory) and Body (optional). Body consists of three optional parts which give rise to four possible command structures according to its presence (see Figure D.5 from [38]). The whole parts are described at the the following:

- CLA (1 byte): Identify an application class of instructions; in other words, identifies the applet among the stored on-card
- INS (1 byte): Specifies the instruction among the available in the CLA set
- P1, P2 (1 byte each one): Parameters 1 and 2, they are used to qualify the INS field or for input data
- Lc (variable): Length of the data included in the command

- Data (variable): Data included in the command
- Le (variable): Maximum length of the expected response

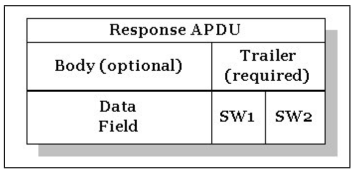


Case 1: No Command data, No Response required	CLA	INS	P1	P2			
Case 2: No Command data, Yes Response required	CLA	INS	P1	P2	Le		
Case 3: Yes Command data, No Response required	CLA	INS	P1	P2	Lc	Data Field	
Case 4: Yes Command data, Yes Response required	CLA	INS	P1	P2	Lc	Data Field	Le

Figura D.5: Possible command APDU structures

Response APDU is made up of the following fields. Its format can be seen at Figure D.6 from [38].

- Data (variable): Data included in the response
- Status Word (2 bytes): SW specifies which was the result of the execution on-card (if no error 0x9000)



Response APDU		
Body (optional)	Trailer (required)	
Data Field	SW1	SW2

Figura D.6: Response APDU

At [14] it is further described the standard for ISO 7816-4. This document is particularly interesting to start to develop Java Card applications because valid CLA, INS and SW values are described. CLA and the necessaries INS have to be defined by the developer.

When smart card starts to receive power, it sends a message to the host called Answer To Reset which contains some parameters for the transmission like the protocol supported. Once this message has been received by the host, the communication can start. First command to be sent should be a select in order to choose the applet with which will be worked. Since the card saves its state, it is also possible to work with the applet selected before the card was powered off. But the CLA in the command has to meet with the CLA of the applet already selected. Any command with a different CLA, whose instruction was different to select, will be ignored.

D.1.3. GlobalPlatform

They are a set of specifications whose goal was to create a standard for cards management irrespectively of hardware, manufacturers or applications. Specifications are related to cards, card terminals and global management of systems using smart cards. That means they can be implemented over any multi-application technology.

Some of the most interesting parts are Security Domains (SD), which ensuring a total separation (complete isolation) of cryptographic keys between Card Issuer and other Security domains. They support the most of the cryptographic services like encryption, key handling, etc. Every time one of the keys is required, application accesses to the corresponding SD through GlobalPlatform API which provides the service [44].

D.2. Open Multi-Application Smart Cards

Multi-Application technologies were strongly pushed few years ago because of the needs of service providers which required a flexible, open and secure platform which allows them to load dynamically applications on cards after their issuance, that is, dynamic load post-issuance. It led to the differentiation of multi-application smart-cards depending on their flexibility to allow dynamic application load. In other words, their content management. They are distinguished among [44]:

- Open policy which allows anybody to load, update or remove any application on the card
- Closed policy which limits load, update or remove applications to the card issuer and some trusted partners

There is an intermediate policy, called mid-open, which allows modifications to "less"trusted parties. That means a partner in contact with a partner of the card issuer could also load its application, for instance. The risk of every policy is obvious. Open policy is more prone to be attacked or infected by malware than closed policy, because anyone can load its application, whilst in closed policy the issuer is the only one who can. That is why the chance to a malicious application was load on the card is as bigger as opened is the policy. Nevertheless, it does not mean that the open policy is the only one which can be attacked.

Some of the main attacks possible against open multi-application cards are the following [44]:

- Collect information about services on-card in order to identify them
- Attack the OS
- Be familiarized with the card in order to select the best attack
- Denial of service

An important risk of open multi-application perspective is that the software to be installed might not be trustworthy; and that is an issue to solve. It should be taken in account that up to date, it was difficult to load new applications in a deployed card, and consequently, it was hard to exploit bugs in the software. But using open multi-application smart cards, new applications loaded in deployed cards might allow attackers to exploit software bugs which may be important (also because they might combine physical and logical attacks). In other words, a problem of the open multi-application cards is that it is possible to load a malicious application in order to carry out internal attacks. These attacks might identify available services on the card, collect information in order to try to deduce the possible behavior of an application or attack the JCVM and the firewall. It is longer explained at [43].

D.2.1. Security Challenge

The main problem with these cards is the interactions among the applications stored on it. In order to avoid them some tools have been developed and the security level of multi-application developments has been enhanced. For example, Java Card added its firewall and SIO. Firewall mechanism isolates applets from the rests within of its own space (context). But it is not enough, because applications can interact through the sharing methods. Let's suppose that a class used to bank account management implements its interface for the SIO, due to it wishes that other application on the card related to bank issues could make use of its methods. The problem is that an application can make use of the shareable interfaces for its own purposes [34]. Any other application on the card will be also able to access its methods on the SIO carrying out malicious tasks. Of course, any application will not be able to access the context of the whole applications on-card (but only the presents on the SIO), but some unexpected behaviors may be carried out like illegal information exchange.

Some companies have already implemented some solutions but they are still only an improvement of Global Platform specifications. These improvements do not deal neither with the compliance of the new applications with the stored on the card nor with how the changes can interfere in the work of the applications already stored on the card.

The problem is that the semantic of the modification (either addition, removal or update) is not checked. It should be verified what the application intends to do on the card, its behavior; in order to make sure that it is not in conflict with the already stored on the card. In such a way, any application can do nothing unexpected or forbidden; because if the change is accepted is because its behavior is compliant with the expected on the card. That is the idea of Security-By-Contract.

Apéndice E

Security-By-Contract for Multi-Application Smart Cards

Open smart cards allow consumers to dynamically load and remove applications during the card's active life. The reason why concrete deployment of these cards is still rare is the lack of solutions to the control of interactions among applications, as the previous chapter has stated. Indeed, the business model of the asynchronous download and update of applications by different parties requires the control of interactions among possible applications after the card has been issued. The key point is to assure to stakeholders (regarding to the owners of the applications deployed onto the card) their applications cannot be accessed by other applications added after theirs, or at least that their applications will interact only with the ones of some business partners.

To date developers have to prove that all the changes that are possible to apply to the card are security-free, so that their formal proof of compliance with Common Criteria is still valid and they do not need to obtain a new certificate. The result is that there are essentially no multi-application smart cards, though the technology already supports them [32].

This chapter gives a brief overview of the Security by Contract (S×C) approach and examines some of the related work in what security of dynamically changes in open multi-application smart cards and mobile code concerns. Finally, the specific problem addressed in the thesis is introduced, namely securing off-card contract-policy matching in the S×C framework.

E.1. Mobile Code Security

The current State of the Art has its origin in the research done for Mobile Code (due to dynamic application load on the card is still only a kind of). That is why the first related work concerns it. The second part of the section will focus on the research on smart cards.

The three main approaches to Mobile Code security are Cryptographic Code-Signing, Proof-Carrying Code (PCC) and Model-Carrying Code (MCC).

Cryptographic Code-Signing is used to certify the origin of mobile code and its integrity by means of a signature. Usually, it is the software developer the responsible for signing the executable content. Using a public key infrastructure, the consumer can verify the content of the application which is loading by means of developer's public key. This approach allows consumer to know that the software comes from a trusted developer, but it does not verify the mobile code behavior. Thereby, two wrong cases come up. First one the case of a right code from an unknown developer and the latter a bad code from a trusted developer. This approach does not allow unknown developers to install their applications, even if it is possible a safe execution of them. However, the code from a known developer can be installed either if it is faulty (case of trusted developer) or malicious (case of untrusted) code [33].

PCC is a technique which requires that the mobile code come bringing a proof regarding its safety. This proof assures the safe execution to the consumers who has to check that the proof is valid. Developer is the responsible for adding the proof to the code. The idea is that the proof should be automatically generated by means of an analysis done by a kind of compiler [36]. As with the previous technique, two problems arise. First one is related to the complexity of the automatic proof generation. The latter is that the technique expect that developer knew the security expectations of the whole potential consumers due to it has to send the suitable safety proof. That is impractical, since security needs change to each consumer [33].

The last approach is MCC, inspired in the previous one. Instead of a proof, MCC force the code to come with a model which stores the security-relevant behavior of the code to which is enclosed. When consumer receives the code and the model, it is also able to get the security needs of the code which is intended to be installed. Consumer has to check its its security policy against the model received together the code in order to state whether the code is compliant with its policy or not. Models are expected to be simple; and consequently, the checking could be automated [41]. The main limitation was that MCC had not developed the whole lifecycle and had limited itself to a finite state automata. That one was too simple to describe a realistic case, but even for that, basic policy could not be addressed [34].

The idea of [15] is to use information flows to specify security policies of the smart card. Every application is certified when is loaded by means of the information flow signature assigned to each method. It is represented as relations established between two method variables together annotations indicating the type of flow. The problem of this approach is that its policies are too simple.

At [28] is proposed a framework and a tool set for compositional (thus allowing post-issuance loading of applications onto the card) verification of the interactions among applications on the card. A maximal applet with a behavioral safety property is built. The idea is that verifying the compliance of the local applications, the global correctness can be achieved. That is why the local properties are compared against the implementation of the new applications when they are loaded. To check that, model checking techniques are used. They assure the global property.

[16] presented an approach which suggests to associate security levels to attributes and methods by means of Bell/La Padula model which is a state machine model used for enforcing access control. The security policies in this model define which are the authorized flows among the levels [34].

Finally, S×C framework is proposed to deal with and address these problems. It works over the idea that the application has to come bringing a specification of its security behavior which will be check against the expected behavior of the target platform. The remainder of the chapter is focused on this framework.

E.2. Security-by-Contract

Security-by-Contract is the approach which is proposed to prevent illegal information exchange among several applications, checking the interactions at load or run-time since the asynchronous loading and updating of applications by different parties business model. It is also expected to solve the problem of the post-issuance changes, that is dynamically loading, removal or update of applications, during card's active life; in other words, dynamic evolution of smart card platform.

S×C approach was built upon the notion of MCC and successfully developed for mobile code

([33]), making more concrete the ideas behind it and allowing card to deal with more practical scenarios. Loosely speaking, it consists in the idea of contract which specifies the security behavior of an applet, policy which specifies the security policy of the card and the contract matching algorithm which compares the contract against to the policy. The goal is to make the checking at load time in order to avoid costly run-time monitoring.The aforementioned problems can be summarized as [35] does in the following way:

1. A new application should not interact with forbidden applications already stored on the card
2. A dynamic change should not affect the correct work of an already stored application. The changes can be:
    - Addition of a new application
    - Updating an existing application
    - Changes in the card's policy
    - Removal of some existing application

A contract is a formal complete and correct specification of the behavior of an application for what concerns relevant security actions and particularly with problems of sensitive data exchange. It does not only store the behavior of the current application, but the desirable for other applications regarding to the direct and indirect communications with it [34]. The aim is that a new application could express its desire to interact with other application still not present on the card, for instance. Contract is provided by the application developer who is the responsible to enclose it to the application to be installed.

A policy is a formal complete specification of the acceptable behavior of applications to be executed on the platform for what concerns relevant security actions (both definitions from [33]). The policy has to be created in first time by the card issuer. It is the responsible for preparing the initial security requirements of the card.

E.2.1. Security-by-Contract Workflow

Working on mobile code, the target platform (i.e., the smart card) follows a workflow similar to the one depicted in Figure E.1 at load time. First, it checks that the evidence is correct. Such evidence can be a trusted signature. An alternative evidence can be a proof that the code satisfies the contract (i.e., [15] for smart cards).

Once we have evidence that the contract is trustworthy, the platform checks that the claimed policy is compliant with the policy that our platform wants to enforce. This is the Contract-Policy Matching. If it is, then the application can be run without further ado. At run-time, a firewall (such as the one provided by the JCRE) can just check that only the declared API in the contract can be called. The matching step guarantees that the resulting interactions are correct. This is a significant saving over full in-line reference monitors [32].

Coming back to what smart cards concerns, the matching algorithm should succeed only in case that every claim that the contract specifies is compliant with every security requirement that the policy demands. Particularly, they should match if contract and policy do not give rise to any illegal information leakage or exchange between the new application and anyone existing on the card.

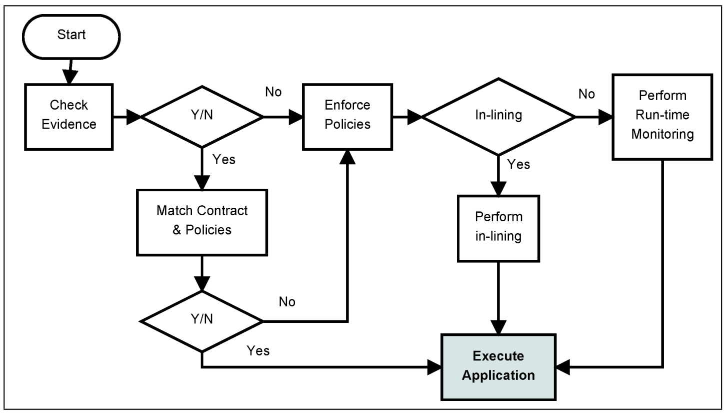


Figura E.1: S×C Workflow

E.2.2. A Hierarchy of Contract/Policy Models

It is considered more efficient and secure to make any checking or validation about the trustworthiness of any extern something on-card because it supposes not to rely on off-card applications. Thanks to be a tamper-resistant device, its data and applications are more trustworthy. However, the constraint resources of the card may lead to some operations cannot be carried out on-card, but off-card [25].

Precisely, because of the limitation of the computational resources of the smart cards, S×C proposes a hierarchical model of contracts and policies. Every level on the hierarchy has contracts and policies with several features and described with different deepness in function of the expected computational capacity for that level. In other words, every level works over different computational efforts and has different expressivity limitations. For instance, the lowest level gets the highest computational benefits, but their contracts and policies loose expressivity; that is, they are less concrete. On the other hand, the highest level spends a lot of resources of the microprocessor, but allows a very complete specification of the contracts and policies.

The levels proposed for S×C are [34]:

L0: Application as Services. At this level, applications are dealt as lists of available and required services, similar to set-up of the Global Platform specification. This is the level which needs less computational effort and it is expected to be run on the card.

L1: Allowed Control Flow. This level builds a call graph of the application where vertices are the states of the application and edges the invocations of different services. It allows doing a more fine grained information exchange control and even a bit of history-based access control. The more abstract levels are based on this, adding more features to the graph.

L2: Allowed and Desired Control Flow. It adds correct and error states to the previous graph. The goal of this addition is to provide a way to check that any change in the policy or the removal of some application do not go to avoid that the rest of applications worked properly; that is, any of the aforementioned change affect the correct work of the rest.

L3: Full Information Flow. At this level, the call graph is enhanced adding the information flow among variables. It requires the highest computational effort.

E.2.2.1. Limitation of the Level 0

The problem of the Level 0 is that it only captures the possible information exchange among the applications instead of the actual exchange; what means that this level cannot specify the behavior of an application. As [35]discusses, it is not able to distinguish between the services that an application might need from the services which an application requires. For instance, let's suppose an application A on-card, which is wished to be removed, provides a method which other application B on-card requires. What Level 0 is not able to extract is whether the application B, which requires the method, will keep working well or not after application A was removed. To do that, a further level of abstraction is needed. It can be solved by means of a call graph which was able to get the actual behavior of an application. It is worth mentioning that this level cannot capture the indirect communication between applications on the card neither.

That is why to get a higher security level is suitable to use some of the other levels. The problem with the limited computational power does not lie in the capacity to build the representation, but in the resources to run the contract-policy matching which is the key phase of the approach. Usually, it is done on-card, but if it requires a very expensive computational effort for a resource limited device, it is also possible to outsource this phase to a Trusted Third Party (TTP). That is called Off-Card Contract-Policy Matching.

E.2.3. Problem: Securing Off-Card Contract-Policy Matching

The Off-Card Contract-Policy Matching idea is depicted in Figure E.2. It is carried out when Contract-Policy Matching Phase is too expensive (computationally talking) for doing on-card. Then it is necessary to make use of a TTP which provides its computational capabilities to run the matching algorithm. TTP supplies then a proof of contract-policy compliance to the smart card which should verify that. Smart Card's (SC) policy is updated according to the results received by the TTP: if the compliance check was successful, then the SC's policy is updated with the new contract and the application can be executed. Otherwise, the application is rejected or the policy enforced off-card (for example, by means of a service provided by TTP in addition to Contract-Policy Matching), as [32] details. In case TTP includes a proof of compliance in the reply, then a further check is needed to verify the proof, as shown in Figure E.2.

Since to the communication between SC and TTP is carried out over an untrusted environment, it has to be secured. The system has to ensure authentication, integrity and confidentiality of the data sent during the whole communication. To guarantee integrity and authenticity, both parts (SC and TTP) have to encrypt and sign their messages by means of their key pairs. They should keep their private keys as secret and send their public keys to each other. Thereby, at the beginning of the communication, it is necessary a kind of key exchange or key set-up.

But it is not easy; some attacker can try to intercept their keys, like it may happen in a very common attack: Man-In-The-Middle. This attack is a kind of eavesdropping and consists in someone who is placed between the host and the card and launches independent connections to them, making them believe they are communicating with each other, while in fact they are only sending messages to the attacker. An attack of this type may be carried out in the aforementioned key exchange, making useless PKI architecture, because attacker can decrypt any message. It would be done like follows. TTP sends a public key to the card, but attacker intercepts the message replacing the key for a new one which only he knows. Card receives key sent by the attacker and reply with its key. Attacker intercepts the key again and replaces it from a new one which is sent to TTP. Therefore the attacker can intercept the rest of encoded messages and modify them as it wants without the

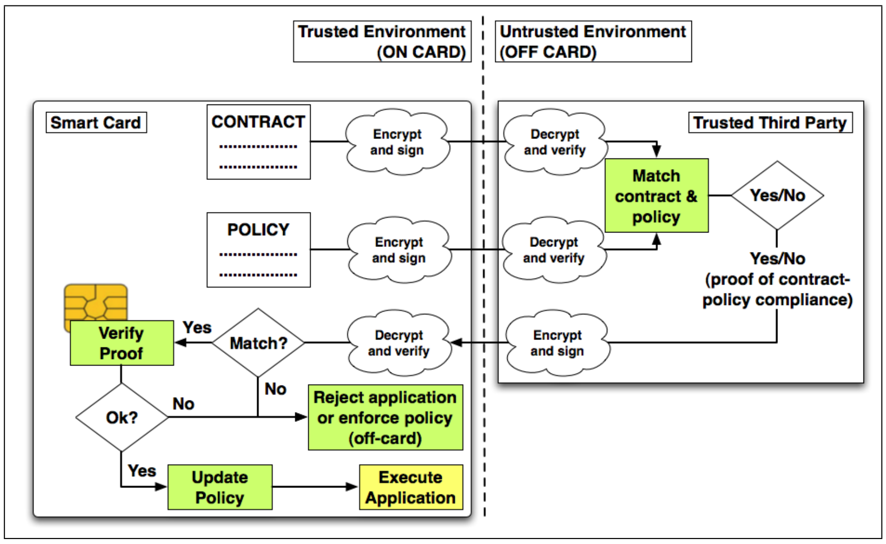


Figura E.2: Off-Card S×C Contract-Policy Matching

rest of the parts of the system realizing of that.

This problem is solved using certificates which have been signed previously by a Certification Authority (CA) in which both parts rely on. Certificates identify its owner unmistakably and they cannot be forged because they are signed with CA's private key. But SC's certificates cannot be sent through an insecure environment to be stored on the card. They must be stored through a secure and trusted environment and only once during the card initialization. That is why an initialization phase is necessary. It is carried out in a trusted environment by means of a trusted reader which works as an installer and is placed between the card and the CA. It is the responsible for sending the certification signing requests to the CA and gives them back signed to the card. The card cannot be used until initialization has properly finished with the storage. Otherwise, security requirements are not accomplished, security verifications cannot be carried out. Any change over any application on the card should be rejected until the end of the initialization. Once everything been stored, the card is ready to work as it is expected.

To summarize, the thesis is focused on solving the problem of securing the communication between SC and TTP during the Off-Card Contract-Policy Matching Phase. Specifically this is done by making the communication over an untrusted environment secure and trustworthy by satisfying the requirements of mutual authentication, integrity and confidentiality. To achieve this it makes use of a PKI scheme which needs certificates to handle identities.

Apéndice F

Extending SxC for Off-card Contract-Policy Matching

Contract-Policy Matching is a key step in the S×C framework. When the limited resources of the device do not allow the card to run this algorithm, it has to be done off-card. A TTP which has enough computational capabilities will run the matching algorithm. To do that it is necessary to send the contract, policy and subsequently the results, over an untrusted environment. Therefore the communication has to be secured. The current chapter introduces the design of the system's architecture designed to solve the problem of securing the communication for outsourcing the matching algorithm. The user will be able to securely rely on system decisions about matching-algorithm output to decide advisability or not of the change (addition, removal or update).

In order to fulfil the requirements of mutual authentication, integrity and confidentiality, the system is based on a PKI where keys and identities are handled through certificates that are exchanged between both parties at the beginning of each communication. For this reason, the card requires an initialization phase where certificates are stored in the SC along with the initial security policy of the card. Notice the difference between this phase and the installation which adds the system to the card and creates the instances necessaries to its proper work.

Since TTP is the responsible for running the matching algorithm, it is expected to be a trusted and secure device. The security of the system relies on this assumption, therefore the communication is what needs to be secured. Each part of the PKI architecture involved in the matching algorithm (SC and TTP) has two key pairs. One of these key pairs is used for encryption, while the other one is used for signing. Although it is perfectly possible to use only one key pair for both encryption and signature, it is safer to use two different key pairs. Since both of them are distinct cryptographic functions, in the unlikely case of one of them being compromised the other will not. Hence, the common recommendation is to use two different key pairs. Therefore, every principal part of PKI architecture has two certificates, one for each key pair. To sum up, the use of two key pairs (and consequently two certificates) is optional, and it has been pointed out in the figures belonging to Initialization Phase; however it makes the system more secure.

It is worth mentioning that the card works always as a server. That means it never starts a communication, but it merely receives a command from off-card clients, processes it, sends the reply back and holds waiting next command as Figure F.1 (modified from [38]) shows. This is important to understand the subsequent design. Throughout this chapter the term *Command* will be used to refer to the messages sent from any off-card entity to the card, whilst the term *Response* will refer the messages from the card to any entity.

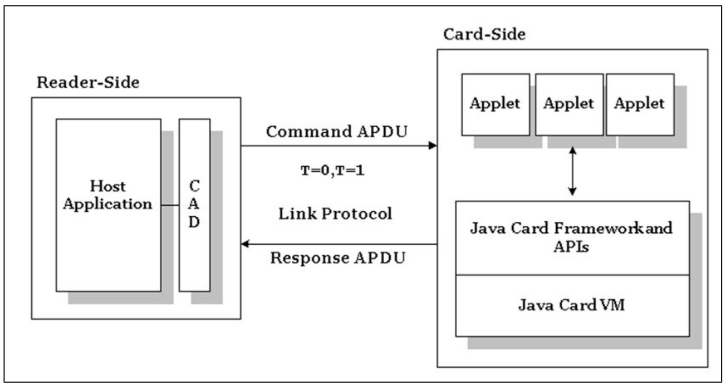


Figura F.1: Smart card's communication by APDU

F.1. Confidentiality and NONCE Issue

In the previous section it has been stated that the requirements of the system are authentication, integrity and confidentiality, but someone might wonder why the last one is necessary in the system. Since during the communication what is sent are the contract and policy and the result of the matching algorithm, all of that might be public, it might seem that this is unnecessary. What is really important it is to keep the integrity and authenticity of the message safe because it guarantees that the message has been sent from the card to the TTP and viceversa without being modified. That is: the card is sure that the result which it receives is the one generated by the TTP by means of the contract and policy that it has sent.

However, let's consider the following scenario. At the beginning, a trustworthy application wants to be installed on the card. Its contract is stored on the card, and those sends this contract and its policy to a TTP in order to run the contract-policy matching algorithm. The result is positive, and TTP gives back a message to the card telling it that the application is trustworthy. Now an attacker is able to intercept and save this message. The attacker wants to install its untrustworthy application on the card. Thereby, it sends the contract of its application to the card, which forwards the contract together the policy to a TTP to run the matching algorithm. The result is negative, the application should not be installed on the card. TTP sends this result to the card, but the message is intercepted again by the attacker, which substitutes it for the previous message containing a positive result. In such a way, the attacker gets to install the malicious application on the card (this kind of attack is known as Replay Attack).

The solution to that problem is to add a number used only once (NONCE, in this case a Cryptographic NONCE). It should be random in order to insure the freshness. This number is used as a kind of time-stamp which prevents the card to accept previous messages. The NONCE has to be sent encrypted in order to avoid malicious entities to know it, and consequently, forge some messages.

Concerning the confidentiality of the message (contract, policy and result), it is used to avoid some kind of spoofing attack against the content. Moreover, an attacker could get information about the behavior of applications on the card and use it in a bad way. That is why some application issuers, whose applications needed a high-security level like bank's applications, may demand the use of confidentiality, refusing the card if it does not provide it. As a final comment, it might be considered to restructure the system for really constrained resource devices which cannot afford message encryption, but it is strongly advised because of the benefits are much bigger than the disadvantages.

F.2. Architecture of the System

The system has several parties involved during its different phases; Initialization, Contract Storage and Contract-Policy Matching. These phases can also be separated in other smaller parts. All of them are addressed in the remainder of this section according to the order in which they have to be run. Note that Installation Phase has to be performed first.

F.2.1. Installation Phase

Applications in any smart card have to be installed in order to be used. First of all, the application is deployed on the card, and the Installation is done afterwards. The keys are usually generated and stored at this phase. Keys generation can be done in the ways proposed at the following:

- TR produce the the keys and gets the certificate after sending the CSR to the CA
- CA is the responsible for generating the keys and the certificates
- The card creates the keys and by means of the TR which sends the CSR to the CA gets its certificates

The first two ways have a particularly significant drawback. They have to send the keys, or rather the private key, to the card in a secure manner. If this key was compromised the card would be useless. Also, they should remove physically all the information related to the generation and the own keys. Even physical security measures shall be used to ensure that the off-card entity and operations are free from tampering [1]. That is why is much more secure to generate the keys inside the own card. Indeed it is one of the security highlights of the system which makes it particularly secure. The reason is that the private keys do not leave never the card simply because there is no reason to do that. Therefore, no one apart from the card can either get or use the private keys.

F.2.2. Initialization Phase

This phase is the responsible for creating and storing SC certificates, CA certificate (needed to verify correctness of TTP certificates) and the policy of the card. The whole process is made up of three stages: Certificate Signing Requests (CSR) building, certificates issuing, and finally certificates and policy storage. The off-card entity involved in this part is a Trusted Reader (TR).

It is carried out in an environment considered trusted, as well as the communication between both parties. Notice that TR is the responsible for storing the certificates and the policy; hence, the security of the card depends on its proper work. If the storage were compromised and what the TR stored on the card were infected, the whole system would be compromised. It is expected to be carried out by the card issuer who is trusted.

It is worth mentioning that it is only possible to run this phase only once, or rather, every storage can be done only once. Therefore it is avoided the case where everyone could store whatever (certificates or policy) they need on the card. Notice that the card is only a server which replies requests without being able to identify the requester. This issue is further discussed in the Future Work section.

F.2.2.1. Certificate Signing Requests Building

In this stage the CSRs are built and stored on the TR in order to be sent to the CA.

A certification request consists of a distinguished name, a public key, and optionally a set of attributes. Everything is signed by the entity which is requesting the certificate. A CA receives the CSR and if it is correct (information and signature), CA creates a public-key certificate containing the information of the CSR. The signature is used to prevent any entity from being able to request a certificate including the public key from another entity. Usually, certification authorities might require other non-electronic ways of request or reply in order to assure the information given by the requester; but that is beyond of the scope of the project.

TR has to create the two CSR, one for each key pair. CSR for encryption is created before, whilst CSR for signature is created later. In order to do that, it needs the public keys stored on the card. That is why to build the CSR, the first *Command*, which TR sends to the card, orders the public key for encryption (PuKSCEnc) and does not contain any data. SC receives the query and replies it with a *Response* whose data is PuKSCEnc.

TR by means of PuKSCEnc creates the CSR for encryption (SCEncCSR) adding the pertinent information. However the card has to sign the CSR since it is the owner of the private key. That is why at this moment TR has to sent SCEncCSR to the card and be signed there with the private key for encryption (PrKSCEnc). In such a way, CA will be able to verify that the signature is right, and consequently, that the public key matches with the private key of the requester. In other words, signature is what CA needs to be sure that PuKSCEnc belongs to whom is sending SCEncCSR, because it is the only one who can sign with the private key corresponding to the public key in the CSR. Once it is signed, the card sends a *Response* containing the signed SCEncCSR ($Sig_{PrKSCEnc}$(SCEncCSR)) attached in the data. This process is shown at Figure F.2.

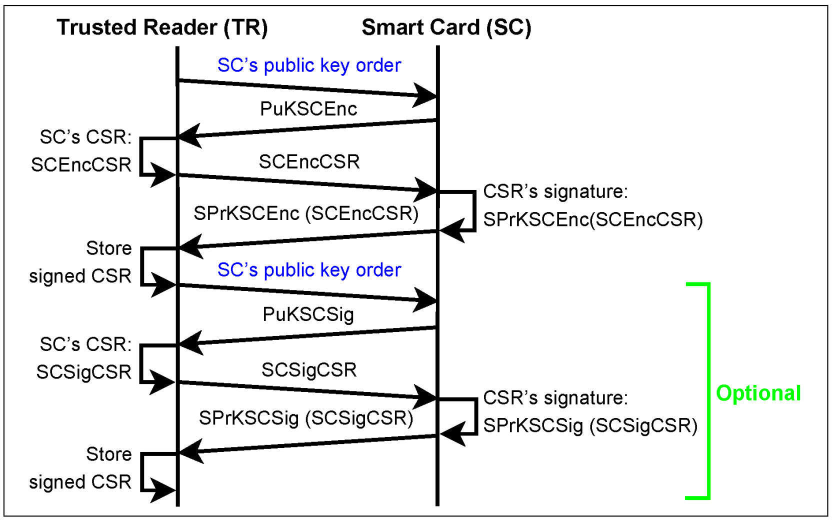


Figura F.2: Initialization Phase: CSR's building diagram

As notation, it is worth mentioning that in the Figure F.2 and subsequent, the messages typed in blue means that they do not contain data, whilst the black messages do.

To sum up the flow of messages for the first CSR's building is:

1. *Command* 1: No data, it is ordering PuKSCEnc

2. *Response* 1: PuKSCEnc
3. *Command* 2: SCEncCSR
4. *Response* 2: Signed CSR, that is $\text{Sig}_{PrKSCEnc}$(SCEncCSR)

TR stores $\text{Sig}_{PrKSCEnc}$(SCEncCSR) and builds afterwards the CSR for signature (SCSigCSR) in the same way: orders the public key for signature to the card (PuKSCSig), builds SCSigCSR and sends it to the card in order to be signed with the private key for signature (PrKSCSig). Hence, the messages for the second CSR's building will contain, in the following order:

1. *Command* 1: No data, it is ordering PuKSCSig
2. *Response* 1: PuKSCSig
3. *Command* 2: SCSigCSR
4. *Response* 2: Signed CSR, that is $\text{Sig}_{PrKSCSig}$(SCSigCSR)

F.2.2.2. Certificates Issuing

Once both CSRs have been built and signed, TR has to send them to a CA in order to get the corresponding certificates. This process is shown in the Figure F.3. TR is called TR-Certificates Manager in this figure because it depends on the actual implementation of the TR which is not within the purpose of this project.

The messages' content exchanged between the TR-Certificates Manager and the CA are the following:

1. *Command* 1: $\text{Sig}_{PrKSCEnc}$(SCEncCSR)
2. *Response* 1: SCCertEncr, that is the SC's certificate to encrypt
3. *Command* 2: $\text{Sig}_{PrKSCSig}$(SCSigCSR)
4. *Response* 2: SCCertSign, that is the SC's certificate to sign

Each certificate contains (among other) information about the owner of the key, the public key and the signature. For instance, previous certificates may contain each one:

- Information which identifies the owner: ID_{SC}
- Public key which intends to be authenticated by the certificate: SCPuKEnc/SCPuKSig
- Certificate's signature: S_{PrKCA} (SCEncInfo/SCSigInfo)

Once the certificates have been issued by the CA, sent and received, TR stores them in order to be available to be sent and stored to the card.

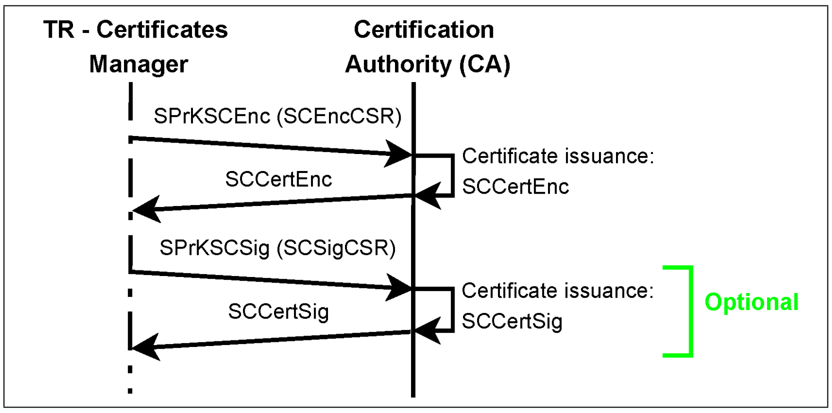

TR - Certificates Manager
Certification Authority (CA)
SPrKSCEnc (SCEncCSR)
SCCertEnc
Certificate issuance: SCCertEnc
SPrKSCSig (SCSigCSR)
SCCertSig
Certificate issuance: SCCertSig
Optional

Figura F.3: Initialization Phase: Certificates issuing diagram

F.2.2.3. Certificates and Policy Storage

The last stage during the Initialization Phase is the storage of all the necessary on the card. TR has to send both SC's and CA certificates and the security policy. On one hand, each one of this things is sent in a different *Command* by the TR. On the other hand, the card always replies with an acknowledgement without any data. The stage is detailed at the Figure F.4. As it has been pointed out previously, these messages can only be sent once, that is, any object can be stored on the card once.

The data sent within the commands from TR are the following (the order is not relevant):

- *Command* 1: CA's Certificate
- *Command* 2: SCCertEncr
- *Command* 3: SCCertSign
- *Command* 4: Card Security Policy

After the SC had been initialized, it is ready to be used to run securely any activity related to the contract-policy matching algorithm. At that time, the card is able to verify the identity of the TTP (validate its certificates), authenticate and authorize its requests.

F.2.3. Contract Storage Phase

At this phase, the contract of the application wished to be installed on the card has to be sent and stored there. It has to be carried out previously to any Contract-Policy Matching Phase since it needs that the contract had already been stored on the card. After every phase which runs the matching algorithm, the contract is removed from the card, that is why other contract should be stored on the card in order to perform the matching algorithm again.

The process is very simple. An off-card entity, called Application Issuer (AI), sends a request to store the contract to the card, attaching aforementioned contract. The card stores the contract and replies the entity with an acknowledgement. The process is shown at Figure F.5.
The entity responsible for storing the contract is the application issuer because it should be the same entity that develops the same which enclose to it the contract with its behavior, as it is proposed in the S×C framework.

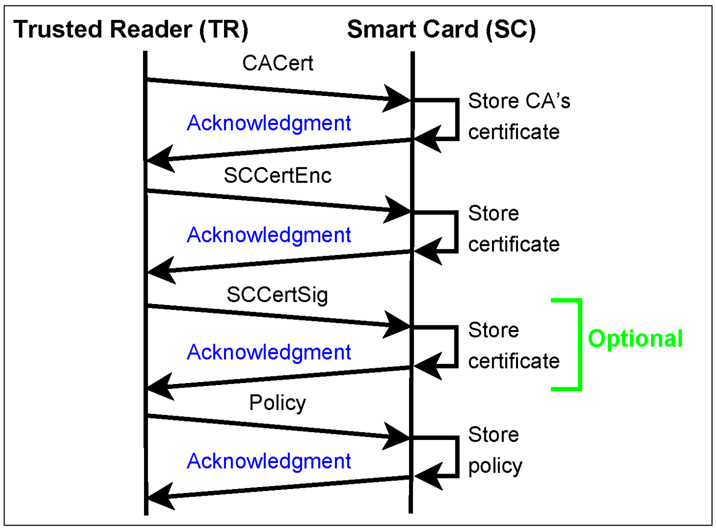


Figura F.4: Initialization Phase

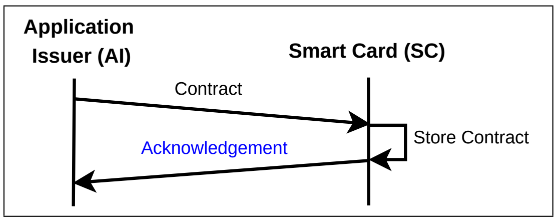


Figura F.5: Contract Storage Phase

F.2.4. Contract-Policy Matching Phase

Contract-Policy Matching is the key phase of the S×C framework. It has to run the matching algorithm by means of the data provided through the secure communication between a TTP and the card. With more detail, contract and policy, stored on the card, are sent encrypted from the card to some TTP which runs the matching algorithm giving the result back to the card. While Initialization Phase is expected to be executed only once, this one is supposed to be executed commonly. In fact, always that a change was necessary in any application on the card; either addition, update or removal. As it has been pointed out in the previous section, Contract-Policy Matching is always performed afterwards Contract Storage Phase.

As far as this phase (contract-policy validation) is concerned, it has three stages:

1. Certificates' exchange

2. Contract and policy sending

3. Matching result sending

The whole process can be observed at Figure F.6.

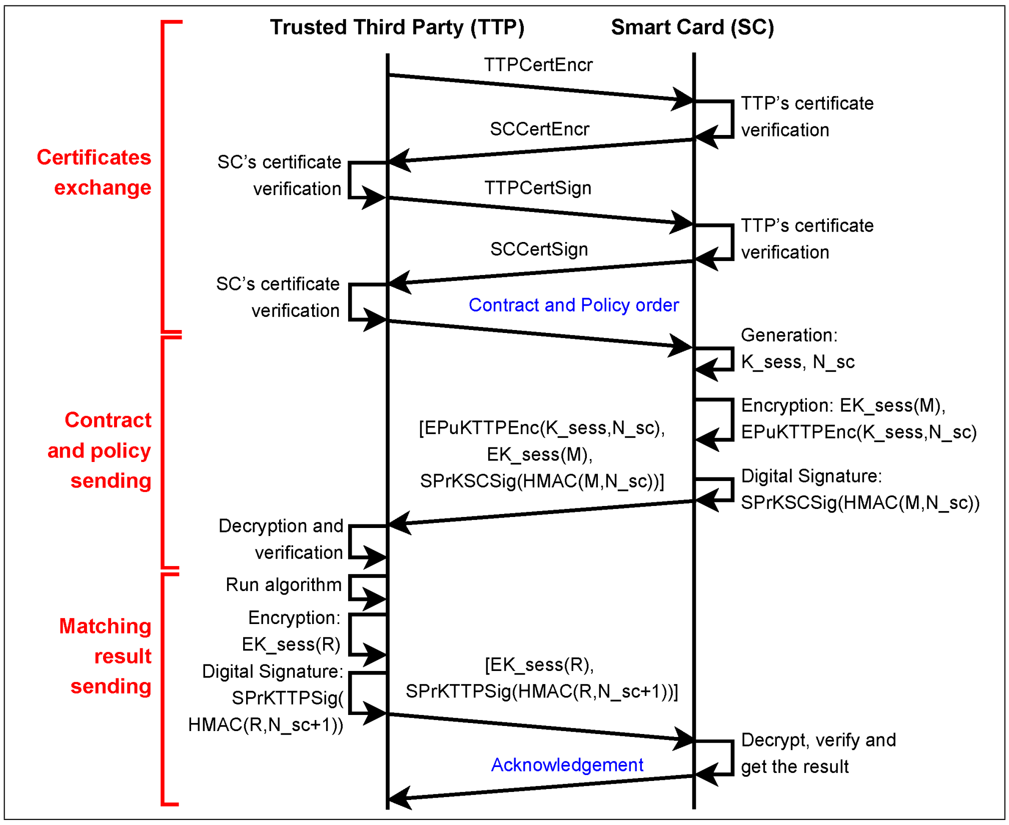

Trusted Third Party (TTP)
Smart Card (SC)
Certificates exchange
TTPCertEncr
TTP's certificate verification
SCCertEncr
SC's certificate verification
TTPCertSign
TTP's certificate verification
SCCertSign
SC's certificate verification
Contract and Policy order
Generation: K_sess, N_sc
Contract and policy sending
Encryption: EK_sess(M), EPuKTTPEnc(K_sess,N_sc)
[EPuKTTPEnc(K_sess,N_sc), EK_sess(M), SPrKSCSig(HMAC(M,N_sc))]
Digital Signature: SPrKSCSig(HMAC(M,N_sc))
Decryption and verification
Run algorithm
Matching result sending
Encryption: EK_sess(R)
Digital Signature: SPrKTTPSig(HMAC(R,N_sc+1))
[EK_sess(R), SPrKTTPSig(HMAC(R,N_sc+1))]
Decrypt, verify and get the result
Acknowledgement

Figura F.6: Contract-Policy Matching Phase

F.2.4.1. Certificates' Exchange

The exchange of the certificates between the card and the TTP is carried out by means of messages which encloses the corresponding certificates. Each party has to exchange two certificates to each other: one for encryption and one for signature. That means four messages are necessary to complete the exchange where two are from TTP and two from the card.

At the beginning, certificates for encryption are exchanged. TTP starts the communication sending its certificate to encrypt to the card enclosed within a *Command*. A parser is implemented by means of which the smart card is able to verify the certificate against CA certificate stored during Initialization Phase. Parser also takes the TTP's public key from the certificate allowing the card to get it. If the verification is positive (the certificate is right), it replies the message with a *Response* attaching its certificate for encryption. TTP verifies the certificate got from the card and gets also smart card's public key to encrypt. This process is repeated to exchange certificates to signature between both parties. It can be observed at Figure F.6. The data which contain the messages sent during this stage are:

- *Command* 1: TTPCertEncr, that is TTP's certificate to encrypt
- *Response*: SCCertEncr
- *Command* 2: TTPCertSign, that is TTP's certificate to sign
- *Response*: SCCertSign

F.2.4.2. Contract and Policy Sending

When certificates' exchange has finished, TTP has to order the contract and policy which are stored on the card. That is why it sends a *Command* without any data to make the query. Both contract and policy will be enclosed together within the same message in order to reduce the amount of messages to exchange, that is: SCContractPolicy (SC acronym has added in front to differentiate from the contract and policy which will be used during the verification of the message which will be TTPContractPolicy).

Contract and policy have to be encrypted and signed by the card before being sent in order to assure the requirements of the system (authenticity, confidentiality and integrity). The encryption will be done through block symmetric ciphering (for instance AES or DES). The reason to use symmetric cryptography instead of asymmetric (based on PKI) is that asymmetric encryption is very slow when it is carried out over a considerable amount of data, whilst symmetric encryption provides higher speed (decryption is the same process; hence, it is also very fast). In addition, symmetric cryptography provides high security due to their no linearity and it depends on the algorithm (i.e., DES can be broken by cryptanalysis [8]) but usually only brute force can work. That is why a Block cipher is suitable to used over these data which may be relatively long.

To use symmetric cryptography implies to both parties have to know the key. Thereby, the card that is which generates the key has to send the shared key to the TTP; but it cannot be sent in plain text because if someone could intercept the message, it could decrypt the content. That is why the key is encrypted and enclosed later to the message. The encryption at this moment is done by means of PKI because the key is not expected to be too long, but a few hundreds bits as maximum. It also guarantees that TTP is the only one which can decrypt the session key. The key for symmetric cryptography will change every session, that is, every time when it has to run a new Contract-Policy Matching Phase in order to assure freshness and randomness and get a higher security level.

Keeping in mind this kind of ciphering and taking in account also the NONCE previously explained, the sequence of actions, which the card has to follow aiming to secure the message containing the requested information (contract and policy) by the TTP, is:

1. Generate a session key that will be used for symmetric cryptography: K_{sess}

2. Generate a NONCE (Number used Once): N_{sc}

3. Encrypt the session key through TTP's public key to encrypt:
   $\mathrm{Enc}_{PuKTTPEnc}(K_{sess})$

4. Encrypt the NONCE through TTP's public key to encrypt:
   $\mathrm{Enc}_{PuKTTPEnc}(N_{sc})$

5. Encrypt the message with the session key:
   $\mathrm{Enc}_{K_{sess}}(\mathrm{SCContractPolicy})$

6. Compute the HMAC (a hash mixed with a salt) of the content:
   $\mathrm{HMAC}(\mathrm{SCContractPolicy},\ N_{sc})$

7. Sign the HMAC previously built through the key to sign:
   $\mathrm{Sig}_{PrKSCSig}(\mathrm{HMAC}(\mathrm{SCContractPolicy},\ N_{sc}))$

As it has been detailed in the previous enumeration, a Hash-based Message Authentication Code (HMAC) function has been used to create the signature instead of a common hash function, like Secure Hash Algorithm (SHA). The reason is that HMAC adds a shared key (called salt) which assures the freshness of the digest: every HMAC built with different salt will result in different digests. In addition, it guarantees that only the partners in the communication which know the shared key can check the integrity and generate the proper digest. That also improves the security of the system. In order to build this kind of digest, it is necessary a random number which was renewed in every session. That is why NONCE has been used, it fits perfectly with the requirements.

Finally, the secure *Response* built to send back to the TTP containing the contract and policy is the following:

- *Response*: [Enc$_{PuKTTPEnc}(K_{sess})$, Enc$_{PuKTTPEnc}(N_{sc})$,
  Enc$_{K_{sess}}$(SCContractPolicy),
  Sig$_{PrKSCSig}$(HMAC(SCContractPolicy, N_{sc}))], which contains:
  - Encrypted session key: Enc$_{PuKTTPEnc}(K_{sess})$
  - Encrypted NONCE: Enc$_{PuKTTPEnc}(N_{sc})$
  - Encrypted contract and policy: Enc$_{K_{sess}}$(SCContractPolicy)
  - Signature: Sig$_{PrKSCSig}$(HMAC(SCContractPolicy, N_{sc}))

TTP receives the *Response* and has to decrypt it and verify the content. To verify the integrity and authenticity, it builds a HMAC of the content, which it has just decrypted, and compares with the HMAC which it has obtained from decrypting the attached signature through the card's public key to sign. If both HMAC match, authenticity has been proved because only the card can sign with its private key. Integrity would have been proved too, because the fact that both HMAC match means that the data, from the HMAC have been done, also match, and consequently anyone could modify the content.

The sequence of steps necessaries to carry out the verification is the following:

1. Decrypt the session key:
   Dec$_{PrKTTPEnc}$(Enc$_{PuKTTPEnc}(K_{sess})) = K_{sess}$
2. Decrypt the NONCE: Dec$_{PrKTTPEnc}$(Enc$_{PuKTTPEnc}(N_{sc})) = N_{sc}$
3. Get the contract and policy decrypting with the session key:
   D$_{K_{sess}}$(Enc$_{K_{sess}}$(TTPContractPolicy)) = TTPContractPolicy
4. Compute the HMAC of the decrypted contract and policy:
   HMAC(TTPContractPolicy, N_{sc})
5. Decrypt the signature through the public key to sign of the card:
   Dec$_{PuKSCSig}$(Sig$_{PrKSCSig}$(HMAC(SCContractPolicy, N_{sc}))) =
   HMAC(SCContractPolicy, N_{sc})
6. If the HMAC which has been computed on the TTP through the content decrypted from the message matches with the HMAC got from the signature attached to the message, both authenticity, confidentiality and integrity requirements have been accomplished; otherwise not. That is:

If (HMAC(SCContractPolicy, N_{sc}) == HMAC(TTPContractPolicy, N_{sc}))
$\rightarrow$ Message OK
else $\rightarrow$ Requirements not accomplished

If the verification is correct, TTP have got the contract and the policy in a trustworthy way.

F.2.4.3. Matching Result Sending

Once contract and policy are in TTP's possession, TTP can perform the matching algorithm against them getting the corresponding result. Then, it has to build a secure message containing the algorithm result to be sent to the smart card in a similar way to how it has been done by the card previously. The key used for encryption is still the same session key with which the card had encrypted the contract and policy. The signature is done as before except with the difference that the HMAC uses as salt the value N_{sc+1} instead of the previous one. This change is done in order to assure that the TTP has been able to read, store and modify the NONCE. It is also a countermeasure against attacks since it increases randomness of the key. Thanks to that, the HMAC function changes because the key used for its encryption operation is different; that increases the effort for an attacker who tries to forge the HMAC.

The sequence of actions which has to follow the TTP to build the secure message to send in a *Command* to the card, is the following:

1. Encrypt the result with the session key: $\text{Enc}_{K_{sess}}$(TTPResult)
2. Compute the HMAC of the content: HMAC(TTPResult, N_{sc+1})
3. Sign the HMAC previously built through the key to sign:
   $\text{Sig}_{PrKTTPSig}$(HMAC(TTPResult, N_{sc+1}))

Finally, the secure *Command* built to send to the card containing the Result is:

- *Command*: [$\text{Enc}_{K_{sess}}$(TTPResult),
  $\text{Sig}_{PrKTTPSig}$(HMAC(TTPResult, N_{sc+1}))], which contains:
  - Encrypted result: $\text{Enc}_{K_{sess}}$(TTPResult)
  - Signature:
    $\text{Sig}_{PrKTTPSig}$(HMAC(TTPResult, N_{sc+1}))

Just in the same way that TTP has verified previously the message, the card has to do the same now. The sequence of actions to be carried out are the following:

1. Get the result by decrypting with the session key:
   $\text{D}_{K_{sess}}(\text{Enc}_{K_{sess}}$(SCResult)) = SCResult
2. Compute the HMAC of the decrypted result: HMAC(SCResult, N_{sc+1})
3. Decrypt the signature through the public key to sign of the TTP:
   $\text{Dec}_{PuKTTPSig}(\text{Sig}_{PrKTTPSig}$(HMAC(TTPResult, N_{sc+1}))) =
   HMAC(TTPResult, N_{sc+1})

4. If the HMAC which has been computed on the SC through the content decrypted from the message match with the HMAC got from the signature attached to the message, both authenticity, confidentiality and integrity requirements have been accomplished; otherwise not. That is:

   If (HMAC(TTPResult, N_{sc+1}) == HMAC(SCResult, N_{sc+1}))
   $\rightarrow$ Message OK
   else $\rightarrow$ Requirements not accomplished

If the message is correct, the card can get the result and sends an acknowledgement to TTP in a *Response*. With the result the card can also decide whether the application should be installed on the card or not.

Apéndice G

Implementation of the Prototype

With the goal of validating the previous design of the system to solve the contract policy matching off-card, a prototype is built. This one should be interpreted as a proof of concept. That means the aim is to build a functional prototype which demonstrate the system can work, but without being deployed in a real card. That is why the previous design has been lightly modified in order to get it running in a simulator.

At this chapter, the tools and programming languages chosen to be used to develop as well to run the prototype are explained. Also, the main parts of the implementation are described together the problems, choices and solutions taken during this stage. Every kind of details are provided in order to help to understand how the prototype was built.

In what Global Platform Security Domains concerns, it is worth mentioning that they have not been considered because of time constraints. It is proposed as future work.

G.1. Programming Languages

As it was explained in the previous chapter, there are four separate parts in the system: AI, SC, TR and TTP.

On one hand, clients (AI, TR and TTP) should run in a reader device able to communicate with a smart card and perform complex matching algorithms like a PC. Any common programming language like C, Java, etc., could be used to build these parts. Java has been the language chosen. On the other hand, there are not so many languages for smart cards which support multi-application. Java Card has been chosen. Both of them and the reasons to have been decided for them, are described below.

G.1.1. Java

Java is a programming language object-oriented, robust and simple. To know more, check [19].

The main reason to choose this language was to be multi-platform and that its API provides a very complete set of methods to work with security issues. Multi-platform issue, if not fundamental, is suitable due to the different places where the TTP could be placed. Java virtual machine could be easily installed every where and thanks to be an interpreted language any code should run properly. Java API provides a wide variety of methods which have been verified by a huge amount of testers from Sun community. That makes the implementation secure and reliable. Developers do not have to to implement new features already presents in the API. Particularly, it provides cryptographic methods to deal with security problems. For example, ciphers or randomness are easily implemented thanks to the API's support.The version of the Java Development Kit (JDK) used has been the latest version to date's project: JDK 1.6.0.18.

It was necessary to use some parts from sun.* package. These packages are not part of the public and supported Java API. What does it mean? They are included within Java Software Development Kit (JSDK) and they are usable, but Sun does not assure neither their portability nor their support in future versions [47]. Sun uses them to support its implementation of Java platform, that is why it wants to reserve the chance to modify them if necessary. Then, why to use that? They are used to generate CSRs because of the Java API does not provide any other way to do that. Other choice would be to build a new complete class to work with certificates generation. That implies to implement classes for Base64 and Distinguished Encoding Rules (DER) encoding or to do hand-made. Anyway, a long and tedious task. Also, it should be taken in account that Java does not provide any other way to deal with certificate generation, that is why it may be expected that if any change is done in future versions, it should be to add these classes to the Java API; consequently the work to modify the classes used should not be too hard. Finally, it is worth underlining that the prototype, as it has been explained before, is only a proof of concept; so the prototype is assured to work at the specified version of the JDK. If it is wished a more reliable version in terms of software's duration (out of the scope of the thesis), the use of these kind of packages should be avoided.

G.1.2. Java Card 2.2.2

Java Card programming language has already been described at multiapplication main standards section. In the following, some more of the main features for version 2.2.2 are exposed.

JCRE works as an operating system; it deals with communications, applet execution and security (it is done by the firewall). Both JCRE and JCVM never stop, since the moment when the card is initialized. This happens only once, at the beginning. JCVM together some static data structures are created and, from then onwards, virtual machine never exits [17]. Every time card is taken out, their content stop, and when is powered on again RAM content has been erased, but JCVM continues working. In other words, when the card is powered off, JCVM is in an infinite clock cycle [53]. For instance, if an application is selected and working in a smart card which, suddenly is taken out from the reader, when the card comes back to be powered on, the same application will be selected and their EEPROM's content will be stored (unlike of RAM's content). Due to card tear is possible to occur in every moment, persistent data writes must be guaranteed and this is reached by atomicity. Every write in non-volatile memory is atomic and if the write is unfinished it is rolled back.

G.1.2.1. Extended Length

APDU has a limitation which is the length of the data to send within a APDU message. Usually this length is restricted up to 255 bytes; a very small amount taking in account that the system has to send certificates (usually from 1 to 4 KB). To avoid the tedious task of implementing a way to send data bigger than 255 bytes, separating it in several messages, extended length functionality was used. It allows sending large data up to 32KB (32767 bytes) in a more efficient way. That is the reason why the length fields are variable; due to with extended length they may be up to three bytes long, whilst in common APDU its length is one byte.

G.1.2.2. Structure of an Applet

Usually, Java Card classes have a particular structure. There are four methods (two mandatory and two optional), in addition to the constructor, which are commonly present in that classes. These methods, always called by the JCRE, are: deselect, install, process and select. Their use is described at the following.

- Deselect is a method called when the applet has been deselected. It is not mandatory unless any cleanup operation was necessary.
- Install is called only once during the installation. It is the responsible for creating an instance of the applet on the card. It must be overridden.
- Process receives the APDU command. As the card works as a server, this is the method which processes the command and decides what to do to reply it. Usually, it is considered a good practice to build the process as a case statement which decides what method from the class will reply the command according to the INS field received. This way to organize the code is useful to make it clearer. It also must be overridden.
- Select is similar to deselect. It has not to be overridden unless some initialization operation was necessary.

The code is completed with constants, objects declarations and other methods to help to reply the command.

G.1.2.3. Why Not to Use Java Card 3

Java Card 3 (JC3) is the latest version of Java Card. It has been more wide explained at multiapplication main standards section.

When the implementation was starting, it was tried to use Netbeans as programming environment with its plugin for JC3. It worked when the entry was a script, but it was not possible to get a communication between an off-card part and the card. That was the basic feature of the system to be built, taking in account that its goal is to make the communication secure. There was not found any tutorial or manual which could help to build the more basic communication between these two parts. This lack of information or examples for JC3 is caused because only a prototype can be built in this version. In other words, there is no any real implementation yet for JC3; there is no any real card which supports JC3. That is why the most of Java Card developers work on the previous version and JC3 is only used by some researchers. Hence, there is no many support and the information or manuals are scants.

Also, not many smart card experts talk positively of JC3. They complain because JC3 add a big overhead over the card response time owing to there are excessive abstraction levels in order to the bytecode was executed. Also, servlets increase transaction times. They claim that is not suitable to substitute APDU protocol due to although it is a bit more complicated than other protocols, it fits very well to smart card's constraint resources. So, any change on that will suppose a loose of speed on-card. Some experts justify the change explaining that the new version is more suitable to target USB dongles and that is why the two editions (classic and connected) are created, maintaining backwards compliance by means of Classic edition which should be able to work with APDU.

Another point to be aware of is their cost. Although the memory and power of the card were improved in JC3; it supposes the cost of the card is higher too.

For all the exposed (mainly for the support), it was decided to move to Java Card 2.2.2 version. It is a reliable and common version used by most of Java Card developers. Anyway, JC3 it is supposed to be backward compatible; hence, in the event of moving to version 3 the changes should be small.

G.2. Limitations of the Prototype: Use of Eclipse, CREF and JCWDE

Eclipse is a multi-language software development environment which includes an Integrated Development Environment (IDE). It provides a comfortable way to develop software at the same time that it may be tested. For the goal of the current project, it exists a plugin to work over Java Card. Eclipse is a free and open source software. The version used has been Eclipse SDK 3.5.2. The main reason to use Eclipse instead of Netbeans (which was used at the beginning, as above mentioned), was the problems to get a communication between the card and an off-card part in the latter. In contrast, by means of the manual in [11], the basic communication between both parts was straightforward in the Eclipse environment. In addition, Netbeans only provided a plugin for the last version of Java Card, that is JC3; therefore Eclipse was the logical and natural choice.

Moreover this is a prototype, a proof of concept, a way to demonstrate the correctness of the system designed; therefore the choice of Eclipse and simulators to carry out the implementation is more than appropriate.

During the implementation phase, two simulators have been used, allowing both to communicate the card (emulated card) with a CAD via socket interface. They are:

- Java Card platform Workstation Development Environment tool (JCWDE) for the first part of this phase
- C-language Java Card Runtime Environment (CREF) for the second part

On one hand, JCWDE is a tool which allows running an applet simulating that applet is masked at a ROM of a Java Card; that is, the applet run as if it were stored on a card. To do that, it makes use of the Java virtual machine to emulate the JCRE. In other words, it uses a subset of the Java virtual machine to emulate a JCVM. That is why some of the features of the actual JCRE are not supported like package installation, persistent card state, firewall and transactions. Its main advantage is that as the applet has not to be stored on the card (because it does not save the card state), it is faster to test with it. That is the reason why it was used for the first part of the implementation stage where the structure of the system and communication were implemented and for the whole initialization phase. At this part, the card state was not stored (from one running to the next), only while the applet is running. To learn more about JCWDE, read chapter 4 from [2].

On the other hand, CREF is a similar simulator written in the C programming language which allows testing applets in a emulated environment in a very accurate way. The main difference is that it may be built with a ROM mask which allows it to simulate the persistent card memory (EEPROM), like a real card which saves its state. That means applets can be installed on the card. The main and obvious advantage over JCWDE is that it can save the card's state; but also, it supports some features that JCWDE does not, like transactions. To learn more about CREF, read chapter 10 from [2]. This simulator was used for the second part of the implementation stage when the initialization phase was already finished. Then, it was necessary its use because contract-policy matching phase needed to work with a card which has already stored the certificates, contract, etc. and which was able to use its cryptographic keys.

Both simulators have a problem which limits seriously their performance. They are designed with the goal to be useful for the people who is starting to work with Java Card. By means of

Entity	**Project**	**Source code**
SC	*SmartCard*	*VerifyPolicyAndClaimApplet*
TR	*TrustedReader*	*InitializationClass*
TTP	*TrustedThirdParty*	*TerminalClass*
AI	*ApplicationIssuer*	*ContractDelivery*

Tabla G.1: Equivalence among entities, projects and source codes

them, they can create and test their own applets. That is why they do not support the whole of cryptographic classes and methods which Java Card 2.2.2 really provides. They only provide a basic security and cryptographic classes that [2] details at chapter 13. It restricts key lengths, available cryptographic algorithms, etc. Indeed, the restrictions caused the system design was modified for the prototype. It may lead to an error: theoretical system design has to be separated from the prototype's implementation. The system design presented at the previous chapter is the correct and which should be used in a real implementation. But, due to these simulators are the only available and what it was expected to build was a prototype as a proof of concept, it was decided to modify as less as possible the necessary parts to get the prototype working on that simulators. The main part which had to be modified was the CSR's generation and the verification of the certificates' signature, because of the lack of support for the RSA cipher implementation without padding. Also random number generation and key lengths have been affected. Every part which was changed will be properly explained at its corresponding section.

Consequently, two different source codes are provided in the appendixes. Source code in Appendix J belongs to the code for the prototype, whilst source code in Appendix K belongs to the code for a real implementation.

G.3. Communication and Involved Parts' Structure

The communication among involved parts is the basis over the whole system is built; hence, their structure and the interaction among them was the first stage in the implementation.

Card works as a server, that is the reason why its process method is limited to assure that the request was replied calling the corresponding method. To select the correct method to be called, process method makes use of a case statement by means of received INS. To work with CLA, INS and SW, there are a lot of necessary constants at the beginning of the applet's code. These constants are also duplicated within off-card applications which make use of them. After the constants, necessary attributes are placed. Among them, it is worth mentioning the bytes array to store contract and policy and the booleans which store whether the certificates, contract and policy have been stored or not. They are used to carry out verification to check if everything is properly stored to run the matching algorithm. Before process method, Constructor, Deselect, Install, and Select are included. Constructor creates instances of algorithms and AES keys and generates RSA keys. Install calls constructor and registers the applet on the card. Deselect and select make cleaning operations. The rest of the code of the applet, is divided among some useful methods for utilities like converts between data types (p.ej., short to byte array), cryptographic methods and APDU management for extended length.

The equivalence among entities of the system design and the implementation projects and source codes files is shown in the Table G.1.

The *InitializationClass*'s main method, responsible for the initialization phase, is presented as a menu. According to the option chosen, corresponding method is called. The APDU communication is carried out by means of methods which work on it. They try to abstract the details of APDU management and make it more general and easy to use. Thereby, to send an APDU command without data it is only necessary to call two methods: *prepareAPDU* and *exchangeAPDUs*, omitting low-level details about the values of the octets of CLA, INS, etc. Result can also be checked by means of *checkAPDUStatus* method. These methods are also available at *TerminalClass* and *ContractDelivery* code. To complete *InitializationClass*'s code structure, cryptographic and some useful methods are included.

TerminalClass and *ContractDelivery* main methods are built in a sequential way. They run their operations and if any error occurs they finished properly. They rest of their structure is similar to *InitializationClass*.

G.4. Certificates

The main issues addressed in this section are the certification request and certificate generation, verification and storage, both on and off-card sides. In order to be able to understand that properly, it is necessary to be familiar with formats, Abstract Syntax Notation One (ASN.1) specification and encoding rules and formats of CSRs and X.509 certificates.

ASN.1 is a notation used to describe both abstract types and values defined by Open Systems Interconnection (OSI). Every ASN.1 object has a tag which is made up of a class and a tag number. Only tag number identifies unequivocally a type. OSI also defined a set of rules which are used to convert the abstract objects in strings of ones and zeros. This set of rules is called Basic Encoding Rules (BER). BER provides an encoding for the object which consists on three parts: Identifier, length and content. Both ASN.1 and BER are explained wider at [18]. Finally, DER are a subset of BER which apply some restrictions getting a unique possible encoding for every object, in spite of BER which allows several encodings (this is not suitable for instance to check digital signatures on certificates). To know more about DER [21].

On one hand, CSR's ASN.1 specification can be studied at Listing I.1 and I.3 and is described at [29]. On the other hand, ASN.1 specification for X.509 certificates can be observed at Listing I.4 and I.5. X.509 are detailed at [7] and [40]. X.509, although it can be large in size, is the most widely used certificate format.

The remainder of the section is organized in the following way. It first deals with the implementation of both certification request and certificates generation. Once the generation has been detailed, certificate's storage and management are described on and off-card sides. Finally, the verification of the certificates on-card is explained through the parser implemented.

G.4.1. CSRs and Certificates Generation

This section examines the implementation of the CSR and Certificate generation. These tasks are carried out by means of the TR. As it has been described at previous chapter, CSR is supposed to be built in TR and signed on-card. After that, card issuer should send the CSR to a CA in order to get the expected certificate.

CSRs to encrypt and sign are built in the same way. First, TR orders public key to the card. Once it is received, CSR structure is built and prepared to be signed with the private key on-card. Main options to create the CSR are to make use of:

- Bouncy Castle
- Java sun.* packages

Bouncy Castle is, roughly speaking, a collection of lightweight cryptography APIs for Java. It provides a way to create CSR, but it is necessary to have the private key of the entity to be certified in order to sign it. That means it does not allow building a CSR structure to be sent to the card and signed there. Hence; the only way to create the CSR by means of Bouncy Castle is exporting the private key from the card, which is a significant security risk.

Java sun.* packages allows developer to create the handmade CSR thanks their classes to work with DER and Base64 Encoding. Once CSR structure has been created, DER encoded digest info structure has to be sent to the card in order to be signed. This one, called Encoded Message (EM), is built as follows ([26]): EM = 00 || 01 || PS || 00 || T, where

- T is the DER encoding of digestInfo structure (ASN.1 specification is at Listing I.6)
- PS is an octet string of length k-3-||T|| with value FF. The length of PS must be at least 8 octets
- k is the RSA modulus size

EM is what has to be sent to the card. At this time a problem with the simulator appears. EM has been built according to PKCS#1 v1.5 (Public-Key Cryptography Standard) scheme, that means padding has been already added. That is why it should be encrypted on-card with the RSA implementation which does not add any padding; that is: ALG_NO_PAD. But the simulator does not provide this implementation (although JC 2.2.2 does), as it may be checked at chapter 13 of [2]. For this reason, the design of this part was modified to adapt to what simulator supports. Change consists in export the private key to the TR in order to sign by means of the needed algorithm off-card. It is shown at Figure G.1. The source code which contains this implementation for the prototype can be observed at Appendix J.

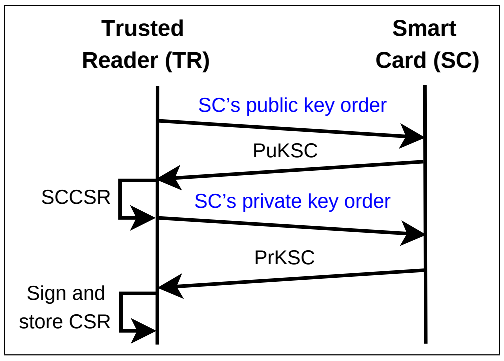


Figura G.1: CSR's building process on the prototype

It is worth mentioning that in the case of a real card implementation, Java Card 2.2.2 provides the necessary method; thus, it would not have to make this risky change. In other words, the change is only acceptable for the building of the prototype with the simulator; the private key never has to leave the card.

Once CSR is built and sent, CA authenticates the requesting entity and verifies its signature. If the request is valid, CA constructs a X.509 certificate. Certificate is built by means of the distinguished name and public key got from the CSR, and adding the issuer name, corresponding serial number, validity period, and signature algorithm from the CA. If any PKCS#9 attribute is included in the CSR, CA may also use these attributes to construct X.509 certificate extensions [29].

Two are the main tools to carry out the creation of the certificate from the CSR, due to Java does not have any support for this operation: Keytool and OpenSSL. Both are tools which can be used to generate and display X.509 certificates. On one hand, Keytool, developed by Sun, is a tool to manage keys and certificates; usually used as a database to store keys and their certificates which authenticate them. On the other hand, OpenSSL is a wider goal tool which provides a toolkit to work with secure communication protocols and cryptographic library. The reason to choose OpenSSL was that it was closer to what it would be the real world. The behavior of this tool is exactly what it was necessary: it receives the CSR and by means of the CA's key pair, it generates the certificate. After that, it finishes its work with certificate, CSR and keys. In contrast, with Keytool, certificate and keys are held in its database.

Generating the certificates with OpenSSL consists in moving the CSRs to the OpenSSL's folder, run by command line the commands shown at Listing H.4. When the command finishes, the certificate is ready. CA certificate used to do that is a self-signed certificate, because it was suitable for the developed prototype (free and quick to get). This is the task of the TR-Certificate Manager aforementioned above.

G.4.2. On-Card Certificates

They are stored as byte arrays because Java Card does not provide any other data structure to work with them. During the lifetime of the smart card, several certificates are sent to the card for different purposes. On one hand, SC certificates (to encryption and signature) are sent and stored on the card for the whole smart card's lifetime. Also, CA certificate. On the other hand, in every Contract-Policy Matching session two TTP certificates are sent to the card. These are not stored definitely, but temporary, during the necessary time to parse the certificate.

Difference is that while CA's and SC's certificates are stored as attributes because they will be used during the whole smart card lifetime, TTP's certificates are stored in a 'temporary' byte array (it is only one attribute because they are not sent at the same time, but sequentially). Temporary is between quotation marks because the variable where current TTP certificate is stored is a global, what means that it is alive during the whole smart card's lifetime. However, certificate is stored only while it is being verified for the parser; because the variable is cleaned (the whole components of the variable are put to zero) once parser has finished. Verification is over, that is why it is not necessary to save the certificate longer. Auxiliary byte array which stores TTP certificates while they are parsed is *currentCertificate*. Reason, to be global (i.e., attribute) instead of a local (temporary) variable inside the method which receives the certificate, is to save space on the JCVM stack. JCVM has a stack-oriented architecture. That means every applet has its own stack ([51]) which stores frames (i.e., pieces of each method called which stores environ, local variables, etc.). Every frame stores its parameter taking up space from the stack. If the certificate is stored as a local variable, this one has to be passed as a parameter to the methods which work with it. The usage of nested methods may get that the certificate was stored several times in the same stack wasting space and time what is not suitable for a constraint resources device. As bigger was the nesting level and the certificate size, bigger was the wasted. To avoid that, a global variable is created and every nested method calls it, saving the time of pass the certificate as a parameter (to copy and delete from the stack) and the space in the stack. Something similar is what concerns to *parserOffset* attribute which stores the current offset used to parse the current certificate.

G.4.2.1. Encoding for On-Card Certificates

Possible ideas for the format to store on-card certificates might be:

- As a certificate data structure sent from the off-card reader to the card
- As a string
- Base64 encoded (how the CA gives it back)
- DER encoded

First and second option are ruled out because of the lack of support in Java Card.

Base64 is not a good idea at all, mainly for two reasons. First one is that although the Base64 encoding were decoded, the certificate would not be usable yet, because it would follow DER encoded, that is why it would be better send it DER encoded directly. Let's think the steps to send certificate Base64 encoded: Two tiresome steps are added if certificate is sent Base64 encoded.

1. TTP DER encodes certificate contained in its data structure
2. TTP Base64 encodes
3. Certificate is sent
4. Certificate is Base64 decoded
5. Certificate is parsed while is DER decoded

The second important reason in order not to send the certificate Base64 encoded is that there is not any support in Java Card to work with it; that is why a new Base64 class to decode should be implemented to work on-card. In contrast, Java Card provides a class to work with BER-TLV (Tag, Length, Value). As it has been explained previously, BER is more generic than DER, and consequently, any tool to work with BER, it will do with DER.

To sum up, certificates are stored DER encoded (as byte array) because there is class which provides support to work with it and it allows to save time avoiding some steps. Classes to work with BER are BER-TLV and BERTag. For instance, BERTag provides a useful method to get the tag number from the tag structure byte, whilst BER-TLV provides another to verify whether the certificate is properly encoded.

G.4.3. Off-Card Certificates

This section includes certificates on TR and on TTP. Also it addresses TTP's private keys issue since they are stored in a similar way than certificates.

Certificates of TTP and TR are stored in files permanently. To retrieve certificates from their respective files, a Byte Array Input Stream is used. Thanks to the classes provided by Java to generate it, a new instance of a X.509 is created containing the certificate, which is Base64 encoded within the file. This file is stored in the device where TTP or TR is running with Privacy-enhanced Electronic Mail (PEM) extension. PEM is a format which can store private and public keys (both RSA and DSA) and X.509 certificates. It stores the certificate Base64 encoded after applying DER format and wrapped between two headers (BEGIN and END CERTIFICATE). All this encoding is suitable to transmit it among systems.

But all the previous information about how to work in Java with certificates does not fit with TTP private keys. TTP keys are created by means of OpenSSL and stored in their respective files: *TTPCertEnc*, *TTPCertEncPrivate*, *TTPCertSig* and *TTPCertSigPrivate*, all with PEM extension. While the public keys' files are certificates which contain them, private keys are Base64 encoded. But Java does not provide any class to work with Base64 encoding in its API (sun.* packages provide, but with the aforementioned problem). To solve that, by means of the last command of OpenSSL from Listing G.1; Base64 encoding is removed allowing to work only with DER encoding, which is comprehensive by a PKCS#8 class provided by Java API. Therefore, private keys are stored with DER extension.

Listing G.1 shows the commands necessaries to build a key pair which can be used by the system. At this example the key pair and public certificate for TTP to encrypt are created. The first command create the key pair, while the second command by means of the CA key pair gets a certificate signed by a CA. Finally, the last command makes the conversion from PEM to DER.

```
openssl req -newkey rsa:512 -subj "/OU=Cryptography/CN=TTPEncrypt"
-keyout TTPCertEncPrivate.pem -out TTPCertEncAux.pem

openssl x509 -CA CA_publicKey.pem -CAkey CA_privateKey.pem -req -in TTPCertEncAux
    .pem -days 3650 -sha1 -CAcreateserial -out TTPCertEnc.pem -extfile config.txt

openssl pkcs8 -topk8 -inform PEM -in TTPCertEncPrivate.pem -outform DER
-nocrypt -out TTPCertEncPrivate.der
```

Listing G.1: OpenSSL commands to create a key pair usable by the system

Certificates on TR Its use is simple because it is limited to verify CA and SC certificates before sending them to the card. TR only has to get the certificates from their respective files, creating a certificate data structure. By means of that structures, certificates can be verified easily and converted in a DER encoded byte array to send to the card.

Certificates on TTP In the same way that TTP certificates on-card, SC certificates are not stored permanently in TTP. They are only present while TTP verifies them and get their public keys. Once, it finishes with them, local variable which stores them disappears. Only SC public keys are stored during the rest of TTP's lifetime. The rest of the content of the certificate is ignored, after verified. It is worth mentioning that TTP gets from its certificates its public keys.

G.4.4. Parser On-Card

Parser on-card is the responsible for verifying the correctness of the certificates which are received. In order to carry out this verification, it has to check:

- Certificate is compliant with DER encoding
- Certificate is compliant with ASN.1
- Key algorithm is the expected

- Signature algorithm is the expected
- Key length is the expected
- Signature is valid

If this verification could not be done on-card, SC would not be able to trust in any TTP since it would not be sure about its identity. In other words, what parser allows is to make in a trusted way the initial key exchange. Card knows then whether the certificate is trustworthy.

It is worth mentioning that it was considered it is not necessary to parse SC's certificates when they are stored because they come from TR (which is trusted environment).

G.4.4.1. What to Parse On-Card

A common certificate comes with quite information about the owner of the public key and issuer CA. All this information which is useful in Web developments, it is not in smart cards because of the limitations of these devices to check information's truthfulness.

What parser needs from the certificate to check or store is:

- Signature algorithm: Both from *TBSCertificate* and *Certificate* (according to ASN.1 specification of X.509 certificate) structure. It has been checked that both algorithms match.
- Issuer
- Public Key Algorithm
- Public key
- Signature

```
Certificate:
Data:
    Version: 3 (0x2)
    Serial Number:
        94:1b:92:b0:e1:10:a9:9d
    Signature Algorithm: sha1WithRSAEncryption
    Issuer: C=DK, ST=Lingby, L=Lingby, O=DTU, OU=IMM.DTU, CN=Secbycontract,
        emailAddress=s091011@student.dtu.dk
    Validity
        Not Before: Jun  2 11:56:15 2010 GMT
        Not After : May 30 11:56:15 2020 GMT
    Subject: ST=Copenhagen, C=DK, O=SCIssuer, OU=Cryptography, CN=SCEncrypt
    Subject Public Key Info:
        Public Key Algorithm: rsaEncryption
        RSA Public Key: (512 bit)
            Modulus (512 bit):
                00:b4:05:c4:0e:[..]
            Exponent: 65537 (0x10001)
    X509v3 extensions:
        X509v3 Basic Constraints: critical
            CA:FALSE
Signature Algorithm: sha1WithRSAEncryption
    5f:89:b7:3e:aa:[..]
```

Listing G.2: Example of X.509 certificate contents (Certificate used by smart card to encrypt)

As it may be observed in Listing G.2 (one of the SC certificates), certificate provides some fields with information useless to the smart card for not being interesting or for the lack of tools to verify them. These fields are Version, Serial Number, Subject (unless the certificate was the CA certificate, case when the offset of this field is stored to be checked against the Issuer field from the rest of certificates) or the most of the extensions (if any, except CA extension).

About extensions, anyone of them is checked on-card. That is why only CA extension would be interesting: It assures that a certificate expected to be a CA certificate, it is really a CA certificate. It may be observed in Listing G.2 that in the extensions part shows up a field CA marked as false because certificate belongs to the SC. This verification is done in the initialization phase in the *InitializationClass*. It checks the certificate before sending it to the card. A function gets the value of *BasicConstraints* extension which stores whether certificate's subject is a CA or not. As [48] indicates, only returns minus one when the latter option.

At this point, it is worth mentioning that two important issues related to certificates were left aside: Validity and Revocation. [37] deals with both of them proposing some solutions, but it has not them into account in its prototype. A solution is proposed in the future work section, but they are ignored during the implementation.

G.4.4.2. Parser's Implementation Details

This section will focus on providing some details of the parser's implementation. Verification process of a certificate, which the parser carries out, can be separated in two parts: the actual parser of the certificate and the verification of the signature. First one checks whether the format and the encoding of the certificate is correct and gets the data elements to be verified. The second one, when the first part has finished and has given back the signature, checks its correctness.

Parser takes some ideas from [37], but adapts them to its needs. The certificate is scanned once, but it is not necessary to save the offset of the fields because their contents will be got during the parser process and the only one which is necessary to store is the public key, but it is stored directly instead of saving its offset and be stored later. Therefore, in contrast to the parser implemented in [37], the content's offsets are not stored, because they will be checked only once.

The only exception is CA certificate which is stored permanently on-card. In order to verify that TTP's certificate has been issued by CA, issuer field has to be checked against CA's name field. Thereby, the offset of this field from CA's certificate is stored in a global variable. In such a way, it is easy and fast to take the CA's name to make the comparison.

Every certificate BER format is verified by means of a method provided by *BERTLV* Java Card class. It is checked that every expected field is present. As it has been described previously, only a few fields' contents are really parsed. Issuer field has already detailed. The public key (not from CA) is got according to the expected BER encoding and stored in its corresponding variable: *TTPPublicKeyRSAEnc* or *TTPPublicKeyRSASig*. It is worth mentioning that when the key is retrieved, its length may vary. The reason is that to avoid modulus and exponent from being understood as negative because of its first byte, a zero is added before. Java Card classes does not work in the same way, thus it is necessary to remove the first component in that cases or the system will fail on-card.

The fields which are left out are signature and public key algorithm, both are *algorithm identifiers* according to ASN.1 specification. Both contains wrapped in a *SEQUENCE* statement an Object Identifier (OID) which identifies theirs respective methods. How to DER encode an OID is explained in a revision of the document [21]. But to make it easier, it was implemented several lines of Java code (at Listing G.3) by means of which the OID is DER encoded. That encoding was wrapped in a byte array which is only compared against the OID got from the certificate, both to check signature and public key algorithms.

```
Oid aoid = null;
aoid = new Oid("1.2.840.113549.1.1.5");
byte[] oid = null;
oid = aoid.getDER();
System.out.println(byteArrayToHexString(oid));
```

Listing G.3: Code to OID generation (sha1WithRSAEncryption example)

The verification of the signature can be made in two ways. After decrypting with the public key of the corresponding CA, an EM is got. Either hash code is retrieved from that *Digest Info* structure and compared against the hash code built or a *Digest Info* structure is built through the hash code of the *TBSCertificate* part (ASN.1 specification) of the certificate and compared against to the *Digest Info* structure got decrypting the signature. The latter was chosen for the current implementation. While parser is scanning the certificate gets the offset and length of *TBSCertificate* part and make a hash code which is stored in order to be used to build the *Digest Info* structure. That one is checked against to the decrypted one.

The problem is coming when the signature has to be decrypted, like it happened with CSRs and certificates generation. To decrypt the signature is necessary to make use of an RSA algorithm implementation with no padding which is not available on the simulators used. It can be observed at Appendix K, which corresponds to the real implementation source code where this algorithm is available, that it is enough with decrypting and following the aforementioned process to compare *Digest Info* structures. Since the algorithm is not available, it is necessary to modify the system design again for the prototype.

There are three methods which have to parse distinct certificates:

- Method which receives TTP certificate to encrypt
- Method which receives TTP certificate to sign
- Method which receives CA certificate

Owing to the previous limitation, this methods were split in two methods each one. Thereby, for instance in the source code of the prototype, there are the methods: *processStoreCACertificate* and *processStoreCACertificate2*. The structure of these two methods for the rest of certificates (TTP certificates) is the same. The first method receives the certificate, parses it, gets the public key (if TTP certificate) and gets the signature encrypted. It gives that signature back to the off-card side which decrypts the signature by means of the CA's public key and an RSA algorithm implementation with no padding. Once decrypted, it sends the *Digest Info* structure to the card, being processed by the second method. It checks if the *Digest Info* received matches with the built. If it was not a CA certificate, the card replies with its corresponding certificate. The whole process is shown at Figure G.2. The result is that is necessary to send one APDU command and response more which make the system more complex. The source code which contains this implementation for the prototype can be observed at Appendix J.

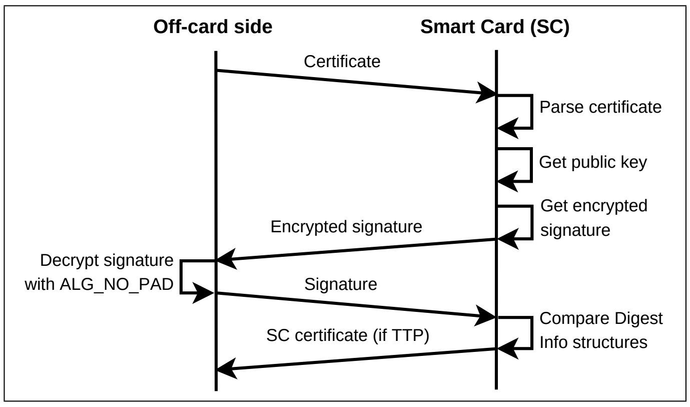


Figura G.2: Signature verification process on the prototype

G.5. Cryptographic Functions

This section is related to the implementation of the cryptographic functions in the second part of the Contract-Policy Matching process, after the exchange of certificates. It can be distinguished between the part of the Symmetric Block and the RSA Ciphering, although it is by means of both when the encryption system makes sense.

Symmetric block cipher chosen was AES instead of DES (both are the provided by the simulator). The reason to use the first one is that it was proved DES is not suitable to transmission of sensitive information. It is vulnerable to differential and linear cryptanalysis because of the usage of weak substitution tables; and its length is too short taking into account the bits used for odd parity [8]. In contrast, AES shortest key length is more than twice the DES'; and AES has been built with the aim of being strong against differential, truncated differential, linear, interpolation and square attacks.

Length used for the AES key is 128 bits because it is the only length provided by the simulator. Since it is a block cipher, it works with blocks of a fixed number of bytes in size, 16 for the length used. That means the length of the input has to be 16 multiple; hence a padding is needed when the length is not. Padding bits are randomly added. In order to recover the encrypted message properly, the length is also added at the beginning.

This block cipher has several modes to work which depends on the implementation chosen to encrypt. The most common are Electronic Codebook (ECB) and Cipher Block Chaining (CBC). The latter is the suitable because it avoids cipher from leaking information about the structure of the plaintext [31]. In contrast to ECB which does not operate among different blocks of the encryption, CBC makes a *XOR* of the data with the encrypted bytes of the previous block, avoiding any information leak. Fortunately, this mode was supported by the simulator and it could be possible to make use of it. The problem is that this mode needs an Initialization Vector (IV) which has to be used in both sides of the communication in order to be able to complete the encryption and decryption process properly. Several approaches can be set out:

- Create at the beginning of every session a new IV
- Use every time the same IV
- Use NONCE as IV

The first approach implies higher traffic, slowness and complexity. Second one is easy to implement and faster, but insecure (it is used the same IV in every communication of the card's lifetime). Finally, NONCE fits perfectly to the needs of the IV. It is random and created newly every session. In addition, it is already necessary to send it; thereby, it is not suppose to increase neither complexity nor traffic. That is why the first part (16 bytes, i.e., AES block size) of the NONCE is used as IV.

On the other hand, RSA encryption has been carried out by means a key length of 512 bits, because again, it is the only key length supported by the simulator. At Contract-Policy Matching process, in contrast to the certificates' issue, it does not matter which algorithm to use, if it is the same in both sides. That is why, the implementation provided by the simulator was useful at this time: it was used a RSA cipher which pads input data according to the PKCS#1 (v1.5) scheme.

A significant security issue is the use of Pseudo-Random Number Generator (PRNG) algorithm in the prototype. This is done again for a limitation of the simulator which only provides this implementation. However, the use of PRNG is a serious security threat. Therefore Secure Random Number Generator (SRNG) should be used. As a matter of fact SRNG has been specifically designed for being used in cryptographic requirements as [49] specifies. The problem with PRNG is the predictability of the linear congruential algorithms used which follow a deterministic sequence according to the values of its parameters. An attacker which could get a small part of the sequence will be able to determine the parameters of the algorithm, and consequently the subsequent numbers [46].

As a final comment for this section, it is worth mentioning that for a real implementation it is highly recommended to increase the length of the keys, both AES and RSA (strongly the latter), used for the prototype's implementation. They are too short (128 bits for AES and 512 for RSA) because of the simulator's limitations. For AES it is not a really significant problem since it is not too small and because it is used only once and the time to break it is much bigger than the time while it is used. Nevertheless it is relevant to RSA whose keys are expected to be used for a long time and its length is very short. Therefore it is strongly suggested to increase the length up to 2048 bits for a real implementation. Further details for changes for real implementation at Appendix J.

G.6. Some Other Implementation Details

At this section, some important implementation details which do not fit in the previous sections are described.

There is some possible attack which can be carried out when an error occurs. For instance, the parser reads the TTP's certificate only once checking and getting the fields which needs, avoiding storing the offset to be accessed later. That is why it stores TTP's public key when it arrives to the corresponding field. If the signature is not valid afterwards, an error appears but the public key has been already stored; hence, an attacker may make use of that. To avoid this and similar situations, clean method is called every time an exception is launched on-card. This method clears or initializes to zero the content of several attributes contained in EEPROM, making them useless after the cleaning operation. It is also called after the end of any phase.

One of the Java Card 2.2.2 features is that there is no automatic garbage collector, but over demand. That means if it is not called every instance created within a method is permanently stored on-card, even a new called to the same method will create a new instance which will be stored on-card. The consequence is logic: after an undetermined number of uses of the applet on-card, the card will be without memory resources. That is why Java Card manuals advise to reuse variables and use global attributes, instead of creating new instances in the methods. Therefore, garbage collector is called every time a request arrives to the card in order to avoid it getting without memory resources. The code is shown at Listing G.4.

```
if(JCSystem.isObjectDeletionSupported())
    JCSystem.requestObjectDeletion();
```

Listing G.4: Code to Garbage collector over demand

The issue of the instances created within methods different to constructor led a problem. If an instance for one algorithm (a cipher for RSA algorithm instance for example) is created out of the constructor, the second time that the method is called and consequently the instance created again, en error occurs and execution is stopped. That is the reason why all this algorithms have to be instanced within the constructor. That the case of *Cipher*, *Message Digest* and *Random Data* classes.

Apéndice H

Case Study

Throughout this section it will be detailed a Case Study whose aim is to present the usage of the prototype developed together the needed tools to run it. Last part of the section assesses the performance of the application in terms of memory.

In order to work with the card saving its state CREF is used, whilst the clients run in Eclipse. That is why it is necessary both tools were installed to be able to work with them properly. [11] provides an excellent guide to install and get them work properly. For the goal of the section, this part is considered as a previous step which is not be longer detailed with the exception of the next paragraph.

It is worth mentioning that depending on the Java version in which it was working, a problem might appear at the moment when the applet is trying to be deployed on the file which stores an image of the EEPROM. This error could say something similar to: ünsupported class file format of version 50.0". It is related to the existence of some conflicts between the format which is expected for a JC 2.2.2 file and the file which the current JDK creates (notice that it is the JDK which simulates the JCVM, and consequently, the JC 2.2.2 file is generated by it). To solve that is necessary to change the compliance level of the JDK compiler. In Eclipse's tool bar→Window→Preferences: Java→Compiler: JDK compliance: Compiler compliance Level from 1.6 to 1.4. Immediately after selecting 1.4; it appears in the bottom the following message: "When selecting 1.4 compliance, make sure to have a compatible Java Runtime Environment (JRE) installed and activated (currently 1.6). Configure...". If Configure is clicked, it carries user out to Installed JREs where clicking to Execution Environments, it is possible to choose the compatible JREs for the Execution Environments which will be used. Select jre6 in every case.

On one hand, let's define *ApplicationContract* as the contract which will be compared against the card's policy. It will be stored on a file within *ApplicationIssuer* folder with the name: Çontract". This contract specifies the behavior of the application which is wished to be installed on the card. On the other hand, the card's policy which contains the security policy of the card, is stored in a file called "Policyïn the *TrustedReader* folder. Let's call it *CardPolicy*. CA certificate is stored both in *TrustedReader* and *TrustedThirdParty* folder. *TrustedThirdParty* also stores its certificates and private keys to encrypt and sign.

Let's call the developed application (which runs Contract-Policy Matching) *VerifyPolicyAndClaimApplet*. First of all, application has to be installed and initialized on the card. To do that it is necessary to create a file which stores the EEPROM of the card in order to be able to save its status. This is done by means of a script called *NewCard.bat* which can be found within *SmartCard* folder. The script's content is shown at Listing H.1. First two lines create the card and install the applet. Last one calls other script (*OldCard.bat*) which is the responsible for running something on the card saving the status afterwards. At this moment it is used to initialize the card (creation and storage of certificates and policy). The content of this script is detailed at Listing H.2. As it is shown at the scripts, CREF is used as the simulator in order to be able to save the status. To run the scripts is necessary to open a command line and to go up to the folder which contains the script (*SmartCard*→*bin*).

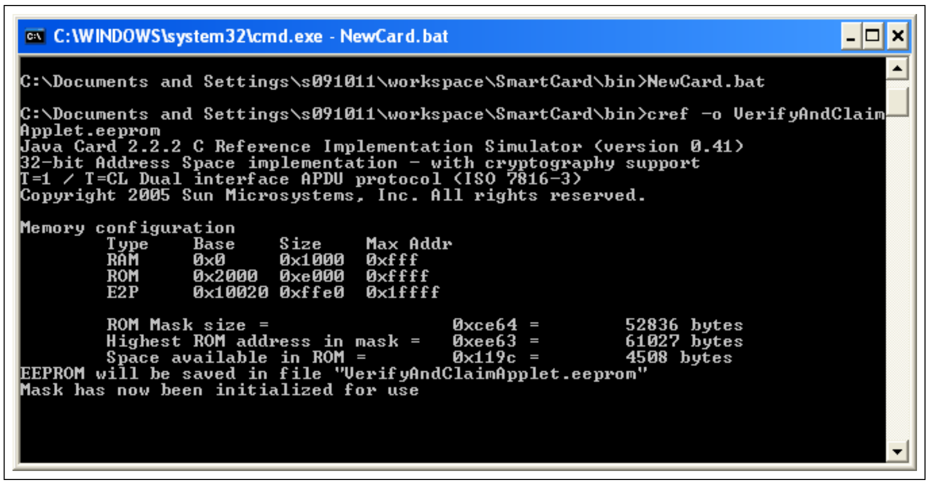
```
cref -o VerifyAndClaimApplet.eeprom
cref -i VerifyAndClaimApplet.eeprom -o VerifyAndClaimApplet.eeprom
OldCard.bat
```

Listing H.1: Script to create, install and initialize a new card

```
cref -i VerifyAndClaimApplet.eeprom -o VerifyAndClaimApplet.eeprom
```

Listing H.2: Script to load the status of an already existent card

When *NewCard.bat* script is called, it keeps waiting for the sending of APDUs which ordered the installation of the applet on the card, as it can be observed at Figure H.1. Then, card issuer should right click over the package security on the application in Eclipse, go to Java Card Tools and select Deploy as it shown at Figure H.2.



```
C:\WINDOWS\system32\cmd.exe - NewCard.bat

C:\Documents and Settings\s091011\workspace\SmartCard\bin>NewCard.bat

C:\Documents and Settings\s091011\workspace\SmartCard\bin>cref -o VerifyAndClaim
Applet.eeprom
Java Card 2.2.2 C Reference Implementation Simulator (version 0.41)
32-bit Address Space implementation - with cryptography support
T=1 / T=CL Dual interface APDU protocol (ISO 7816-3)
Copyright 2005 Sun Microsystems, Inc. All rights reserved.

Memory configuration
        Type    Base    Size    Max Addr
        RAM     0x0     0x1000  0xfff
        ROM     0x2000  0xe000  0xffff
        E2P     0x10020 0xffe0  0x1ffff

        ROM Mask size =                 0xce64 =        52836 bytes
        Highest ROM address in mask =   0xee63 =        61027 bytes
        Space available in ROM =        0x119c =        4508 bytes
EEPROM will be saved in file "VerifyAndClaimApplet.eeprom"
Mask has now been initialized for use
```

Figura H.1: New Card script running

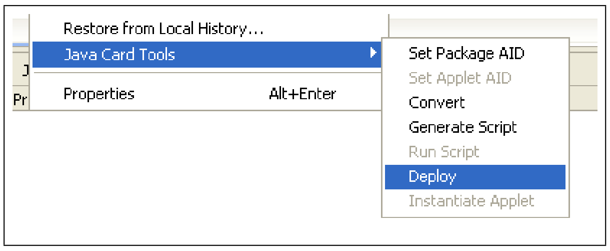
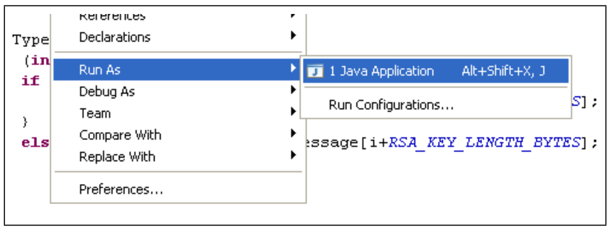


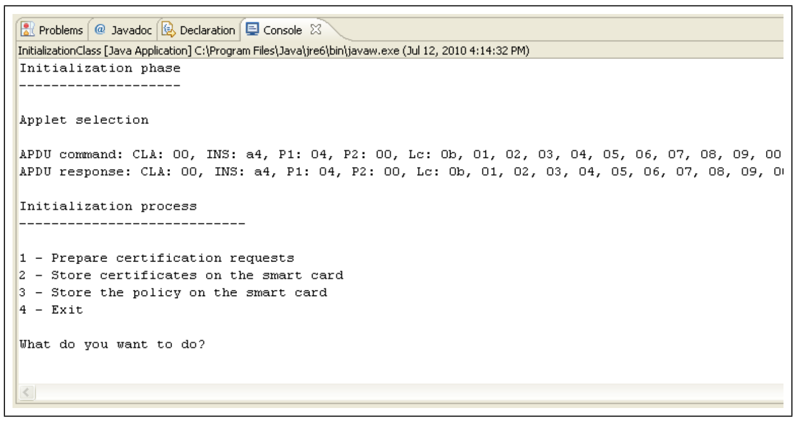
Figura H.2: Deploying applet

After that, the command line has changed, but still will be waiting more APDUs. Similarly to the previous order to deploy the applet, Card Issuer should right click on *create-VerifyPolicyAndClaimApplet* script, Java Card Tools and choose Run Script, which will install the applet on the card making the application ready for its use. But it is still left out the initialization, and if it is observed again the command line it is waiting for more APDUs yet because of the last line of the script has been executed. *InitializationClass* should be called now. To do that, card issuer should go to *TrustedReader* project in Eclipse, open *InitializationClass* source code and over it, right click, Run as, Java Application as it is shown at Figure H.3. The menu of the Figure H.4 should appear.



```
Type
 (in
 if
 }
 els                                    ssage[i+RSA_KEY_LENGTH_BYTES];
```

Figura H.3: Running Initialization Phase from Eclipse



```
InitializationClass [Java Application] C:\Program Files\Java\jre6\bin\javaw.exe (Jul 12, 2010 4:14:32 PM)
Initialization phase
--------------------

Applet selection

APDU command: CLA: 00, INS: a4, P1: 04, P2: 00, Lc: 0b, 01, 02, 03, 04, 05, 06, 07, 08, 09, 00
APDU response: CLA: 00, INS: a4, P1: 04, P2: 00, Lc: 0b, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0

Initialization process
----------------------------

1 - Prepare certification requests
2 - Store certificates on the smart card
3 - Store the policy on the smart card
4 - Exit

What do you want to do?
```

Figura H.4: Initialization Phase Menu on Eclipse

First, it should be chosen option 1. It creates two CSRs for the keys on the card: one to encrypt and the other to sign. Both files are stored within *TrustedReader* folder with the names: *EncCertReq.pem* and *SigCertReq.pem*. These CSRs have to be sent to the CA to get the certificates. Since OpenSSL does that, it is necessary that files which contain the CSRs were dragged to *bin* folder within OpenSSL folder. Previously, a CA should have been created and stored there. To do that, use Listing H.3 establishing a password. A private key and a self-signed certificate will be created.

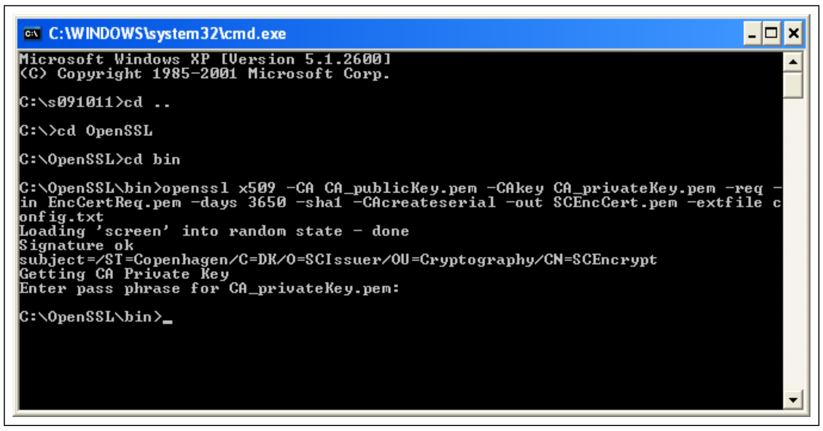
```
openssl req -x509 -newkey rsa:512 -keyout CA_privateKey.pem -out CA_public.pem -
    days 3650
```

Listing H.3: Command to create a CA certificate and private key

Once CSRs are located at bin folder, open a new command line, go to this folder and run the commands of the Listing H.4 in order to get the certificates. It will be necessary to write the password inserted previously during the CA generation. At Figure H.5 can be observed the certificate generation by command line.

```
openssl x509 -CA CA_publicKey.pem -CAkey CA_privateKey.pem -req -in EncCertReq.
    pem -days 3650 -sha1 -CAcreateserial -out SCEncCert.pem -extfile config.txt
openssl x509 -CA CA_publicKey.pem -CAkey CA_privateKey.pem -req -in SigCertReq.
    pem -days 3650 -sha1 -CAcreateserial -out SCSigCert.pem -extfile config.txt
```

Listing H.4: Commands to get certificates from CSRs



```
Microsoft Windows XP [Version 5.1.2600]
(C) Copyright 1985-2001 Microsoft Corp.

C:\s091011>cd ..

C:\>cd OpenSSL

C:\OpenSSL>cd bin

C:\OpenSSL\bin>openssl x509 -CA CA_publicKey.pem -CAkey CA_privateKey.pem -req -
in EncCertReq.pem -days 3650 -sha1 -CAcreateserial -out SCEncCert.pem -extfile c
onfig.txt
Loading 'screen' into random state - done
Signature ok
subject=/ST=Copenhagen/C=DK/O=SCIssuer/OU=Cryptography/CN=SCEncrypt
Getting CA Private Key
Enter pass phrase for CA_privateKey.pem:

C:\OpenSSL\bin>_
```

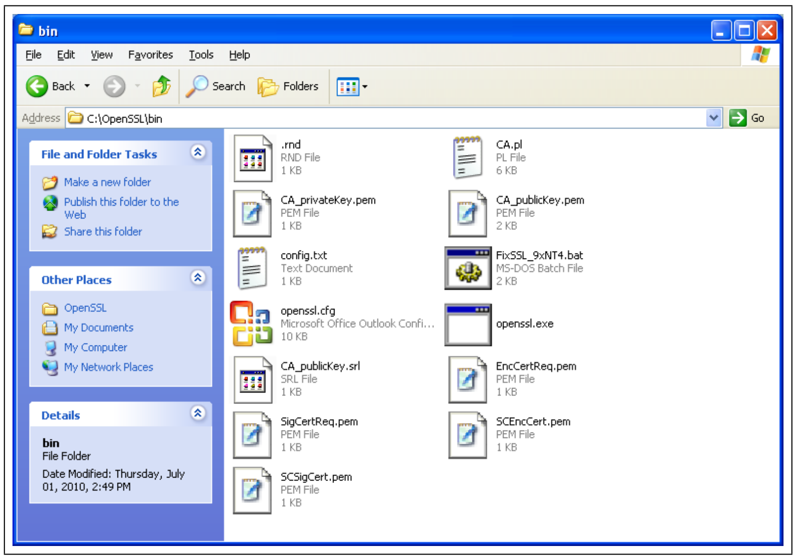
Figura H.5: Certificate generation with OpenSSL

As a result of the previous generation, two certificates should have been created in the folder: *SCEncCert.pem* and *SCSigCert.pem*. The content of the folder is expected to be similar to the shown at Figure H.6. To sum up, it should contain at least both CSRs and certificates, CA certificate and its private key. When both certificates have been generated, card issuer must to drag them to *TrustedReader* folder, and then, option 2 of the Initialization Phase menu can be launched. It will store CA and SC certificates on the card. A screenshot of its storage can be observed at Figure H.7. At this moment both CSRs and certificates should be removed from OpenSSL and *TrustedReader* respective folders.

Finally, Card Issuer must store *CardPolicy* choosing option 3. Once everything aforementioned has been done, what supposes CA and SC certificates and Policy have been stored, Card Issuer can finish with the initialization phase choosing option 4. Notice that the *TrustedReader* can be called only once in the sense that, since the moment when certificates and policy are stored on the card, they cannot be stored again. Certificate's renewal will be discuss in the future work section.

At the end of the initialization phase, the card can be used as many times as required to check the compliance of any change of the applications on the card. To do that, before running the Contract-Policy Matching algorithm, it is necessary to load *ApplicationContract*. That is carried out by Application Issuer who is the responsible for sending the contract to the card. Hence, *ContractDelivery* class has to be run on Eclipse before *TerminalClass*. Otherwise, the error shown at Figure H.8 appears. This error also appears if some of the elements expected to be on-card when the algorithm is run (like certificates) are not already stored. Every error which can be captured on-card, it is shown with the same error modal window than the previous one.

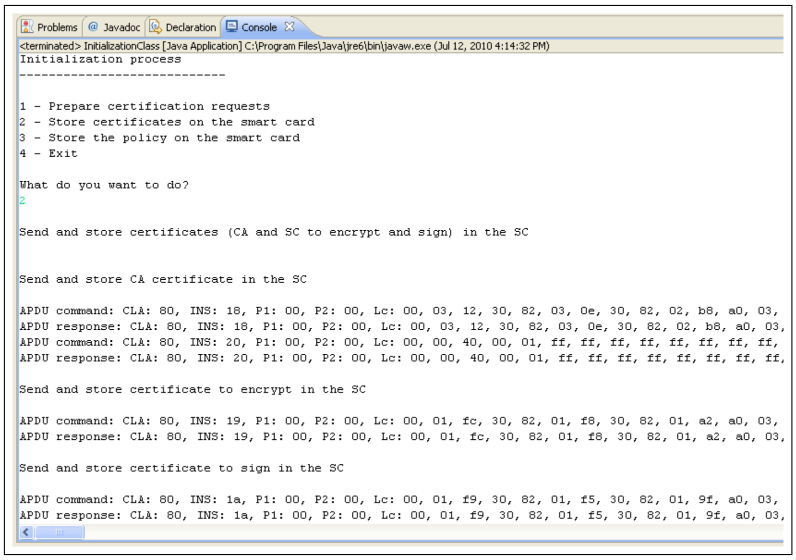
To run *ContractDelivery* class, it has to be run *OldCard.bat* script. After that, right clicking over



bin
File Folder
Date Modified: Thursday, July 01, 2010, 2:49 PM

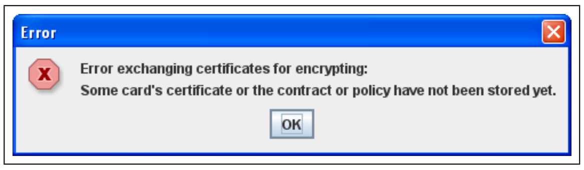
```
.rnd                RND File                            1 KB
CA.pl               PL File                             6 KB
CA_privateKey.pem   PEM File                            1 KB
CA_publicKey.pem    PEM File                            2 KB
config.txt          Text Document                       1 KB
FixSSL_9xNT4.bat    MS-DOS Batch File                   2 KB
openssl.cfg         Microsoft Office Outlook Confi...   10 KB
openssl.exe
CA_publicKey.srl    SRL File                            1 KB
EncCertReq.pem      PEM File                            1 KB
SigCertReq.pem      PEM File                            1 KB
SCEncCert.pem       PEM File                            1 KB
SCSigCert.pem       PEM File                            1 KB
```

Figura H.6: OpenSSL\bin folder after certificates generation



```
<terminated> InitializationClass [Java Application] C:\Program Files\Java\jre6\bin\javaw.exe (Jul 12, 2010 4:14:32 PM)
Initialization process
----------------------------


1 - Prepare certification requests
2 - Store certificates on the smart card
3 - Store the policy on the smart card
4 - Exit

What do you want to do?
2

Send and store certificates (CA and SC to encrypt and sign) in the SC


Send and store CA certificate in the SC

APDU command: CLA: 80, INS: 18, P1: 00, P2: 00, Lc: 00, 03, 12, 30, 82, 03, 0e, 30, 82, 02, b8, a0, 03,
APDU response: CLA: 80, INS: 18, P1: 00, P2: 00, Lc: 00, 03, 12, 30, 82, 03, 0e, 30, 82, 02, b8, a0, 03,
APDU command: CLA: 80, INS: 20, P1: 00, P2: 00, Lc: 00, 00, 40, 00, 01, ff, ff, ff, ff, ff, ff, ff, ff,
APDU response: CLA: 80, INS: 20, P1: 00, P2: 00, Lc: 00, 00, 40, 00, 01, ff, ff, ff, ff, ff, ff, ff, ff,

Send and store certificate to encrypt in the SC

APDU command: CLA: 80, INS: 19, P1: 00, P2: 00, Lc: 00, 01, fc, 30, 82, 01, f8, 30, 82, 01, a2, a0, 03,
APDU response: CLA: 80, INS: 19, P1: 00, P2: 00, Lc: 00, 01, fc, 30, 82, 01, f8, 30, 82, 01, a2, a0, 03,

Send and store certificate to sign in the SC

APDU command: CLA: 80, INS: 1a, P1: 00, P2: 00, Lc: 00, 01, f9, 30, 82, 01, f5, 30, 82, 01, 9f, a0, 03,
APDU response: CLA: 80, INS: 1a, P1: 00, P2: 00, Lc: 00, 01, f9, 30, 82, 01, f5, 30, 82, 01, 9f, a0, 03,
```

Figura H.7: Certificates storage on-card

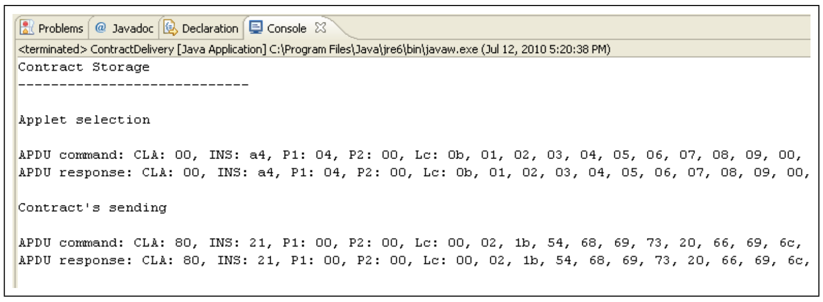


Error exchanging certificates for encrypting:
Some card's certificate or the contract or policy have not been stored yet.

Figura H.8: Message when *ApplicationContract* has not been stored

the corresponding class and choosing Run as, Java Application, like to run the *TrustedReader*, *ApplicationContract* is stored on the card. The APDUs involved at this process can be observed at

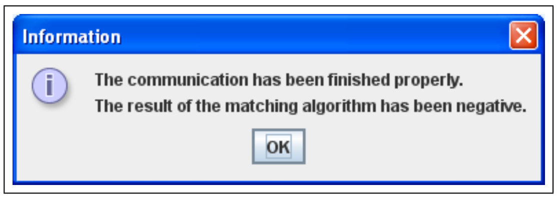
Figure H.9.



```
<terminated> ContractDelivery [Java Application] C:\Program Files\Java\jre6\bin\javaw.exe (Jul 12, 2010 5:20:38 PM)
Contract Storage
----------------------------

Applet selection

APDU command: CLA: 00, INS: a4, P1: 04, P2: 00, Lc: 0b, 01, 02, 03, 04, 05, 06, 07, 08, 09, 00,
APDU response: CLA: 00, INS: a4, P1: 04, P2: 00, Lc: 0b, 01, 02, 03, 04, 05, 06, 07, 08, 09, 00,

Contract's sending

APDU command: CLA: 80, INS: 21, P1: 00, P2: 00, Lc: 00, 02, 1b, 54, 68, 69, 73, 20, 66, 69, 6c,
APDU response: CLA: 80, INS: 21, P1: 00, P2: 00, Lc: 00, 02, 1b, 54, 68, 69, 73, 20, 66, 69, 6c,
```

Figura H.9: Contract storage process

The last part is the Contract-Policy Matching. In order to avoid a message like the shown at Figure H.8; certificates, contract and policy have to be already stored on the card. Notice that when a matching algorithm finishes, contract is removed; hence, any contract has to be stored again before running the algorithm again. Like the other clients, to run *TrustedThirdParty*, it is necessary to run the *OldCard.bat* script and from Eclipse, right click on the source code, Run as, Java Application. The communication will start and at the end a modal info window communicate which has been the result of the algorithm, as it can be seen at Figure H.10.



The communication has been finished properly.
The result of the matching algorithm has been negative.

Figura H.10: Message with the matching result

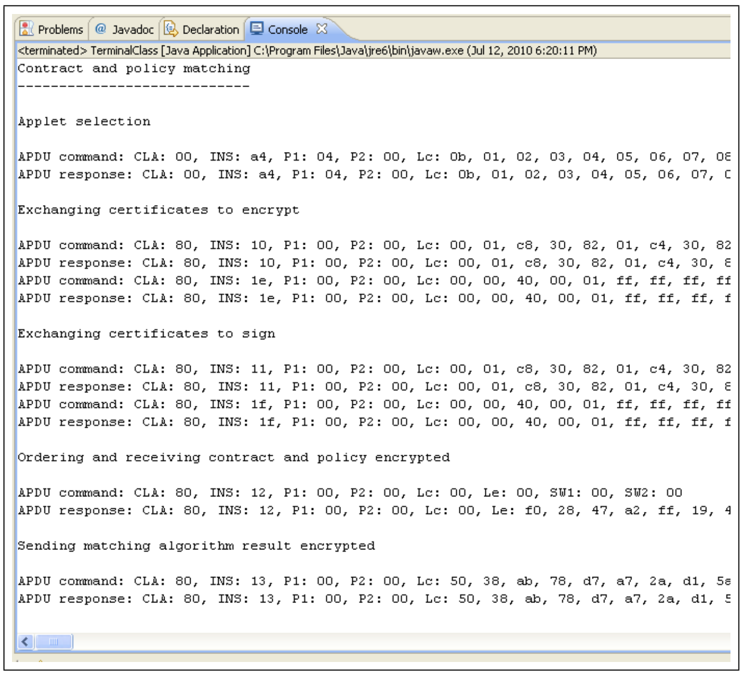
Together the window with the result, the APDUs which have been sent during the communication between TTP and SC can be observed. They are shown separated according to the parts of the communication, as Figure H.11 illustrates.

H.1. Memory Analysis

Smart Cards are devices with constraint resources particularly in terms of memory. There lies the importance of this analysis, because if the theoretical idea needed to take advantage of more than the half of the available memory, it would not be the suitable solution.

The analysis has been done by means of the data provided by a command line option of CREF. This option prints resource consumption statistics of memory usage at the startup and the shutdown of the card, giving an idea of the needed resources for installing and executing the applet as it is explained at Chapter 10 of [2]. Every time that CREF is launched with this option the statics related to the following resources appear (once at startup and once at shutdown):

- EEPROM



```
<terminated> TerminalClass [Java Application] C:\Program Files\Java\jre6\bin\javaw.exe (Jul 12, 2010 6:20:11 PM)
Contract and policy matching
----------------------------

Applet selection

APDU command: CLA: 00, INS: a4, P1: 04, P2: 00, Lc: 0b, 01, 02, 03, 04, 05, 06, 07, 0
APDU response: CLA: 00, INS: a4, P1: 04, P2: 00, Lc: 0b, 01, 02, 03, 04, 05, 06, 07,

Exchanging certificates to encrypt

APDU command: CLA: 80, INS: 10, P1: 00, P2: 00, Lc: 00, 01, c8, 30, 82, 01, c4, 30, 82
APDU response: CLA: 80, INS: 10, P1: 00, P2: 00, Lc: 00, 01, c8, 30, 82, 01, c4, 30,
APDU command: CLA: 80, INS: 1e, P1: 00, P2: 00, Lc: 00, 00, 40, 00, 01, ff, ff, ff, ff
APDU response: CLA: 80, INS: 1e, P1: 00, P2: 00, Lc: 00, 00, 40, 00, 01, ff, ff, ff, f

Exchanging certificates to sign

APDU command: CLA: 80, INS: 11, P1: 00, P2: 00, Lc: 00, 01, c8, 30, 82, 01, c4, 30, 82
APDU response: CLA: 80, INS: 11, P1: 00, P2: 00, Lc: 00, 01, c8, 30, 82, 01, c4, 30,
APDU command: CLA: 80, INS: 1f, P1: 00, P2: 00, Lc: 00, 00, 40, 00, 01, ff, ff, ff, ff
APDU response: CLA: 80, INS: 1f, P1: 00, P2: 00, Lc: 00, 00, 40, 00, 01, ff, ff, ff, f

Ordering and receiving contract and policy encrypted

APDU command: CLA: 80, INS: 12, P1: 00, P2: 00, Lc: 00, Le: 00, SW1: 00, SW2: 00
APDU response: CLA: 80, INS: 12, P1: 00, P2: 00, Lc: 00, Le: f0, 28, 47, a2, ff, 19, 4

Sending matching algorithm result encrypted

APDU command: CLA: 80, INS: 13, P1: 00, P2: 00, Lc: 50, 38, ab, 78, d7, a7, 2a, d1, 5
APDU response: CLA: 80, INS: 13, P1: 00, P2: 00, Lc: 50, 38, ab, 78, d7, a7, 2a, d1,
```

Figura H.11: Contract storage process

- Transaction buffer
- Stack usage
- Clear-on-reset RAM
- Clear-on-deselect RAM

Also some statics about the ROM are shown at the beginning of the statics. At Appendix D, screenshots corresponding to the memory statics of each stage of the applet lifetime can be observed. To sum up, the results of these statics are shown at Table H.1. There only results related to EEPROM are included. The reason why only these statics are shown is because are the most interesting for a smart card developer. On one hand, ROM is the memory which stores binary codes of the OS and the JCVM among others. This memory is created and initialized by the smart card manufacturer and it is not able to be modified later. That is why it is lacking in interest for a developer who cannot alter it. On the other hand, RAM is the memory which stores the whole application which is running at every moment and its data. This is very important due to if an applet needs for its running more memory than RAM provides and uses it up, an error appear because of RAM memory resources of the card are exhausted. However, that is a problem which every developer has to keep in mind when it is working on smart cards; but it is not interesting from the point of view of the project. That is because the RAM is always the same and the developer should know with which size it can work and to adapt its development to that. Also RAM is cleared at every shutdown and cleaned by the garbage collector over demand; hence, it changes every card-tearing. That is why the statics are referred to EEPROM memory which stores the applications and data which are dynamically loaded to the card; load which is tried to be properly managed by the S×C framework. The key point of checking the memory statics is to know whether it is worth adding the system developed to the card or in change, it takes too many memory resources reducing excessively the space on-card and making multi-application framework useless. A structure of the non-volatile memory can be observed at Figure H.12 from [38], which shows the common content of the ROM at the bottom (OS, JCVM, etc.) and of the EEPROM (the applets) at the top.

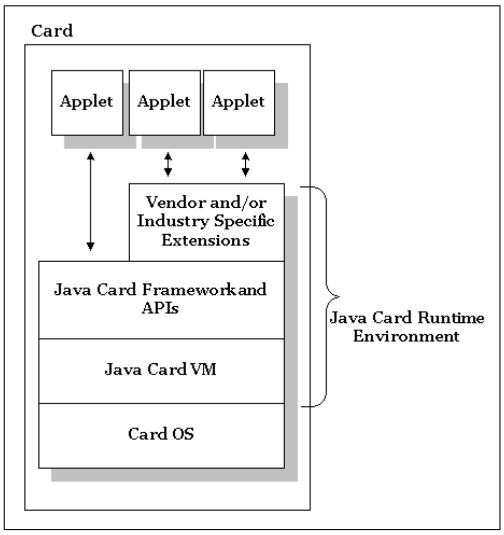

Card
Applet
Applet
Applet
Vendor and/or Industry Specific Extensions
Java Card Framework and APIs
Java Card VM
Card OS
Java Card Runtime Environment

Figura H.12: EEPROM and ROM content

The statics of the Table H.1 are shown in bytes. They have been taken from the prototype developed by means of CREF. This simulator provides an EEPROM memory with a size of 64 KB (i.e., 65536 bytes). The common size for Java Card 2.2.2 real implementations ranges between 32 (old and constrained) and 128 KB, although it is starting to use greater.
The stages chosen to appear on the table are compliant with the highlights in the applet lifetime. They cause the main changes over the EEPROM. These stages are the following:

- Deployment: It consists in download the applet to the card; store the bytecode there
- Installation: It is done calling the applet's static install method which install the applet on the card invoking somewhere register method
- Initialization: This stage corresponds with the Initialization Phase detailed in previous sections
- Running: That is the Contract-Policy Matching Phase

The last static (Running) is taken after several runnings in order to see the statics when the memory is established. About the tags used for the columns they are referred to the moment previous and next to the stage was run. For example, Çonsumed beforerefers to the bytes which were used from the EEPROM before the corresponding stage started.

As it can be seen at the table, the card reserves almost 7 KB for itself before storing something what seems to be some space for the OS or some card's needs. Downloading the applet to the card takes almost 6 KB, whilst its installation more than 1 KB. It is worth mentioning that during the installation is when the most of necessary data create their instance, reserving space on the card. That is what happened with keys and algorithms, for instance. The initialization decreases the available memory in 3 KB. At this stage certificates (both SC and CA) and Policy have been

Stage	**Figure**	**Consumed before**	**Consumed after**	**Available before**	**Available after**
Deployment	L.1	6994	12837	58510	52667
Installation	L.2	12837	14322	52667	51182
Initialization	L.3	14322	17919	51182	47585
Running	L.4	18298	18135	47206	47369

Tabla H.1: Memory Analysis statics in bytes

stored. As an example of initial Policy for the card, a file of 518 bytes was used. Obviously, this value will change according to security needs of the card, installed applications, etc. Finally, the EEPROM's consumption of the matching algorithm only makes memory vary a few hundred bytes. To sum up, the system developed needs a rough memory space in the EEPROM of 11 KB.

Previous result has to be taken as an upper-limit for the necessary space on the memory of the developed system since an optimal implementation was not a goal during its implementation. That is why the result of the analysis is positive. There are also several points to take in account.

- If the statics are looked through, what takes more bytes is the applet's download because of the extensive source code. That is because the applet has to deal with several cryptographic problems, even including a parser on-card. The common applets are not as large as it what means that a high number of applets are still possible to be stored. For instance, let's suppose that every application takes between 4 and 5 KB of memory space as average; still more than eleven applets could be stored on-card. If the size is smaller (commonly) the approach is better since much more applets could be stored.
- The heaviest issue is the bytecode download. Notice that the analysis has been done over the prototype which contains some methods necessaries because of the limitations of the simulator, but which there were not in a real implementation. Therefore this performance is expected to be better there.
- It should keep in mind than the smart card like the rest of the current hardware is continually evolving what carries out to think that the available memory will be greater in short time, whilst the necessary space for the system developed will be the same.
- As it is pointed out in Future work section, the priority while the implementation stage was to get a clear and easy to understand source code. Thereby, an optimization is able (and recommended) to be made over the code, reducing its weight.

Although an optimization should be done over the code, it is considered that the system is suitable and could fit properly in a multi-application smart card. It takes more space than a usual applet since it has to carry out more operations than them, but it does not reduce the available memory considerably allowing to store a large number of applications in a secure way.

Apéndice I

ASN.1 Specifications

The current appendix contains the ASN.1 specifications of the Certification Signing Request and X.509 certificates. These specifications could be found also in [29] for Certification Signing Request's and in [1], [7] and [40] for X.509 certificate's specification.

I.1. Certification Signing Request

I.1.1. Certification Request

```
CertificationRequest ::= SEQUENCE {
    certificationRequestInfo CertificationRequestInfo ,
    signatureAlgorithm AlgorithmIdentifier{{ SignatureAlgorithms }},
    signature BIT STRING
}

AlgorithmIdentifier ::= SEQUENCE {
    algorithm OBJECT IDENTIFIER,
    parameters ANY DEFINED BY algorithm OPTIONAL
}
```

Listing I.1: ASN.1 specification for Certification Signing Request

I.1.2. Alternative Certification Request

```
CertificationRequest ::= SIGNED { EncodedCertificationRequestInfo }
    (CONSTRAINED BY { -- Verify or sign encoded -- CertificationRequestInfo -- })

EncodedCertificationRequestInfo ::= TYPE-IDENTIFIER.&Type(
    CertificationRequestInfo)

SIGNED { ToBeSigned } ::= SEQUENCE {
    toBeSigned ToBeSigned ,
    algorithm AlgorithmIdentifier { {SignatureAlgorithms} },
    signature BIT STRING
}
```

Listing I.2: Alternative ASN.1 specification for Certification Signing Request

I.1.3. Certification Request Info

```
CertificationRequestInfo ::= SEQUENCE {
    version INTEGER { v1(0) } (v1 ,...) ,
    subject Name,
    subjectPKInfo SubjectPublicKeyInfo{{ PKInfoAlgorithms }},
    attributes [0] Attributes{{ CRIAttributes }}
}

SubjectPublicKeyInfo { ALGORITHM : IOSet} ::= SEQUENCE {
    algorithm AlgorithmIdentifier {{IOSet}},
    subjectPublicKey BIT STRING
}

PKInfoAlgorithms ALGORITHM ::= {
    ... -- add any locally defined algorithms here --
}

Attributes { ATTRIBUTE:IOSet } ::= SET OF Attribute{{ IOSet }}

CRIAttributes ATTRIBUTE ::= {
    ... -- add any locally defined attributes here --
}

Attribute { ATTRIBUTE:IOSet } ::= SEQUENCE {
    type ATTRIBUTE.&id({IOSet}),
    values SET SIZE(1..MAX) OF ATTRIBUTE.&Type({IOSet}{@type})
}
```

Listing I.3: ASN.1 specification for Certification Request Info

I.2. X.509 Certificate

I.2.1. Certificate

```
Certificate ::= SEQUENCE {
    tbsCertificate TBSCertificate,
    signatureAlgorithm AlgorithmIdentifier,
    signatureValue BIT STRING
}

AlgorithmIdentifier ::= SEQUENCE {
    algorithm OBJECT IDENTIFIER,
    parameters ANY DEFINED BY algorithm OPTIONAL
}
```

Listing I.4: ASN.1 specification for Certificate

I.2.2. TBS Certificate

```
TBSCertificate ::= SEQUENCE {
    version [0] EXPLICIT Version DEFAULT v1(0),
    serialNumber CertificateSerialNumber,
    signature AlgorithmIdentifier,
    issuer Name,
    validity Validity,
    subject Name,
    subjectPublicKeyInfo SubjectPublicKeyInfo,
    issuerUniqueID [ 1 ] IMPLICIT UniqueIdentifier OPTIONAL,
        -- If present, version MUST be v2 or v3
    subjectUniqueID [ 2 ] IMPLICIT UniqueIdentifier OPTIONAL,
        -- If present, version MUST be v2 or v3
    extensions [3] EXPLICIT Extensions OPTIONAL
        -- If are present, version MUST be v3
}
```

```
Version ::= INTEGER { v1(0), v2(1), v3(2) }

CertificateSerialNumber ::= INTEGER

Name ::= CHOICE {RDNSequence}

RDNSequence ::= SEQUENCE OF RelativeDistinguishedName

RelativeDistinguishedName ::= SET OF AttributeTypeAndValue

AttributeTypeAndValue ::= SEQUENCE {
    type AttributeType,
    value AttributeValue
}

AttributeType ::= OBJECT IDENTIFIER

AttributeValue ::= ANY DEFINED BY AttributeType

Validity ::= SEQUENCE {
    notBefore Time,
    notAfter Time
}

Time ::= CHOICE {
    utcTime UTCTime,
    generalTime GeneralizedTime
}

UniqueIdentifier ::= BIT STRING

SubjectPublicKeyInfo ::= SEQUENCE {
    algorithm AlgorithmIdentifier,
    subjectPublicKey BIT STRING
}

Extensions ::= SEQUENCE SIZE (1..MAX) OF Extension

Extension ::= SEQUENCE {
    extnId OBJECT IDENTIFIER,
    critical BOOLEAN DEFAULT FALSE,
    extnValue OCTET STRING
}
```

Listing I.5: ASN.1 specification for Certificate Info part

I.3. Signature

```
digestInfo ::= SEQUENCE {
    digestAlgorithm AlgorithmIdentifier,
    digest OCTET STRING
}
```

Listing I.6: ASN.1 specification for digestInfo structure

Apéndice J

Source Code of the Prototype

The current appendix contains the source code of the prototype implemented. As it was explained as the document progressed, this code is not the suitable for a real card, but it was built according to the limitations of the simulator.

Since it is very large to include in the appendices, the code of the implementation of the prototype can be found in the CD attached to the report. In the following sections, which correspond to the entities of the system, it is detailed where the project and the source code of each one of these entities is placed inside the CD.

J.1. SmartCard

Project can be found at: Implementation\Projects\Prototype\SmartCard

Source code is in two different places in order to make easier to access it:

- Implementation\Projects\Prototype\SmartCard\src\security\
  \VerifyPolicyAndClaimApplet.java
- Implementation\Source Codes\Prototype\
  \VerifyPolicyAndClaimApplet.java

J.2. TrustedReader

Project: Implementation\Projects\Prototype\TrustedReader

Source code:

- Implementation\Projects\Prototype\TrustedReader\security\
  \InitializationClass.java
- Implementation\Source Codes\Prototype\InitializationClass.java

J.3. TrustedThirdParty

Project: Implementation\Projects\Prototype\TrustedThirdParty

Source code:

- Implementation\Projects\Prototype\TrustedThirdParty\security\
  \TerminalClass.java
- Implementation\Source Codes\Prototype\TerminalClass.java

J.4. ApplicationIssuer

Project: Implementation\Projects\Prototype\ApplicationIssuer

Source code:

- Implementation\Projects\Prototype\ApplicationIssuer\ \appIssuerPackage\ContractDelivery.java
- Implementation\Source Codes\Prototype\ContractDelivery.java

Apéndice K

Source Code for a Real Implementation

The current appendix contains the source code for a real implementation of the prototype which has been built. In order to try to deploy this applet in a real card, it should be necessary to check that the card supports the security services that the implementation makes use. All of them are contained in the Java Card API, therefore it is expected not to be difficult to find a suitable card. Main changes from the implementation of the prototype are the following:

- Not to export the private key. Sign the data sent by TR by means of ALG_NO_PAD RSA algorithm (not available at the simulator used)
- Use Secure random (suitable to cryptographic operations) method to generate random numbers, instead of Pseudo-Random algorithm
- Increase RSA keys' length at least to 2048 bits
- Not to send the signature from CA and TTP certificates to TR and TTP respectively, in order to they decrypt and give it back to the card. Use ALG_NO_PAD RSA algorithm (not available at the simulator used)

The structure of the section is similar to the previous appendix (Appendix J).

K.1. SmartCard

Project can be found at: Implementation\Projects\RealImplementation\
\SmartCardRI

Source code is in two different places in order to make easier to access it:

- Implementation\Projects\RealImplementation\SmartCardRI\src\
\security\VerifyPolicyAndClaimApplet.java
- Implementation\Source Codes\RealImplementation\
\VerifyPolicyAndClaimApplet.java

K.2. TrustedReader

Project: Implementation\Projects\RealImplementation\TrustedReaderRI

Source code:

- Implementation\Projects\RealImplementation\TrustedReaderRI\
\security\InitializationClass.java

- Implementation\Source Codes\RealImplementation\
  \InitializationClass.java

K.3. TrustedThirdParty

Project: Implementation\Projects\RealImplementation\TrustedThirdPartyRI

Source code:

- Implementation\Projects\RealImplementation\TrustedThirdPartyRI\
  \security\TerminalClass.java
- Implementation\Source Codes\RealImplementation\TerminalClass.java

K.4. ApplicationIssuer

Project: Implementation\Projects\RealImplementation\ApplicationIssuer

Source code:

- Implementation\Projects\RealImplementation\ApplicationIssuer\
  \appIssuerPackage\ContractDelivery.java
- Implementation\Source Codes\RealImplementation\
  \ContractDelivery.java

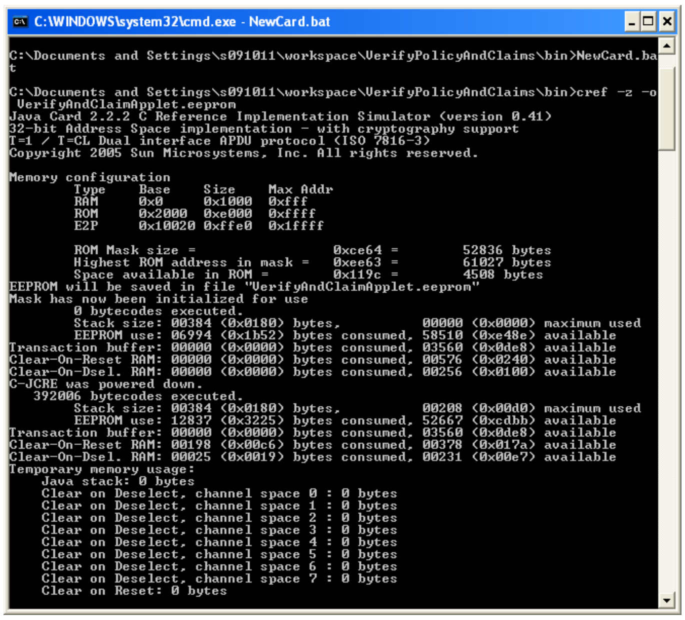
Apéndice L

Memory Analysis Figures

The current appendix contains the figures corresponding to the memory analysis' screenshots. In each one of the four figures it can be observed the statics at the startup and the shutdown of the following resources:

- EEPROM
- Transaction buffer
- Stack usage
- clear-on-reset RAM
- clear-on-deselect RAM

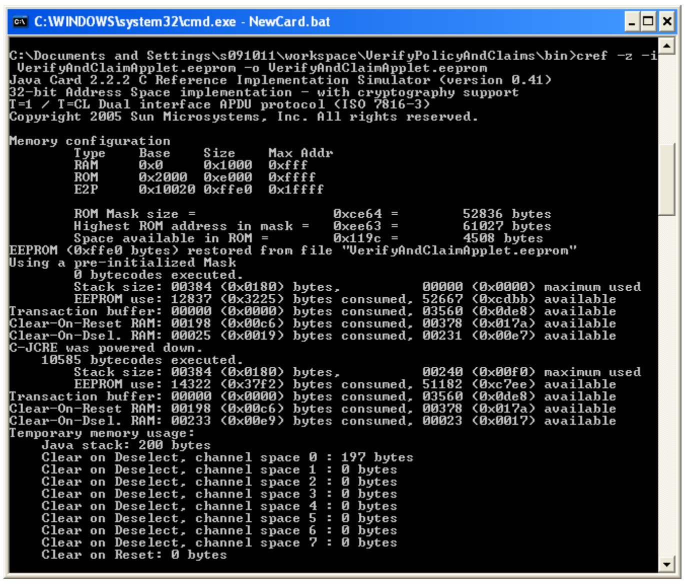
The four stages of the system which have been considered (and they appear in that order along the appendix) have been deployment of the applet on the card, its installation, its initialization and the matching algorithm after several running.



C:\WINDOWS\system32\cmd.exe - NewCard.bat

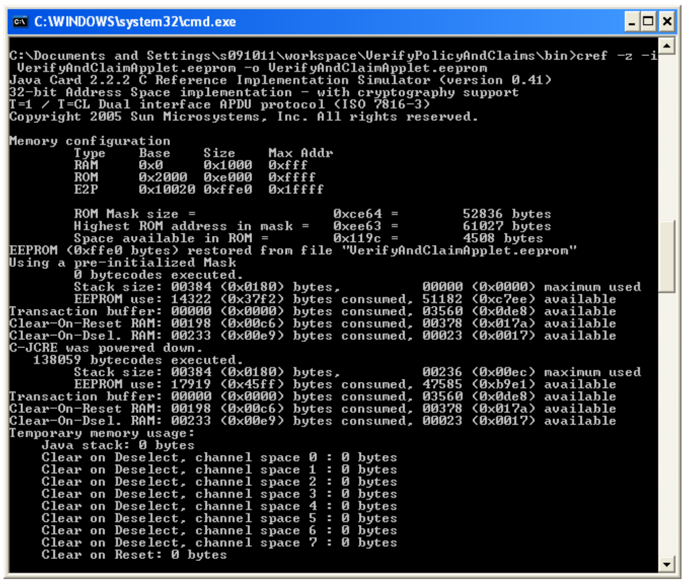
```
C:\Documents and Settings\s091011\workspace\VerifyPolicyAndClaims\bin>NewCard.ba
t

C:\Documents and Settings\s091011\workspace\VerifyPolicyAndClaims\bin>cref -z -o
 VerifyAndClaimApplet.eeprom
Java Card 2.2.2 C Reference Implementation Simulator (version 0.41)
32-bit Address Space implementation - with cryptography support
T=1 / T=CL Dual interface APDU protocol (ISO 7816-3)
Copyright 2005 Sun Microsystems, Inc. All rights reserved.

Memory configuration
        Type    Base    Size    Max Addr
        RAM     0x0     0x1000  0xfff
        ROM     0x2000  0xe000  0xffff
        E2P     0x10020 0xffe0  0x1ffff

        ROM Mask size =                 0xce64 =        52836 bytes
        Highest ROM address in mask =   0xee63 =        61027 bytes
        Space available in ROM =        0x119c =        4508 bytes
EEPROM will be saved in file "VerifyAndClaimApplet.eeprom"
Mask has now been initialized for use
        0 bytecodes executed.
        Stack size: 00384 (0x0180) bytes,          00000 (0x0000) maximum used
        EEPROM use: 06994 (0x1b52) bytes consumed, 58510 (0xe48e) available
Transaction buffer: 00000 (0x0000) bytes consumed, 03560 (0x0de8) available
Clear-On-Reset RAM: 00000 (0x0000) bytes consumed, 00576 (0x0240) available
Clear-On-Dsel. RAM: 00000 (0x0000) bytes consumed, 00256 (0x0100) available
C-JCRE was powered down.
   392006 bytecodes executed.
        Stack size: 00384 (0x0180) bytes,          00208 (0x00d0) maximum used
        EEPROM use: 12837 (0x3225) bytes consumed, 52667 (0xcdbb) available
Transaction buffer: 00000 (0x0000) bytes consumed, 03560 (0x0de8) available
Clear-On-Reset RAM: 00198 (0x00c6) bytes consumed, 00378 (0x017a) available
Clear-On-Dsel. RAM: 00025 (0x0019) bytes consumed, 00231 (0x00e7) available
Temporary memory usage:
    Java stack: 0 bytes
    Clear on Deselect, channel space 0 : 0 bytes
    Clear on Deselect, channel space 1 : 0 bytes
    Clear on Deselect, channel space 2 : 0 bytes
    Clear on Deselect, channel space 3 : 0 bytes
    Clear on Deselect, channel space 4 : 0 bytes
    Clear on Deselect, channel space 5 : 0 bytes
    Clear on Deselect, channel space 6 : 0 bytes
    Clear on Deselect, channel space 7 : 0 bytes
    Clear on Reset: 0 bytes
```

Figura L.1: Analysis before and after of the deployment



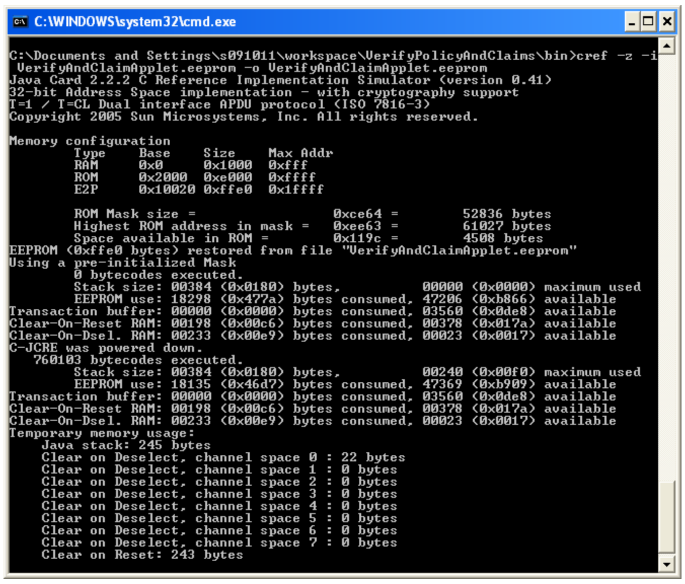
```
C:\Documents and Settings\s091011\workspace\VerifyPolicyAndClaims\bin>cref -z -i
 VerifyAndClaimApplet.eeprom -o VerifyAndClaimApplet.eeprom
Java Card 2.2.2 C Reference Implementation Simulator (version 0.41)
32-bit Address Space implementation - with cryptography support
T=1 / T=CL Dual interface APDU protocol (ISO 7816-3)
Copyright 2005 Sun Microsystems, Inc. All rights reserved.

Memory configuration
        Type    Base    Size    Max Addr
        RAM     0x0     0x1000  0xfff
        ROM     0x2000  0xe000  0xffff
        E2P     0x10020 0xffe0  0x1ffff

        ROM Mask size =                 0xce64 =        52836 bytes
        Highest ROM address in mask =   0xee63 =        61027 bytes
        Space available in ROM =        0x119c =        4508 bytes
EEPROM (0xffe0 bytes) restored from file "VerifyAndClaimApplet.eeprom"
Using a pre-initialized Mask
        0 bytecodes executed.
        Stack size: 00384 (0x0180) bytes,          00000 (0x0000) maximum used
        EEPROM use: 12837 (0x3225) bytes consumed, 52667 (0xcdbb) available
Transaction buffer: 00000 (0x0000) bytes consumed, 03560 (0x0de8) available
Clear-On-Reset RAM: 00198 (0x00c6) bytes consumed, 00378 (0x017a) available
Clear-On-Dsel. RAM: 00025 (0x0019) bytes consumed, 00231 (0x00e7) available
C-JCRE was powered down.
    10585 bytecodes executed.
        Stack size: 00384 (0x0180) bytes,          00240 (0x00f0) maximum used
        EEPROM use: 14322 (0x37f2) bytes consumed, 51182 (0xc7ee) available
Transaction buffer: 00000 (0x0000) bytes consumed, 03560 (0x0de8) available
Clear-On-Reset RAM: 00198 (0x00c6) bytes consumed, 00378 (0x017a) available
Clear-On-Dsel. RAM: 00233 (0x00e9) bytes consumed, 00023 (0x0017) available
Temporary memory usage:
    Java stack: 200 bytes
    Clear on Deselect, channel space 0 : 197 bytes
    Clear on Deselect, channel space 1 : 0 bytes
    Clear on Deselect, channel space 2 : 0 bytes
    Clear on Deselect, channel space 3 : 0 bytes
    Clear on Deselect, channel space 4 : 0 bytes
    Clear on Deselect, channel space 5 : 0 bytes
    Clear on Deselect, channel space 6 : 0 bytes
    Clear on Deselect, channel space 7 : 0 bytes
    Clear on Reset: 0 bytes
```

Figura L.2: Analysis before and after of the installation



```
C:\Documents and Settings\s091011\workspace\VerifyPolicyAndClaims\bin>cref -z -i
 VerifyAndClaimApplet.eeprom -o VerifyAndClaimApplet.eeprom
Java Card 2.2.2 C Reference Implementation Simulator (version 0.41)
32-bit Address Space implementation - with cryptography support
T=1 / T=CL Dual interface APDU protocol (ISO 7816-3)
Copyright 2005 Sun Microsystems, Inc. All rights reserved.

Memory configuration
        Type    Base    Size    Max Addr
        RAM     0x0     0x1000  0xfff
        ROM     0x2000  0xe000  0xffff
        E2P     0x10020 0xffe0  0x1ffff

        ROM Mask size =                 0xce64 =        52836 bytes
        Highest ROM address in mask =   0xee63 =        61027 bytes
        Space available in ROM =        0x119c =        4508 bytes
EEPROM (0xffe0 bytes) restored from file "VerifyAndClaimApplet.eeprom"
Using a pre-initialized Mask
        0 bytecodes executed.
        Stack size: 00384 (0x0180) bytes,          00000 (0x0000) maximum used
        EEPROM use: 14322 (0x37f2) bytes consumed, 51182 (0xc7ee) available
Transaction buffer: 00000 (0x0000) bytes consumed, 03560 (0x0de8) available
Clear-On-Reset RAM: 00198 (0x00c6) bytes consumed, 00378 (0x017a) available
Clear-On-Dsel. RAM: 00233 (0x00e9) bytes consumed, 00023 (0x0017) available
C-JCRE was powered down.
   138059 bytecodes executed.
        Stack size: 00384 (0x0180) bytes,          00236 (0x00ec) maximum used
        EEPROM use: 17919 (0x45ff) bytes consumed, 47585 (0xb9e1) available
Transaction buffer: 00000 (0x0000) bytes consumed, 03560 (0x0de8) available
Clear-On-Reset RAM: 00198 (0x00c6) bytes consumed, 00378 (0x017a) available
Clear-On-Dsel. RAM: 00233 (0x00e9) bytes consumed, 00023 (0x0017) available
Temporary memory usage:
    Java stack: 0 bytes
    Clear on Deselect, channel space 0 : 0 bytes
    Clear on Deselect, channel space 1 : 0 bytes
    Clear on Deselect, channel space 2 : 0 bytes
    Clear on Deselect, channel space 3 : 0 bytes
    Clear on Deselect, channel space 4 : 0 bytes
    Clear on Deselect, channel space 5 : 0 bytes
    Clear on Deselect, channel space 6 : 0 bytes
    Clear on Deselect, channel space 7 : 0 bytes
    Clear on Reset: 0 bytes
```

Figura L.3: Analysis before and after of the initialization



```
C:\Documents and Settings\s091011\workspace\VerifyPolicyAndClaims\bin>cref -z -i
 VerifyAndClaimApplet.eeprom -o VerifyAndClaimApplet.eeprom
Java Card 2.2.2 C Reference Implementation Simulator (version 0.41)
32-bit Address Space implementation - with cryptography support
T=1 / T=CL Dual interface APDU protocol (ISO 7816-3)
Copyright 2005 Sun Microsystems, Inc. All rights reserved.

Memory configuration
        Type    Base    Size    Max Addr
        RAM     0x0     0x1000  0xfff
        ROM     0x2000  0xe000  0xffff
        E2P     0x10020 0xffe0  0x1ffff

        ROM Mask size =                 0xce64 =        52836 bytes
        Highest ROM address in mask =   0xee63 =        61027 bytes
        Space available in ROM =        0x119c =        4508 bytes
EEPROM (0xffe0 bytes) restored from file "VerifyAndClaimApplet.eeprom"
Using a pre-initialized Mask
        0 bytecodes executed.
        Stack size: 00384 (0x0180) bytes,           00000 (0x0000) maximum used
        EEPROM use: 18298 (0x477a) bytes consumed, 47206 (0xb866) available
Transaction buffer: 00000 (0x0000) bytes consumed, 03560 (0x0de8) available
Clear-On-Reset RAM: 00198 (0x00c6) bytes consumed, 00378 (0x017a) available
Clear-On-Dsel. RAM: 00233 (0x00e9) bytes consumed, 00023 (0x0017) available
C-JCRE was powered down.
   760103 bytecodes executed.
        Stack size: 00384 (0x0180) bytes,           00240 (0x00f0) maximum used
        EEPROM use: 18135 (0x46d7) bytes consumed, 47369 (0xb909) available
Transaction buffer: 00000 (0x0000) bytes consumed, 03560 (0x0de8) available
Clear-On-Reset RAM: 00198 (0x00c6) bytes consumed, 00378 (0x017a) available
Clear-On-Dsel. RAM: 00233 (0x00e9) bytes consumed, 00023 (0x0017) available
Temporary memory usage:
    Java stack: 245 bytes
    Clear on Deselect, channel space 0 : 22 bytes
    Clear on Deselect, channel space 1 : 0 bytes
    Clear on Deselect, channel space 2 : 0 bytes
    Clear on Deselect, channel space 3 : 0 bytes
    Clear on Deselect, channel space 4 : 0 bytes
    Clear on Deselect, channel space 5 : 0 bytes
    Clear on Deselect, channel space 6 : 0 bytes
    Clear on Deselect, channel space 7 : 0 bytes
    Clear on Reset: 243 bytes
```

Figura L.4: Analysis before and after of running the matching algorithm

Apéndice M

Securing Off-Card Contract-Policy Matching in Security-By-Contract for Multi-Application Smart Cards

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Securing Off-Card Contract-Policy Matching in Security-By-Contract for Multi-Application Smart Cards

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***Abstract*—The Security-by-Contract (S×C) framework has recently been proposed to support applications evolution in multi-application smart cards. The key idea is based on the notion of *contract*, a specification of the security behavior of an application that must be compliant with the security policy of a smart card. In this paper we address one of the key features needed to apply the S×C idea to a resource limited device such as a smart card, namely the outsourcing of the contract-policy matching to a Trusted Third Party. The design of the overall system as well as a first implemented prototype are presented.**

***Keywords*- Multi-Application Smart Cards; Security; Contract Matching.**

I. Introduction

Java card technology has progressed at the point of allowing several Web applications to run on a smart card and to dynamically load and remove applications during the card's active life[1]. With the advent of these new *Web enabled multi-application smart cards* the industry potential is huge. However, concrete deployment of multi-application smart cards have remained extremely rare. One reason is the lack of solutions to an old problem: the control of interactions among applications. Indeed, the business model of the asynchronous download and update of applications by *different parties* requires the control of interactions among possible applications *after* the card has been fielded. In other words, what is missing is a quick way to deploy new applications on the smart card once it is in the field, so that applications are owned and asynchronously controlled by different stakeholders. In particular, owners of different applications (banks, airline companies, etc.) would like to make sure their applications cannot be accessed by new (bad) applications added after theirs, or that their applications will interact only with the ones of some business partners.

To date, current security models and techniques for smart cards (namely, permissions and firewall) do not support any type of applications' evolution. Smart card developers have to prove that all the changes that are possible to apply to the card are security-free, so that their formal proof of compliance with Common Criteria is still valid and they do not need to obtain a new certificate. The result is that there are essentially no multi-application smart cards, though the technology already supports them (Java Card and Global Platform specifications).

The Security-by-Contract (S×C) framework has recently been proposed to address this challenge [1]. The approach was built upon the notion of Model Carrying Code (MCC) [2] and successfully developed for mobile code ([3], [4] to mention only a few). The overall idea is based on the notion of *contract*, that is a specification of the security behavior of an application that must be compliant with the security policy of the hosting platform (i.e., the smart card). This compliance can be checked at load time and in this way avoid the need for costly run-time monitoring.

The effectiveness of S×C has been discussed in [1], [5], where the authors show how the approach can be used to prevent illegal information exchange among several applications on a single smart card, and how to deal with dynamic changes in both contracts and platform policy. However, in those papers the authors assume that the key S×C phase, namely *contract-policy matching*, is done on the card, which is a resource limited device. What they leave open is the issue of outsourcing the contract-matching phase to a Trusted Third Party, in case this phase requires a too expensive computational effort for the card. In this paper we explicitly address this issue, discussing the design and a first prototype of this key functionality of the S×C framework.

The paper is organized as follows. In Section II we introduce the S×C framework and the problem we tackle. Then the discussion of the design and implementation details of the proposed system are depicted in Section III and IV, respectively. Section V concludes the paper summarizing its contribution.

II. Security-By-Contract (S×C)... in a Nutshell

In the S×C approach, mobile code carries with a claim on its security behavior (an *application's contract*) that could be matched against a mobile *platform's policy* before downloading the code. In this setting, a digital signature does not only certify the origin of the code but also binds together

[1]http://java.sun.com/javacard/specs.html

the code with a contract with the main goal to provide a semantics for digital signatures on mobile code.

At *load time*, the target platform follows a workflow similar to the one depicted in Fig. 1 (see also [6]). First, it checks that the evidence is correct. Such evidence can be a trusted signature as in standard mobile applications [7]. An alternative evidence can be a proof that the code satisfies the contract (and then one can use PCC techniques to check it [8] or specific techniques for smart-cards such as [9]).

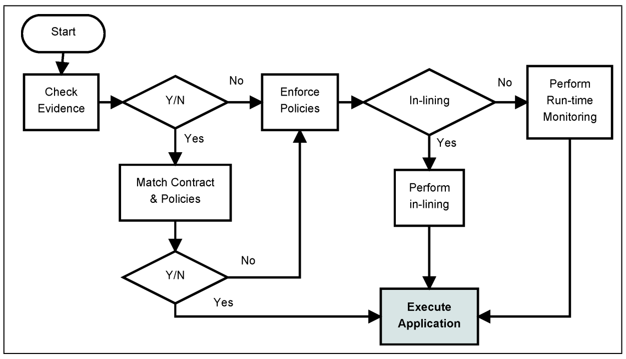


Figure 1. S×C Workflow

Once we have evidence that the contract is trustworthy, the platform checks that the claimed policy is compliant with the policy that our platform wants to enforce. This is a key phase called *contract-policy matching* in the S×C jargon. If it is, then the application can be run without further ado. At run-time, a firewall (such as the one provided by the Java Card Runtime Environment) can just check that only the declared API in the contract can be called. The matching step guarantees that the resulting interactions are correct. This is a significant saving over full in-line reference monitors.

A. *Off-Card Contract-Policy Matching*

A key issue in the S×C framework concerns who is responsible for executing the contract-policy matching. Due to the computational limitations of a resource limited environment such as a smart card (SC), running a full matching process on the card might be too expensive. In the S×C setting, the choice between "on-card" and "off-card" matching relies on the level of contract/policy abstraction [1], [5]. Indeed, the framework is based on a hierarchy of contracts/policies models for smart cards, so that each level of the hierarchy can be used to specify contracts/policies with different computational efforts and expressivity limitations.

This paper focuses on the situation where contract-policy matching is too expensive to be performed on the card. The idea, depicted in Fig. 2, is that a Trusted Third Party (TTP), for instance the card issuer, provides its computational capabilities to perform the contract-policy compliance check. The TTP could supply a proof of contract-policy compliance to be checked on the smart card. The SC's policy is then updated according to the results received by the TTP: if the compliance check was successful, then the SC's policy is updated with the new contract and the application can be executed. Otherwise, the application is rejected or the policy enforced off-card (for example, by means of a service provided by the TTP in addition to contract-policy matching). In case the TTP includes a proof of compliance in the reply, then a further check is needed to verify the proof, as shown in Fig. 2.

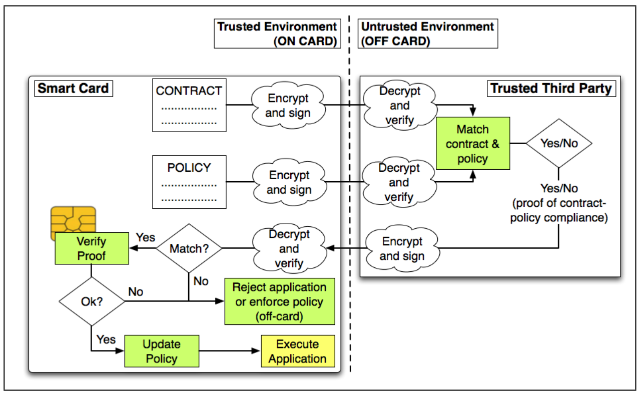


Figure 2. Off-Card S×C Contract-Policy Matching

In this scenario, the communication between SC and TTP must be secured in order to deal with an untrusted environment. Both contract and policy must be encrypted and signed by SC before they are sent to the TTP to ensure authentication, integrity and confidentiality. Analogously, the results of the compliance check should be encrypted and signed by TTP before they are sent back to SC.

III. Securing Off-Card Matching

To secure the system we use *Public Key Infrastructure* (PKI), where keys and identities are handled through certificates (namely, X.509 certificates [10]) that are exchanged between parties during communication. For this reason, the SC must engage an *initialization phase*, where certificates are stored in the SC along with security policies. The security of the system relies on the assumption that the environment in this phase is completely trusted and secure. As above mentioned all messages between SC-TTP will be signed and encrypted. We have decided to use two certificates (i.e. two different key-pairs), one for the signature and one for the encryption, so that in the unlikely event of one being compromised the other is not. The use of two certificates is optional, but it makes the system more secure.

In this Section we first show the design of the *initialization phase* and then pass over the *contract-policy matching* one. Since the system is based on *Java card 2.2.2*, the SC acts as a server which responds only to Application Protocol Data Unit (APDU) commands by means of APDU-response messages.

Initialization Phase. This phase is divided into three different steps: *Certificate Signing Request* (CSR) building [11], certificates issuing, and finally certificates and policy storage. As shown in Fig. 3 the first step consists in building the CSR for the two certificates to be sent to the *Certification Authority* (CA). The Trusted Reader (TR) queries the SC for its *public key*, then TR builds the CSR and sends it back to SC that signs it. Message #4 `SPrKSCEnc(SCEncCSR)` means that the CSR for encryption is signed (`S`) with private key (`PrK`) of `SC` for encryption (`Enc`). Messages throughout all figures are likewise.

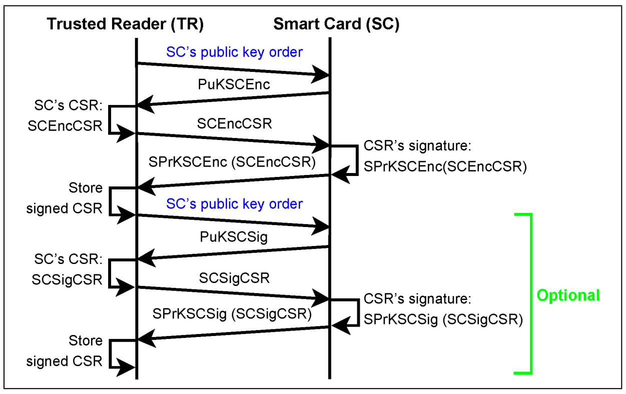
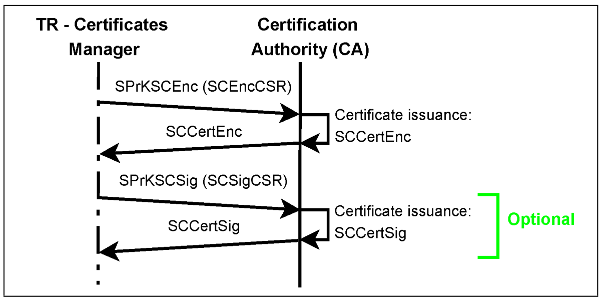


Figure 3. CSRs Building

In the second step (Fig. 4) the TR - Certificates Manager (TRCM) sends to CA the CSRs previously built, CA issues the certificates and then sends them back to the TRCM.



TR - Certificates Manager
Certification Authority (CA)
SPrKSCEnc (SCEncCSR)
Certificate issuance: SCCertEnc
SCCertEnc
SPrKSCSig (SCSigCSR)
Certificate issuance: SCCertSig
SCCertSig
Optional

Figure 4. Certificates Issuing

The final step, shown in Fig. 5, completes the *initialization phase* by storing in the SC the two certificates, the security policy and the CA digital certificate (this is needed by the SC to verify certificates of TTP).

After the SC has been initialized it is ready to securely engage in any activity that involves the *contract and policy matching*. Specifically the card will be able to verify the identity of the TTP, authenticate and authorize its requests.

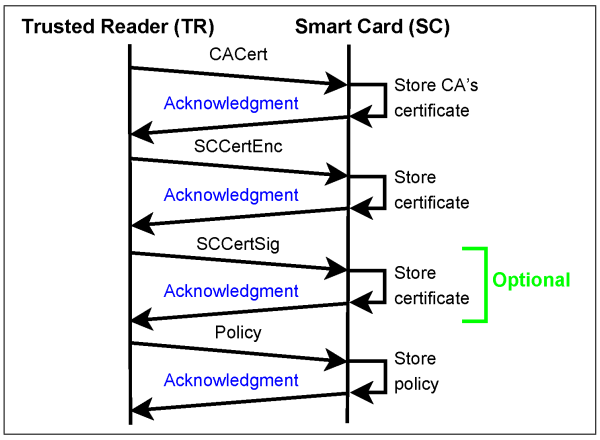
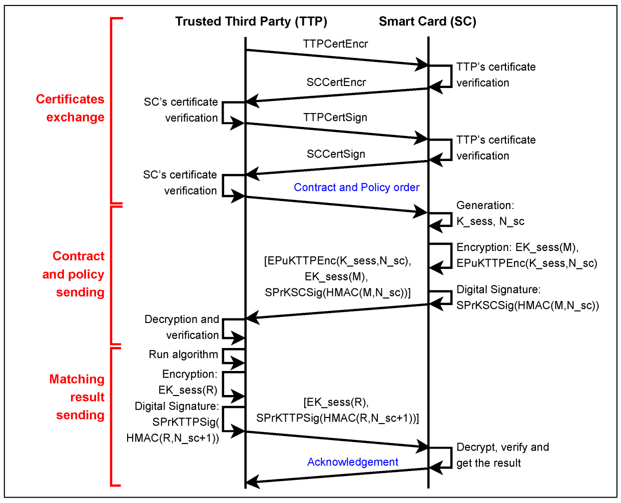


Figure 5. Storage of Keys and Certificates on Smart Card

Contract-Policy Matching Phase. During this phase the contract and the security policy, stored in the card, are sent from SC to some TTP which runs the matching algorithm and then sends the result back to SC. Our goal is to secure communication between TTP and SC in terms of mutual authentication, integrity and confidentiality. The solution we propose is shown in Fig. 6. It is divided into three parts: *certificates exchange*, *contract and policy sending*, *matching result sending*.



Trusted Third Party (TTP)
Smart Card (SC)
Certificates exchange
TTPCertEncr
TTP's certificate verification
SCCertEncr
SC's certificate verification
TTPCertSign
TTP's certificate verification
SCCertSign
SC's certificate verification
Contract and Policy order
Generation: K_sess, N_sc
Contract and policy sending
Encryption: EK_sess(M), EPuKTTPEnc(K_sess,N_sc)
[EPuKTTPEnc(K_sess,N_sc), EK_sess(M), SPrKSCSig(HMAC(M,N_sc))]
Digital Signature: SPrKSCSig(HMAC(M,N_sc))
Decryption and verification
Matching result sending
Run algorithm
Encryption: EK_sess(R)
Digital Signature: SPrKTTPSig(HMAC(R,N_sc+1))
[EK_sess(R), SPrKTTPSig(HMAC(R,N_sc+1))]
Decrypt, verify and get the result
Acknowledgement

Figure 6. Protocol for Off-Card Contract-Policy Matching

In the first part TTP and SC exchange their own pair of certificates (one for encryption and one for the signature) and then respectively check the validity of those. Particularly, the SC checks them against CA certificate stored during *Initialization phase*. If the certificates are valid then the TTP asks SC for the contract and policy. At this point the SC engages in a sequence of actions aiming to secure the message *M* containing requested information that needs to be sent back to TTP. Specifically:

1) It generates a *session key* and a *NONCE* (Number used Once) that will be used for this communication.
2) It encrypts the *session key* and the *NONCE* with TTP *Public Key*, and then message *M* with the *session key*.
3) It computes the HMAC (a hash mixed with a salt, i.e. the NONCE (N_{sc})) and it signs it.

Then the message is sent to TTP which verifies the message and extracts the needed information.

In the last part TTP runs the matching algorithm against contract and policy, and builds a secure message containing the algorithm result *R* to be sent to SC. The key used for encryption is still the *session key* generated previously by SC. The signature is done as before except that the HMAC uses as salt the value $N_{sc} + 1$. At this point SC decrypts and verifies the result and sends an acknowledgement to TTP.

IV. Prototype Implementation

A first prototype of the proposed framework has been implemented, representing almost a fully-functional implementation. Java version 1.6 has been used to implement the TTP and the TR, and Java Card 2.2.2 was used for the SC. This version was used instead of Java Card 3 due to the lack of mature in version 3 (actually, there are no cards supporting its real implementation). An APDU extended length capability has been implemented in order to allow sending up to 32KB data messages instead of the by-default maximum 255 bytes size.

All message exchange protocols have been implemented and authentication, integrity and confidentiality are ensured by means of X.509 certificates in communications between the TTP and the card. These certificates are managed by means of the CA, which generates self-signed certificates using OpenSSL 0.9.8n.

The implementation of the initialization phase is almost finished. All required data is stored and sent to the installer and also sent back to the card. On the other hand, some work must be done in the contract and policy matching phase. Certificate exchange is working properly, but verification is only carried out in the TTP and not on the card yet. RSA keys are used to achieve PKI encryption, but digital signatures and block ciphering must be developed too.

To test the prototype, two different simulation environments have been used. At first stages, the Java Card platform Workstation Development Environment tool (Java Card WDE) was used. However, saving the status of the card and all the session data is currently being addressed, so the environment has been changed to the C-language Java Card RE (CREF), which eases this feature.

V. Conclusion

In this paper we have addressed the issue of outsourcing the S×C contract-policy matching service to a Trusted Third Party. The design of the overall system as well as a first implemented prototype have been presented. The solution provides confidentiality, integrity and mutual authentication altogether. In particular, the following mechanisms have been implemented to strengthen the security of the system: (i) The use of two different certificates for signature and encryption. (ii) A NONCE created for each session to ensure freshness of the messages. (iii) Both the *session key* and the *NONCE* are generated within the SC, and then sent encrypted to TTP. The fact that TTP uses them to correctly compose the message *R* is a proof that TTP is the one that decrypted the message in the same session (due to the freshness of *NONCE*) and no one else did (the only way would be to get the Private Key of TTP but Public Key Cryptosystems are considered secure and unbreakable). (iv) The HMAC sent within the response is salted with $N_{sc} + 1$. The change in the value of the salt introduces variability in the hash making it more unlikely to forge.

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Apéndice N

Glosario de Acrónimos

N.1. Acrónimos en castellano

AC Autoridad de Certificación

Cif$_A$**(B)** Cifrado de B mediante A (en las figuras: C_A(B))

CPuA Clave Pública de A

CPrA Clave Privada de A

CSes Clave de sesión para criptografía simétrica

CSRTI Petición de certificación de la tarjeta inteligente

EA Emisor de la Aplicación

Fir$_A$**(B)** Firma B mediante A (en las figuras: F_A(B))

LS Lector Seguro

S Servidor (en el trabajo futuro)

SxC Seguridad-mediante-Contrato

TI Tarjeta Inteligente

TICertCifr Certificado de TI para cifrar

TICertFirm Certificado de TI para firmar

TICifCSR Petición de certificado de TI para cifrar

TICPrCif Clave Privada de TI para cifrar

TICPrFir Clave Privada de TI para firmar

TICPuCif Clave Pública de TI para cifrar

TICPuFir Clave Pública de TI para firmar

TIFirCSR Petición de certificado de TI para firmar

TPC Tercera Parte de Confianza

TPCCertCifr Certificado de TPC para cifrar

TPCCertFirm Certificado de TPC para firmar

TPCCPrCif Clave privada de TPC para cifrar

TPCCPrFir Clave privada de TPC para firmar

TPCCPuCif Clave pública de TPC para cifrar

TPCCPuFir Clave pública de TPC para firmar

N.2. Acrónimos en inglés

AES Advanced Encryption Standard

AI Application Issuer

APDU Application Protocol Data Unit

API Application Programming Interface

ASN.1 Abstract Syntax Notation One

BER Basic Encoding Rules

CA Certification Authority

CACert Certification Authority Certificate

CAD Card Acceptance Device

CAP Converted Applet

CBC Cipher Block Chaining

CISC Complex Instruction Set Computer

CLA Field from an APDU message which identifies an application class of instructions

CREF C-language Java Card Runtime Environment

CRL Certificate Revocation List

CSR Certificate Signing Request

DER Distinguished Encoding Rules

DES Data Encryption Standard

DPA Differential Power Analysis

ECB Electronic Codebook

EEPROM Electrically Erasable Programmable Read-Only-Memory

EM	Encoded Message
Enc$_A$(B)	Encryption of B by means of A (in figures: EA(B))
FAT	File Allocation Table
HMAC	Hash-based Message Authentication Code
HTTP	Hypertext Transfer Protocol
ICC	Integrated Circuit Chip
ID$_A$	Identity of A
IDE	Integrated Development Kit
IEC	International Electrotechnical Commission
INS	Field from an APDU message which specifies the instruction
ISO	International Organization for Standardization
IV	Initialization Vector
JCRE	Java Card Runtime Environment
JCVM	Java Card Virtual Machine
JCWDE	Java Card platform Workstation Development Environment
JC3	Java Card 3
JDK	Java Development Kit
JRE	Java Runtime Environment
JSDK	Java Software Development Kit
KB	Kilobyte
MCC	Model-Carrying Code
NONCE	Number used only once
OID	Object Identifier
OS	Operating System
OSI	Open Systems Interconnection
PCC	Proof-Carrying Code
PEM	Privacy-enhanced Electronic Mail
PIN	Personal Identification Number
PKCS	Public-Key Cryptography Standard
PKI	Public Key Infrastructure

PRNG Pseudo-Random Number Generator

PrKSC Smart Card Private Key

PrKSCEnc Smart Card Private Key for Encryption

PrKSCSig Smart Card Private Key for Signature

PuKSC Smart Card Public Key

PuKSCEnc Smart Card Public Key for Encryption

PuKSCSig Smart Card Public Key for Signature

RAM Random Access Memory

RISC Reduced Instruction Set Computer

ROM Read-Only-Memory

RSA Rivest, Shamir and Adleman

SC Smart Card

SCCertEnc Smart Card Certificate for Encryption

SCCertSig Smart Card Certificate for Signature

SCContractPolicy Smart Card data used to build the message containing Contract and Policy

SCCSR Smart Card Certificate Signing Request

SCEncCSR Smart Card Certificate Signing Request for Encryption

SCEncInfo Smart Card Certificate for Encryption Information Part (public key, distinguished name, etc.)

SCSigCSR Smart Card Certificate Signing Request for Signature

SCSigInfo Smart Card Certificate for Signature Information Part (public key, distinguished name, etc.)

SD Security Domain

SHA Secure Hash Algorithm

Sig$_A$(B) Signature of B by means of A (in figures: SA(B))

SIM Subscriber Identity Model

SIO Shared Interface Objects

SPA Simple Power Analysis

SRNG Secure Random Number Generator

STEP Secure Trusted Environment Provisioning

SxC	Security-By-Contract
TLV	Tag Length Value
TR	Trusted Reader
TTP	Trusted Third Party
TTPCertEncr	Trusted Third Party Certificate for Encryption
TTPCertSign	Trusted Third Party Certificate for Signature
TTPContractPolicy	Data recovered by TTP from the message containing Contract and Policy and whose HMAC is checked against to HMAC in the signature of the message
WfSC	Windows for Smart Cards

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