D08.2: Porting Security Services to a Mobile Platform to Support a Trusted Mobile Application

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Abstract	This document presents the “Secure Wallet”, a countermeasure against identity theft on the Internet. The Secure Wallet supports automated secure logins on web-pages, using Trusted Computing and Virtualisation on the client side. We analyse the security of our approach and discuss related work. Moreover, a security kernel based architecture to support such a wallet is sketched, together with an architecture for a prototype, where some part of the implementation is running on a PC, and the other part on a mobile platform (Infineon's X-GOLD™ 208 platform). Recent standardization activities, in particular the TCG Mobile Reference Architecture and OMTP TR1 specifications, are then examined in light of the Secure Wallet use case.
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Table of contents

Index of tables

Index of figures

1 Introduction

Identity theft has become one of the fastest growing crimes on the Internet, leading to huge financial losses and privacy violations [1,2]. Various attacks have been identified in the past. A prominent class of attacks are those termed as illusion attacks, such as phishing and pharming, where the user is lured to a faked site and asked to disclose her identity credential information. Essentially, the attackers make use of the fact that the average Internet user is unable to distinguish a legitimate site from a fake one, and the underlying security mechanisms and indicators do not efficiently and effectively support her in making the right decision [26]. Hence, the first core security objective is to provide a strong password mechanism for the user while reducing the user's intervention with the system as much as possible. Ideally, the user should not know the passwords. This requirement seems to be contradictory, however, relying on a system that knows the passwords and automatically performs the login on behalf of the user, including an automatic verification of the legitimacy of the web site, prevents the mentioned attacks.

In addition to illusion attacks and the related social engineering attacks, a more powerful class of attacks is due to malware compromising and infiltrating the user's computing platform with malicious code. Examples include Trojan horses like keyloggers[1] or transaction generators[2] [12,3]. Typical sources of malware are various offers on supplementary software and plug-ins that may contain malicious code. In this context, commodity operating systems (OS's) cannot appropriately prevent or even reduce the impact of these attacks since they still suffer from various conceptual shortcomings: beside architectural security problems and the inherent vulnerabilities resulting from high complexity, they require careful system administration skills which ordinary users typically do not have. Hence the second main security objective is to have a small Trusted Computing Base (TCB) that can provide the following security properties:

1. a secure execution environment for handling users' authentication credentials, ideally isolated from potentially malicious programs (isolation);
2. a secure user interface to interact with trusted applications, which cannot be faked or eavesdropped by malicious programs (trusted path); and
3. a secure environment for the credentials when the system is offline (secure storage). In particular, credentials are bound to the TCB to prevent attacks where an adversary tries to gain access to the data by replacing software (e.g., booting a different OS).

Both the scientific and industrial community have addressed many of the known attacks on web authentication and proposed promising identity management solutions to alleviate the threat of identity theft. On the one hand, delegated identity management systems, where the user calls a trusted third party in form of a distributed server for hosting and providing identity information, exist but showed to have deficiencies [32,34,62,54]. For example, as analysed in [32], authentication tools

1Keyloggers record all keystrokes of the user, especially during entering passwords, and transmit them to a phisher.
2Transaction generators wait until the user has logged in, e.g., to her financial online account, and create fraudulent transactions in the background.

such as Microsoft’s CardSpace [38] can successfully be attacked even in a weaker adversary model (assuming the DNS is under the control of the adversary), whereas our adversary model considers malware as well.

On the other hand, wallet-like approaches such as SpyBlock [55,40,39], Delegate [43], Vault [45], or Wallet-Proxy [31] have gained more attention recently and seem to be very promising towards secure web authentication. Those approaches use a password wallet as authentication agent in an isolated trusted environment (using virtual machines, or as with Delegate, a separate physical machine) to separate the handling of credentials from the normal web browsing (see also [55,70]). The wallet-based approach has the advantage that the user owns a “guardian angel” who protects against disclosure of sensitive data and potentially prevents identity theft caused by wrong user behavior. Further, there is no need to trust a distributed server hosting the credentials. Another issue is that a wallet can perform cryptographic tasks that cannot be performed by the user or provided by the current browser implementations. In this work, we focus on password phishing. To protect against transaction generators, the secure wallet could be extended according to ideas presented in [40].

In this deliverable, we describe our approach to counter identity theft: the Secure Wallet use case and prototype. We present the requirements and architecture, analyse the security, and propose a prototype implementation. This includes the architecture for a demonstrator using Infineon's X-GOLD™ 208 (formerly called S-GOLD3™) mobile platform. Moreover, the relation of the Secure Wallet to current mobile standards, in particular the TCG Mobile Reference Architecture and OMTP TR1 specifications, is discussed.

2 The Secure Wallet Use Case and Prototype

In this section, we describe the Secure Wallet, our solution to counter identity theft based on the concepts from [31], and give an overview of the system architecture. We sketch the system architecture (based on generic security services as developed in OpenTC WP05) that has been used for our prototype implementation on a PC. We describe an architecture for a mobile platform, and propose a “hybrid” architecture for a demo-prototype, where functionalities are split between a PC and a mobile platform.

2.1 Overview of the Secure Wallet

According to the Anti-Phishing Working Group (APWG) [1], phishing attacks are still on the rise. Especially crimeware attacks reached a new all-time high in December 2006, when the APWG recorded 340 unique applications designed for phishing and identity theft. More than 28.000 different phishing sites were recorded during the same month, each with an average online time of 4 days. Although those were about 10.000 sites less than in October and November, the number of phishing sites has almost tripled since summer 2006. In April 2007 that number almost doubled to 55.000 unique sites, whereas in the last months of 2007 it dropped to about 30.000 sites again. Gartner [11] estimates direct financial losses due to phishing to $2.8 billion in 2006, while indirect losses are much higher, including account replacement costs and higher expenses for mitigating damage in trust and brand values. As attacks increase in frequency and become more sophisticated with every generation, increasing losses can be expected as well.

In this chapter, we describe the basic ideas underlying the secure wallet. Note that we focus on password phishing. To address transaction generators, ideas from [40] can be combined with our approach.

2.1.1 Classical phishing

Basically, there are two types of phishing attacks. We define the first category, which is the oldest and still most widespread attack, as *classical phishing*. The normal user login procedure for an arbitrary web server is shown in Figure 1. The user enters her username and password into a web form provided by the web server and submits this form.

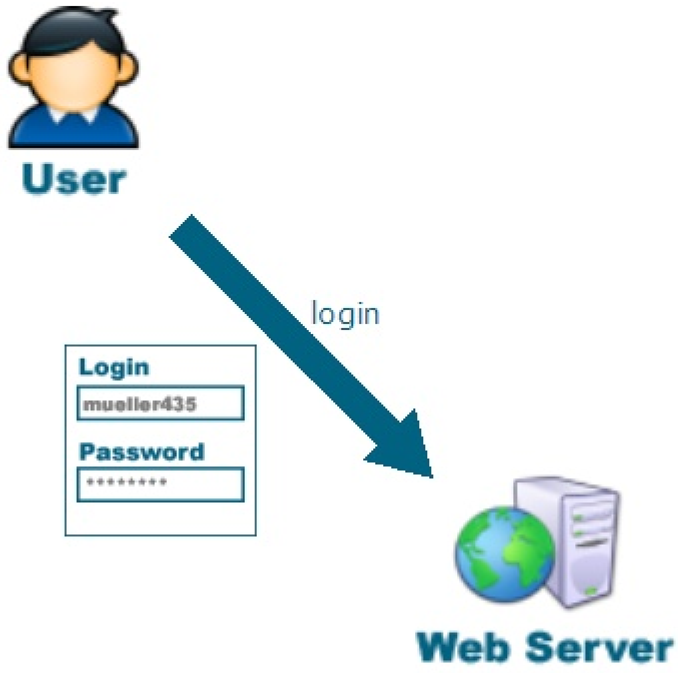


Figure 1: Web Server Login

In the phishing attack, the phisher tries to lure the unwary victim to a faked web site, which is designed to mimic a known web site (e.g. an online banking site of a common bank), using social engineering techniques. Such a lure typically is a spoofed email that appears to come from the organization associated with the original web site, asking to fill out some web form or to log into the victim's account in order to prevent it from being locked down permanently. Those sites have in common that a user with a given technical knowledge can distinguish them from the original sites by comparing the URLs or other security indicators (e.g. an SSL certificate). More sophisticated attacks include DNS poisoning techniques (e.g., see [75]), thereby using the URL of the original site and forwarding the request to the phisher's web server. If the phisher was able to fake the site well enough to be plausible for the victim, he hopes that the user enters her credential in order to use the site or to carry out the requested operation (e.g. confirm her account). Since the phisher controls the faked web site, he is in possession of the victim's credential afterwards.

Figure 2: Classical Phishing Overview

Websites that disclose personal information about their users, e.g. the fact whether a specific email address is registered with it or not, can be used by phishers to build up hostile profiles. Those profiles are then used by phishers to create custom phishing mails tailored to the respective user, increasing the likelihood that the user believes the mail [9].

2.1.2 Malware phishing

The other type of phishing attacks we define as *malware phishing*. Generally, those attacks can be categorized as attempts to collect personal information directly at the client through the use of malware, i.e. malicious software like trojans or keyloggers. Malware can have various effects on the client system. Besides keyloggers, which gather keystrokes and send them to the phisher, trojans can hijack browsers and trick users by altering their user interface or redirecting data streams to rogue servers. More sophisticated tools make use of numerous distributed machines gathering and collecting data silently using covert channels [42]. Phishers exploit known flaws in widely used software (e.g. buffer overruns) to distribute their malicious code. As malware improves more and more, becoming increasingly resilient to detection and countering techniques, phishing through malware seems appealing and can be expected to increase in frequency. This is confirmed by the fact that in December 2006 the number of unique variants of phishing malware increased by 110 to 340 [1].

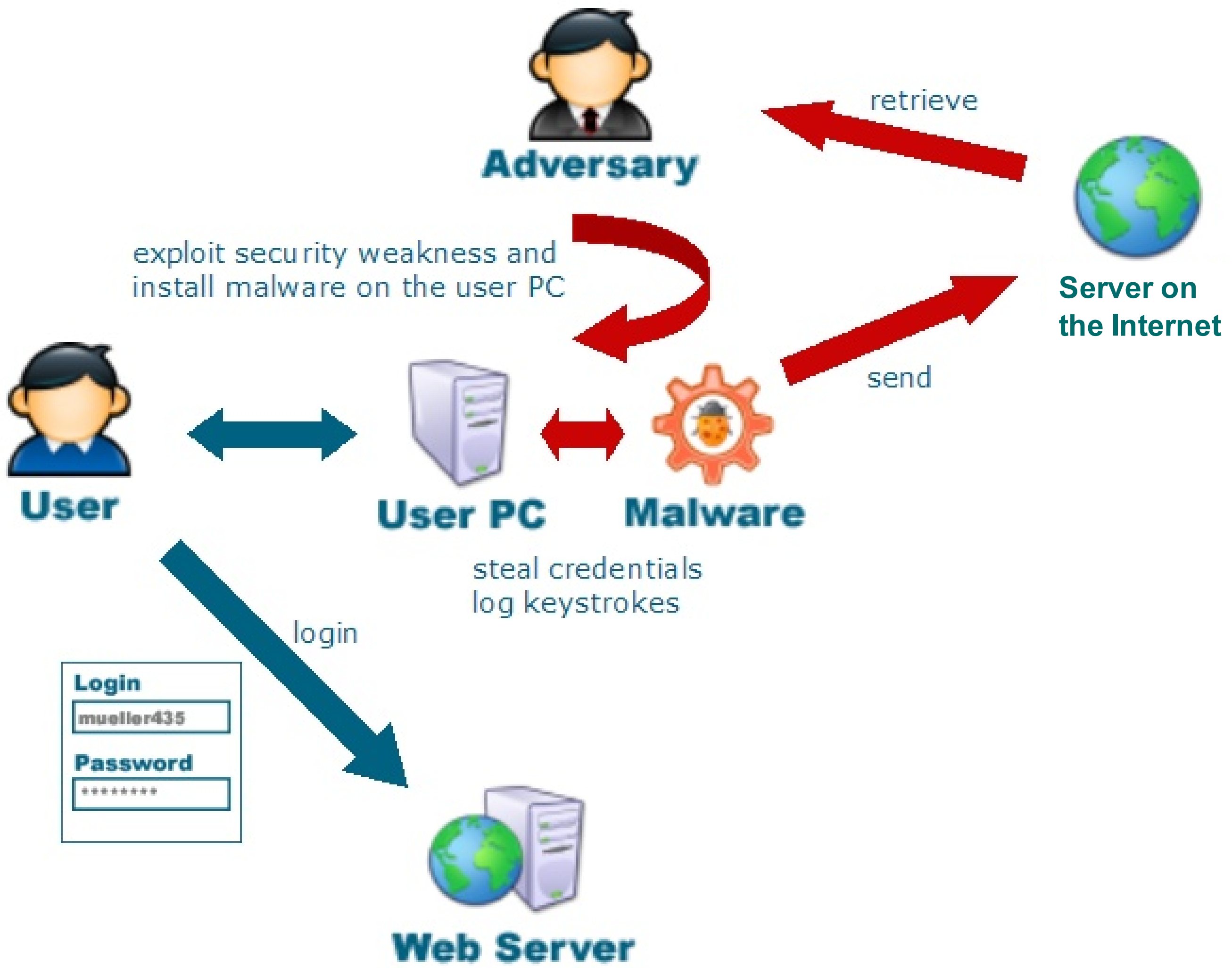


Figure 3: Malware Phishing Overview

2.1.3 Countering phishing

What makes countering phishing attacks difficult is the broad range of different attack vectors. On the one hand, the security engineer has to account for the unwary, technically inexperienced user being tricked by a convincing web site fake. On the other hand, credentials could also leak directly at the client without the user ever noticing it (at least until the phisher makes use of the stolen data). While solutions exist, targeting either the first or the second type of attacks in more or less detail, there is still no technique available that protects against both threats equally. The related work section provides some examples of existing solutions and illustrate why they do not suffice to target both kinds of attacks.

This document takes up the idea from [31] and presents an implementation for the proposed trusted wallet. This wallet, hence called Secure Wallet, will be used to securely store user credentials and authenticate to remote services on behalf of the user without requiring specific security-related skills (i.e. as stated above, to be able to recognize a web site fake or detect malware on her computer). In contrast to most other solutions, the wallet will equally protect against classical and malware phishing attacks.

The wallet will be executed on top of a virtualisation platform based on trusted computing functionality. This platform provides integrity and isolation by combining a security kernel and controlled access mechanisms. Running on top of this platform, no malicious software will be able to access or intercept the credentials stored in the wallet.

2.2 Security Problem Definition

2.2.1 Threats

Internet users are subject to the following security threats regarding their identities:

Threat 1 (Identity Theft through Faked Web Sites) *The user U is lured to a faked web site A where she enters her credential for the original site P, thereby exposing them to the creator of the faked site.*

The user may arrive at the fake site through different means, e.g., a spoofed email containing a link to the site, a link on some other (probably not even compromised) web site or through redirection by DNS poisoning. If the user disregards possible security warnings or does not notice that browser security indicators are missing and hence trusts the displayed content, she may be inclined to enter her credential $C_{u,p}$ for the original site P in order to log into the fake site A. The adversary and creator of the fake site A then can take possession of the user's credential for the original site. Afterwards, the adversary can use them to impersonate the user in order to perform transactions or gain access to other data belonging to the user.

Threat 2 (Malware Identity Theft) *Malicious software installed by an adversary A on user U's system gathers identity data and credentials when they are entered by U (for various applications). The software somehow exposes that data for A to retrieve.*

Malicious software (i.e. malware) can be various kinds of trojans – maybe containing keyloggers or other spyware – on the user's system. It could have been installed by intention (and perhaps the user does not notice the software contains spyware), or without the user ever noticing it. Depending on the type of malware, user credentials may leak through different means. A keylogger might log all characters entered into the target application, whereas a trojan might display a faked login dialog for the target application persuading the user that it is the real application. Note that this includes login forms on web sites as well, since the trojan could have altered the browser's behavior.

As soon as the malware has gathered sufficient credentials, it will somehow contact the adversary to send the gathered data to A, or it uses covert channels to expose the data at some public place, where A can retrieve it. Afterwards, A can use those credentials to impersonate the user as described in Threat 1.

Threat 3 (Wallet Credential Theft) *Malicious software reads the wallet's credential store directly.*

A reasonable approach for malicious software is to bypass all protection mechanisms supplied by the Secure Wallet during web site setup or login and read the wallet's credential store directly. If that credential store is not sufficiently protected, attackers can gain access to all credentials that U has already stored.

Threat 4 (Configuration Modification) *Malicious software modifies the wallet's configuration in order to somehow intercept unprotected credentials.*

If a malicious program cannot overcome the wallet's defences while interacting with a remote server or cannot read its credential store directly, it could try to change the wallet's configuration to weaken its security or disable it completely. If the wallet's configuration files are not protected from unauthorized access, malicious code could alter them in any possible way.

Threat 5 (Fake Dialog Attack) *Malicious software displays faked dialogs resembling the wallet's user interface and lures the user to enter credentials into those faked dialogs.*

Instead of disguising as some other application where the user could possibly enter credentials, malware could also try to disguise as the wallet itself. If the user has learned to enter credentials only into the wallet, this approach would be more promising than faking another application. Once the user is convinced that she uses the original wallet, the malicious program can intercept any credentials entered.

An additional threat, not directly addressed by this work, comprises the use of Transaction Generators [40] to generate an arbitrary amount of unauthorized transactions once the user has successfully logged into a specific web site. This threat is not introduced by the wallet concept though, but is a general threat regarding web sites allowing for commercial transactions. Therefore, it will (briefly) be discussed in the security analysis below.

2.2.2 Assumptions

As outlined in [31], the wallet solution is based on the following three assumptions:

Assumption 1 (Honest Provider) *We assume that the service provider P and his services used by the user U are not compromised.*

If the service provider P did not reliably protect his services, malicious users are able to steal identities directly from the provider's database. Therefore, P must enforce that his services cannot be exploited. This especially holds true for certifying services. We assume that appropriate protection of the services includes the use of secure communication protocols such as SSL/TLS.

Assumption 2 (Genuine Internet) *We assume that U uses a genuine internet connection, i.e. an adversary A cannot spoof the whole web.*

Web spoofing attacks were first described by Felten et al. [28,71], and comprise an attack where A is able to fake the whole internet and any associated service for a user U. If such attacks were taken into account, the user would already disclose her credentials to the adversary when signing up for a service. Therefore, it is assumed in the following that U always signs up at an honest provider P using an unspoofed internet connection.

Assumption 3 (Ordinary User) *We assume that the user U is an ordinary Internet user unable to properly authenticate a service provider P.*

In order to authenticate a web site provided by P, the user has to verify the service identifiers id_p. Such identifiers are the domain name, the 'https' protocol specifier in the URL, and the SSL server certificate. However, studies show that most Internet users cannot distinguish legitimate web sites from faked ones and do not understand indicators, which signal trustworthiness, or where to look for those [36,37].

Assumption 4 (Trustworthy Public Key Infrastructure) *We assume that a trustworthy PKI exists, whose Certificate Authorities (CA) issue certificates for a web site P only to individuals associated with P.*

The whole point of a public key infrastructure lies in trusting some distinct Certificate Authorities to issue certificates only to authorized individuals, e.g. a certificate for www.ebay.com should only be issued to eBay Inc. or another entity explicitly authorized by eBay Inc. If a CA does not conform to secure practices for the verification of an applicant's identity, an arbitrary individual could, in theory, acquire a certificate for any web site he desires, thus being able to impersonate that site in a man-in-the-middle attack. Such an attack has been effective in the past at least once for a prominent victim, when an attacker managed to disguise himself as a Microsoft employee and acquired two certificates issued to Microsoft from Verisign [6].

Assumption 5 (Private Key Protection) *We assume that the service providers protect the private keys of their certificates sufficiently and revoke them as soon as they are compromised or not used anymore.*

If a service provider does not sufficiently protect his private keys, an adversary who manages to steal them can impersonate the service provider and trick users into disclosing their credentials. This kind of attack cannot be countered by any mechanisms on the client-side.

Assumption 6 (Single Credential Storage Mechanism) *We assume that the user enters all credentials into the wallet exclusively.*

The wallet can only work to its maximum effect if the user uses it exclusively to store her credentials for web sites. When she still attempts to enter credentials into web sites directly or into other applications not associated with the wallet, no assumptions can be made about the credentials' security since the wallet cannot cover those external factors. This also includes “recovery options” for forgotten passwords offered by many websites. If the user uses such an option to get an email containing the password, the adversary might obtain the password from this email, hence we have to assume that the user does not use such options (which are not necessary in any case, because passwords are stored by the secure wallet). In practice, this assumption is more realistic and thus weaker than the assumption that the user always verifies the results of SSL certificate verifications provided by the browser.

Assupmtion 7 (Feasability of Secure Software Development) *We assume that it is possible to develop secure software components of limited complexity and to verify their correctness.*

Without secure software, we cannot protect the user's credentials. However, we try to limit the number and complexity of trusted software components. For instance, we do not assume that a complete web browser or an operating system where the user can install software can be implemented securely. But we do assume that a basic “security kernel” and a simple secure wallet application can be implemented securely, and that the correctness of their implementation can be verified.

2.2.3 Objectives

The main objective is to preserve the *confidentiality of the user's credentials*. However, this is made difficult by the fact that most service providers offer only entity authentication, i.e., authentication is based on the credentials alone and does not include all components in the communication path. This can be exploited by compromising such an unauthorized component. Therefore, the Secure Wallet will attempt to achieve the following partial security objectives:

Objective 1 (Protection against Fake Sites) *Let P be a web site for which the Secure Wallet stores U's credential* $C_{u,p} = (id_p, id_{u,p}, pw_{u,p})$. *The wallet will change the password* $pw_{u,p}$ *in order to prevent U from being able to disclose it to a fake site* A. *Moreover, the password generated by the wallet will be a* strong *password with high entropy, unique for each site, to protect against dictionary attacks and common password attacks.*

The user may possibly give away everything she knows to a phishing attack, especially her credentials for a specific web site P. An effective way of preventing credential leakage is not letting the user know those credentials. Thus, even if faced with a faked web site A, U cannot disclose any secret information apart from the outdated credential $C_{u,p}$ that U knew before the wallet changed it to $C'_{u,p}$. In order to prevent the adversary from computing $pw'_{u,p}$ from $pw_{u,p}$ (in case he managed to get $pw_{u,p}$ from the unwary user), the wallet incorporates random values into the transformation.

This seems to have a great impact on usability, since U cannot log into the web sites stored in the wallet from other computers anymore because she does not know the password. While the question remains whether it is wise for U to expose her password to a possibly insecure or compromised computer beyond her control, there are certain ways to improve usability, such as migrating the user's data to other platforms. Further work in this direction is needed.

Objective 2 (Secure Environment) *The system S ensures that the Secure Wallet's internal credential store can only be accessed if the wallet is executed in a secure and trusted environment.*

If the user attempts to execute the wallet in an insecure environment, the system must prohibit further access to the wallet to prevent leakage of credentials. Therefore, the system must ensure that no security-critical components have been compromised by verifying whether they have changed since the last time the wallet was used.

Objective 3 (Secure Storage) *The Secure Wallet uses a secure storage that cannot be read by any other application.*

The storage is the wallet's most important component since it contains all credentials stored by the user. Unauthorized applications that manage to read the wallet's storage directly, immediately gain access to all credentials, rendering all the wallet's other protection mechanisms useless. Therefore, the wallet must protect its storage or rely on the system to sufficiently protect it. No other application than the wallet should have access to that storage.

Objective 4 (Secure Configuration) *The Secure Wallet software and configuration* *cannot be altered by unauthorized applications in such a way that an adversary may gain access to the user's credentials.*

The configuration controls how the wallet is used or whether it is used at all. By altering the configuration, an adversary could disable the wallet completely and prevent it from protecting the user's credentials during web site login. Alternatively, the wallet could be misconfigured to prevent affective protection of user credetials. By modification of untrusted software components, an adversary should only be able to prevent the automated login operations (i.e., denial of service) but should never get access to the wallet's credentials. To prevent any further modifications, the configuration files must be stored separately, so that unauthorized applications cannot reach them. Moreover, the wallet software must not contain security-critical implementation flaws, such as buffer overflows.

Objective 5 (Secure Input and Output) *No other application should gain unauthorized access to input or output of the Secure Wallet .*

A common attack of Trojan horse programs is to emulate password input dialogs. The unwary user believes to enter her credentials into the genuine password dialog she expects. Thus she exposes those credentials to the malicious program. Therefore, the user must feel confident about the integrity, authenticity and confidentiality of the communication path to the wallet application as well as the integrity and authenticity of the secure wallet itself.

2.2.4 Security Objective Rationale

Objective 1 (*Protection against Fake Sites*) counters Threat 1 (*Identity Theft through Faked Web Sites*). When the user does not know the password for a web site, she cannot give that password away to an adversary trying to fake the web site. Therefore, faked web sites no longer pose a risk for the user's credentials.

Objective 3 (*Secure Storage*) counters Threat 3 (*Credential Theft*), Objective 4 (*Secure Configuration*) counters Threat 4 (*Configuration Modification*) and Objective 5 (*Secure Input and Output*) is meant to prevent Threat 5 (*Disguising as the Wallet*), since no malicious code can pretend to be the Secure Wallet as long as a trusted path to the wallet exists and is used. In addition, when the system already recognizes unexpected changes to security-critical components, protection against malware is significantly increased. Thus, all three Objectives 3 to 5 together with Objective 2 (*Secure Environment*) counter Threat 2 (*Malware Identity Theft*).

Table 1: Threats and the objectives addressing them

	Objective				
Threat	Fake Site	Env.	Storage	Config	Input
Fake Sites	X				
Malware		X	X	X	X
Credential Store			X		
Config Modification				X	
Fake Dialog					X

By ensuring a secure authentication process and preventing insecure communication channels, both faked web sites and malicious programs lose their ability to disguise as a trusted entity. Thus, the overall security objective, being the preservation of the confidentiality of the user's credentials, is achieved if the partial objectives can be achieved. The following table provides a compact overview of the discussed relations between objectives and threats.

Assumption 1 (*Honest Provider*) is important to exclude the service provider system from all security considerations. If the adversary can steal identities directly at the provider, no action taken on the client can prevent that. Even if the adversary can “only” compromise the provider instead of stealing the identities at once, the client won't presumably detect that. Thus, Assumption 1 is crucial for all following considerations.

As already described in Assumption 2 (*Genuine Internet*), if an adversary was able to spoof the whole internet, the user U would already disclose her credentials when signing up for a service. In this case, no protections on the client side would have an effect either.

On the other hand, if Assumption 3 (*Ordinary User*) is not taken into account, the proposed solution will also work for a skilled user who knows how to distinguish a phishing site from an original site (in the case of Threat 1). Regarding Threat 1, a skilled user will probably refuse to install any kind of suspicious software in the first place or recognize faked login dialogs displayed on her system. The assumption is reasonable, though, because studies show that most Internet users do not possess such knowledge and therefore it helps to prevent phishing attacks for a larger user base.

The importance of Assumption 4 (*Trustworthy Public Key Infrastructure*) becomes immediately clear when dealing with certificates that have been issued without authorization. Certificates represent the primary source of trust in a public key infrastructure. If there exists a certificate that seems to belong to a certain web site P but was issued to an adversary A instead, A can impersonate P for arbitrary users without them noticing.

If an adversary manages to steal a private key from a service provider and impersonates him in a form of redirection attack, there is nothing that the client could do to detect that apart from verifying the actual web site content. Without Assumption 5, a client cannot trust a single certificate since it could possibly be stolen.

2.2.5 Requirements

In order to achieve the security objectives introduced above, both the system S (i.e., the platform together with the operating system) and the wallet must meet several requirements. Those requirements are as follows:

Requirement 1 (System Integrity) *The integrity of security-critical components in S should not be compromised.*

If malicious software infects critical system components in S , the system is rendered incapable of providing protection against attacks and cannot meet the other security requirements. Thus, security-critical components of S have to be isolated from non-critical components. While this preserves system integrity at runtime, additional measures must be taken to protect against offline-attacks, e.g. when a different operation system is booted. A secure boot mechanism is required to prevent modification of initial system components.

Requirement 2 (Isolation) *Runtime and offline protection of application code and data in S must be assured.*

The internal state or persistently stored state of processes must not be accessible by malicious processes. Since malware may try to log the user's key strokes or modify the system configuration, applications for different tasks of the user should be separated, such that they cannot interfere with each other. The Secure Wallet should store the user's credentials securely. Thus, having a clearly security-related task, the wallet's internal credential store should never be read by applications unrelated to security tasks, e.g. a web browser or active scripts running therein.

Requirement 3 (Information Flow) *Credentials should be relayed to authorized applications only.*

Credentials must enter and leave the wallet in order to be used effectively. If credentials could not be passed on to other applications (e.g. in order to log into a web site), the wallet has no other use than storing them. Only trusted components known by the wallet or components that can identify and authorize themselves (e.g. a remote web server using a valid SSL certificate) should gain access to any of the stored credentials. The wallet should warn the user when she attempts to send credentials over an insecure communication channel (e.g. to a web site without SSL encryption). Moreover, inter-process communication should only be performed through strictly controlled communication interfaces, i.e. no bypassing of those interfaces should be possible.

Requirement 4 (Trusted Path) *No other application should gain unauthorized access to input or output of the application in S used by U to enter her credentials (i.e., the secure wallet).*

To ensure that the user enters credentials only into the wallet and no other applications can access the user's input, the system must provide a mechanism which allows separation of input channels. While the user enters her credentials, she must feel confident that those credentials are sent over a secure communication channel. A visual proof of the current channel's security state should be displayed to the user at all times.

Requirement 5 (Robustness) *Wrong configuration or setup of security-critical components of S should not have adverse effects on the security features provided.*

As pointed out in Assumption 3 (*Ordinary User*), this deliverable assumes an ordinary user without any technical knowledge to configure or understand security-critical applications or indicators. Thus, any configuration necessary to fulfil the security objective must be easy to understand and tolerate mistakes. In the context of the wallet this implies that the user should preferably only enter user credentials without having to worry about any inner workings. Because of assumption 3 (ordinary user), this requirement does not only address usability: in order to protect the credentials of unskilled users, the secure wallet *must* be easy to setup ad configure.

Requirement 6 (Authentication) *Unauthorized individuals should not be able to access the wallet's data stored by other users.*

On a multi-user system or in a multi-user environment (e.g. an open-plan office) the system must ensure that credentials stored by one user are not accessible by other users. A user has to authenticate herself before she can use the wallet and her stored credentials. The system must provide a method to let the user authenticate herself. This can either happen as part of a general user authentication or it can be specific to the wallet. Moreover, the system's security policy may define that the user has to reauthenticate herself after a specific timespan.

2.3 Related Work

2.3.1 Client-based Phishing Countermeasures

Several existing solutions add security toolbars to the browser's user interface that should warn the user of fraudulent sites by checking certain indicators like a valid SSL certificate or by maintaining a blacklist of known phishing sites. Examples of such toolbars are TrustBar [37], Netcraft Toolbar [7] or SpoofGuard [22]. While those solutions tend to lessen the success of phishing attacks, they are not sufficient to counter them completely, as a recent study shows [69]. Users fail to continuously check the displayed security indicators, since their primary goal is not security but to finish the task that led them to the phishing site. Even when the toolbars showed suspicious signs, users often did not know how to interpret them. They tend to trust the actual web site content more than the security indicators that were installed. This is especially harmful if a phishing site displays real web site content in a man-in-the-middle attack or in a picture-in-picture attack, where a picture of a browser window containing the image of a legitimate site is shown as the content of a fraudulent site [41].

Dynamic Security Skins [25] offer a better alternative in requiring the user to recognize only an image and a low-entropy password while freeing them from the burden of checking all browser security indicators, but they have two drawbacks. First, this approach is not resistant to malware attacks, since a trojan altering the browser's behavior or user interface could fake the images by generating a matching set of images itself. Second, they require a change to the web server, which significantly lowers the chance for this technique to be deployed.

A related approach was taken with Synchronized Random Dynamic Boundaries [73]. In an attempt to separate status information from web site content, the authors implemented a protection scheme that changed the border colours of the browser and its associated windows in random intervals, thereby exposing spoofed windows generated by malicious code. While this technique does not require a change to the web server, it still suffers from similar drawbacks as the dynamic security skin approach, e.g., it is vulnerable to malware attacks.

Password Managers

Password managers are readily available for many different operating systems and desktop environments. A familiar example is KWallet [59] included in the KDE Project. Passwords are encrypted and stored on the user's system and can be automatically retrieved, e.g. by the Konqueror browser, whenever the user enters a web site that the wallet has a password for. Such wallet approaches neither provide Isolation nor a Trusted Path, though.

The Web Wallet [70] separates the input of credentials and the usage of a web site by locking the HTML forms requiring credentials. After the user presses a predefined security key, the Web Wallet verifies the security properties of the target web site and displays a dialog to the user where she has to explicitly choose the destination site the credentials should be sent to, instead of displaying simple confirmation dialogs. The user can choose from a list of web sites previously stored by the wallet. While this is quite effective in countering classical phishing attacks, no protection against malware attacks is provided.

Yee and Sitaker proposed the PassPet browser extension [72] which addresses the issue of re-used passwords across multiple different web sites. It lets the user assign a *pet name* for each of her used sites and generates a new password incorporating the domain name. When the user wants to log into one of her sites, she enters the pet name into the extension and it copies her password into the designated password fields. Similar to other password manager solutions, this is effective against classical phishing but lacks resistance to certain kinds of malware attacks.

Platforms & Operating Systems

Virtualisation

To prevent malware attacks, a secure operating system is vital, and for the solution proposed in this deliverable, virtualisation is an important building block. Because of the abundance of literature on this topic, we do not provide a review of recent work here, but refer the reader to previous work, such as [33,46,57].

Cox et al. [24] introduced the Tahoma Web browsing system which added a new separate trusted software layer called browser operating system (BOS) on which browsers execute. They separated several browser instances running in the Xen virtual machine monitor [18], thereby isolating different web applications from each other. While this approach proved to counter 87% of the browser flaws and malware attacks presented in their paper, no protection against classical phishing is available. This is due to the fact that Tahoma can only provide an isolated browser instance when the user enters a phishing site but does not prevent her from actually entering her credentials. Moreover, offline modification of critical system components is possible. Thus, malware attacks targeting the BOS itself are still feasible.

While not exactly related to protection of credentials, the SpyBlock [40] browser extension employs a similar approach by using VMWare to set up a virtual machine running an isolated web browser. While this defends against certain malware attacks, it suffers from the same problem as Tahoma, i.e. no protection against classical phishing attacks is provided.

Secure User Interfaces

The security of user interfaces was examined by several papers. Epstein et al. introduced the Trusted X system [27] which aimed to replace the X windows system found on UNIX systems with a security-enhanced version. In the course of creating the EROS operating system, a secure GUI called EROS Trusted Window System (EWS) was also developed [58]. A minimum-complexity secure user interface was introduced with Nitpicker [29], which is an implementation based on an L4-microkernel [5] that adds floating labels to active views while dimming out inactive views. This allows users to authenticate the application they are currently using.

Trusted Computing

Other more general work on preventing malware attacks focuses on integrity preservation and verification. The authors of [16] construct a chain of integrity checks during the bootstrap process in an attempt to provide a *Secure Boot*. Their AEGIS system compares computed cryptographic hash values with stored digital signatures previously associated with each bootstrap component utilizing a special hardware component for reference. An implementation of this approach using a TPM was shown in [48].

A similar attempt in secure booting was realized with TrustedGRUB [10], which is an extension of the GNU GRUB bootloader. It allows detection of available TPMs and measurement of arbitrary files during the boot process.

In [56] an integrity measurement system for Linux is presented. The system measures all executable content that is loaded into the Linux system and protects those measurements using a TPM. The loaded software stack can be proved to a third party by using the TCG attestation mechanisms.

2.3.2 Server-based Phishing Countermeasures

Several server-based countermeasures attempt to extend the SSL protocol in order to effectively thwart man-in-the-middle attacks [21]. For such attacks, the man-in-the-middle creates two SSL connections, one with the server and one with the client. To prevent such attacks, the authors of [60] propose a password-based extension, while [52] utilizes trusted mobile devices for automatic verification of web sites instead of using the web browser for that task. By linking passwords to SSL sessions, Oppliger et al. [51] successfully counter man-in-the-middle attacks since passwords now contain information about the parties involved in the communication.

While these approaches are effective to counter classical phishing attacks, they provide no mechanisms for countering malware phishing attacks, since malware on the user's system can still modify the communication.

A rather different anti-phishing approach was proposed by Birk et al. In their work the authors fill collection servers of phishers with fingerprinted credentials and lure them to virtual accounts. As a result, they attempt to profile phishers to prevent future misuse of stolen credentials. Since this approach does nothing to prevent current phishing attacks, it can be rather classified as a supporting measure [20].

2.3.3 Proxy Components

In 1997, Gabber et al. proposed the Janus Personalized Web Anonymizer [30] which was an HTTP proxy that filtered incoming and outgoing traffic to anonymize the user. It was executed locally and set up as the browser's HTTP proxy. Since the SSL protocol had not been widely adopted yet, it provided no support for the HTTPS protocol.

The PwdHash browser extension [55] discussed the idea of an SSL-capable proxy that is able to forge SSL certificates on the fly to enable inspection and filtering of SSL-protected traffic. A related implementation approach is examined in [15].

2.4 The General Secure Wallet Architecture

To prevent the user from disclosing her credentials to any phishing site, a new trusted component is introduced. This component, hence called Secure Wallet, will store all of the user's credentials for web sites and will be used as a proxy for the web browser.

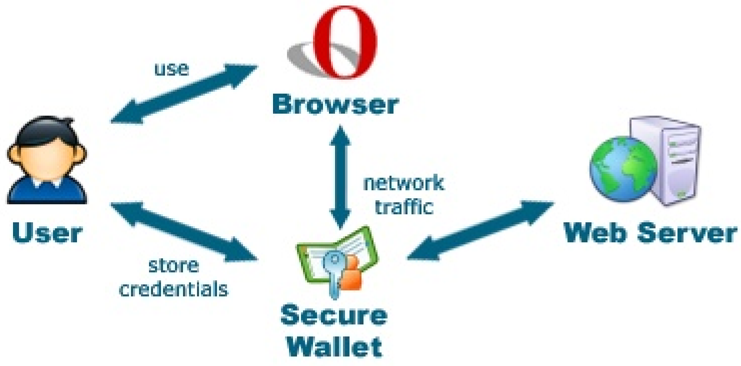


Figure 4: The Secure Wallet

The user will utilize her web browser for viewing web pages as before but will enter her passwords only into the wallet. In order to access the wallet, she needs to request a secure input path (i.e. a *trusted path*) from the system to ensure that only the wallet receives her password inputs. Whenever she attempts to log into a web site with the browser, the wallet will handle those login operations automatically by modifying the browser's requests. Thus, she never needs to enter passwords into the untrusted browser again. In fact, password fields in the browser are locked to remind her that passwords are not to be entered into the browser anymore.

By strengthening the user's passwords with random values and binding them to the domain they belong to, the wallet also prevents common password attacks and dictionary attacks. Protection against malware attacks is provided by taking advantage of trusted computing functionality and strong isolation properties of a suitable system platform.

2.4.1 Wallet Behavior

This section describes the general behavior of the wallet system from a user's perspective.

General Use

The user opens her web browser and attempts to use a web site that requires a login.

1. The user enters the web page containing the login form for the web site. The login form's password fields are disabled, i.e. the user can only enter non-sensitive values directly into the browser (see also Figure 5).
2. After entering all required non-sensitive values into the login form, the user clicks on the Submit button.
3. The browser receives the next site-specific web page indicating a successful login and displays it.

4. The user can now use the web site as usual.

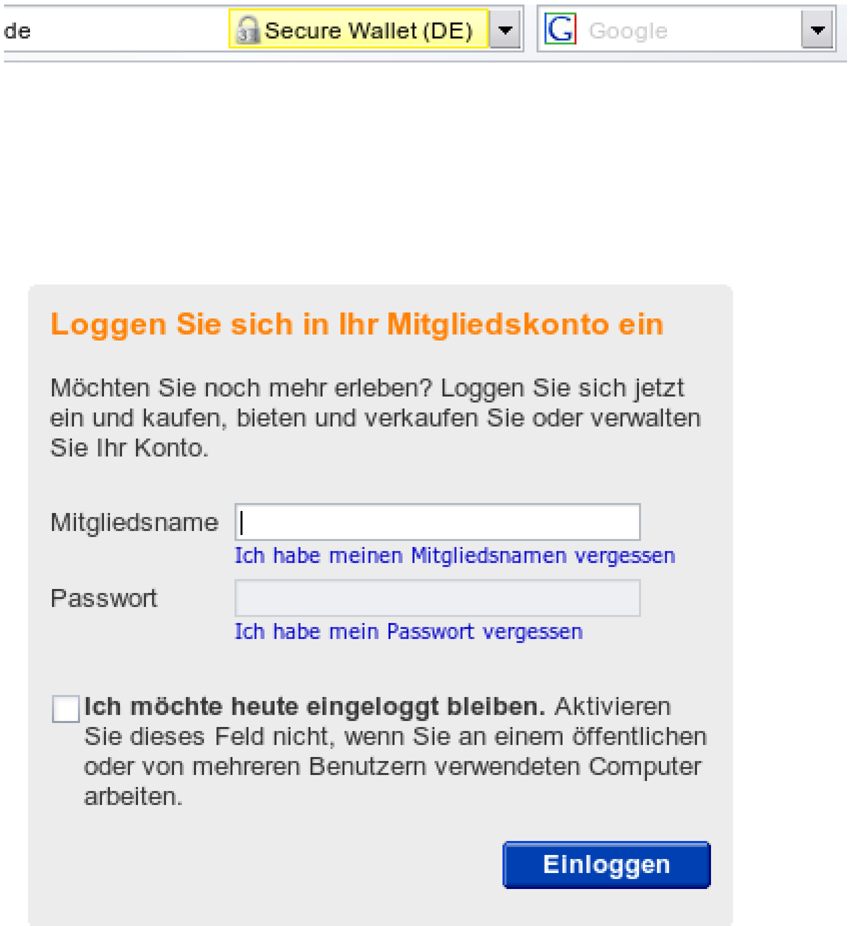


Figure 5: Password fields are disabled automatically

Web Site Setup

To enable the automatic login described above, the user must set up a web site in the wallet. Setup for an existing account occurs the first time the user attempts to use it.

1. The user enters a value for each non-sensitive field in the login form (e.g. the username) and clicks on the Submit button afterwards.
2. The wallet displays a notification message indicating that the user should initiate the trusted path to the wallet.
3. The user initiates the trusted path to the wallet and sees a dialog containing all password fields of the login form (see Figure 6).
4. The user enters her credentials and clicks on the OK button afterwards.
5. The wallet displays a security message requesting the user to initiate the password changing process for the web site as soon as she returns to the browser.
6. The user leaves the trusted path to the wallet and returns to her browser.
7. The browser displays the site-specific web page indicating a successful login.
8. The user changes her password for the web site (see below).
9. The user can now use the web site as usual and any further login attempts are carried out as described above.

Note that registering a new account for a web site works in a similar way. The user can set up the page in the wallet whether or not the registration form allows to choose the user password. If the registration form contains no password fields, some providers pre-generate the password and send it by email, i.e. web site setup occurs when the user first submits the login form and proceeds as described above. The setup process for a registration form with password fields is slightly different from the one shown above.

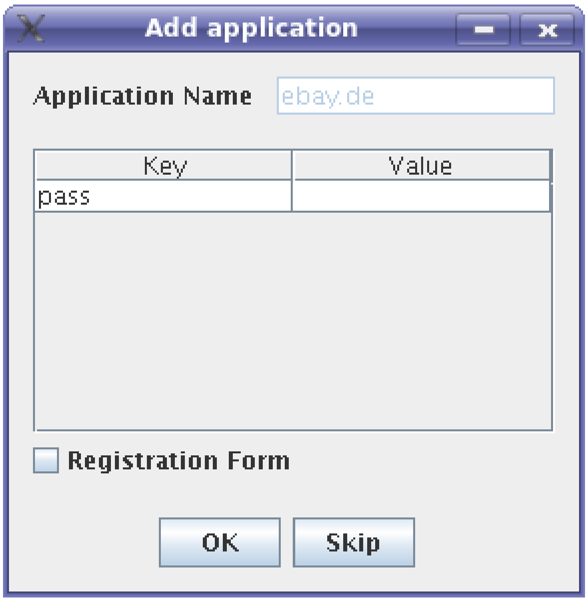


Figure 6: Setup dialog for a web site

Password Change

Changing of the user's password occurs in a similar way to setting up a web site in the wallet.

1. The user enters the web page containing the form for changing her password for the web site. The form's password fields have been disabled just like the password fields in the login form had been before.
2. If any non-sensitive values are required, the user enters them and then clicks on the Submit button.
3. The wallet displays a notification message, indicating that she should initiate the trusted path to the wallet.
4. The user initiates the trusted path to the wallet and sees a dialog containing all password fields of the password changing form. A password changing form usually contains fields for entering the old password and the new desired password.
5. For each field, the user chooses between the two options "Fill in old password" and "Generate new password" without entering passwords herself.
6. The user clicks on the OK button, leaves the trusted path to the wallet and returns to her browser.

Registration Forms

If the registration form contains fields for an initial password choice, the setup executes as described above. But when the user first submits the login form after registration, a setup dialog will be displayed once again. This dialog works just like the password change dialog, i.e. the user has to choose whether to use the stored password for the password field in the login form (which is the obvious choice in this case) or a newly generated password. After that, each subsequent login attempt will execute as described above.

2.4.2 Design and Architecture

The design and architecture presented in the following was developped to address the issues detailed in Section 2.2. Many of the general design decisions described in this section have already been discussed in [31]. The purpose of this actual work was to find a concrete approach to implement the wallet as a demo application while still adding new ideas. In the process, some original ideas were refined or adapted to accommodate the actual implementation.

Protection against Classical Phishing Attacks

This section provides a short overview of the general design decisions and their impact on usability.

Deny credential input into the browser

An ordinary user is susceptible to all kinds of classical phishing attacks. For example, a faked web site could trick her to enter her credentials for her home bank. Letting the user enter credentials directly into the browser makes it hard to counter all various attacks. Thus, the first major design choice for the wallet was to deny the user the ability to enter credentials directly into web forms. Instead, the user should enter those credentials only into the wallet.

The most efficient way of preventing the user to enter credentials into the browser is to simply lock all web forms by modifying the HTML source code and setting the disabled flag on all contained <input type=”password”> tags. The default behavior for logging into a web site is now equivalent to entering non-sensitive data and clicking on the Submit button, i.e. the user is trained to just express her intent of logging in without entering her password into the browser. All further steps required for logging in are then executed by the wallet internally. Usually that means replacing the empty web form variables for the password with the previously stored user credentials and forwarding the modified login request to the web server. Note that locking the password fields alone does not provide sufficient security since that mechanism can be countered quite easily. The next section discusses this attack more detailed.

To allow the wallet access to received web pages, it needs to be able to read and modify the communication between the browser and the remote web server. Thus, the wallet is realized as a web proxy and set up as the browser's HTTP and HTTPS proxy. To free the user of the burden to verify the browser's security indicators of web pages, the wallet will also verify those indicators automatically, e.g. by verifying the remote server's SSL certificate and rejecting invalid connections. Furthermore, the wallet will issue a warning when the user attempts to set up credentials for a site unprotected by SSL since those credentials could be stolen by an eavesdropper.

Whenever the user clicks on the Submit button of a locked login form for a web site that has not been set up in the wallet yet, the user has to enter her credentials into the wallet. Data fields required for a successful login are extracted from the submit request and compared to previously encountered login forms, i.e. the user enters a value for all fields of the login form. This is the only time when the user should actually type in her password. After the site has been set up, the password should not have to be entered again.

Change the user's passwords

Locking the login forms is just a visual support mechanism and not foolproof to prevent the user from entering credentials. An adversary could embed JavaScript code into his fake site that automatically unlocks all locked forms. Or the user could be tricked by cleverly designed malware to enter her credentials into other applications than the browser or the wallet (also confer to the next section for a discussion of malware protection). The paradigm that users should not know their own passwords prevents such attacks to succeed. Furthermore, users tend to re-use passwords for several (or even all) web sites because it is tedious or even unmanageable to memorize a new password for each new site the user registers with. This way an adversary could gain access to a whole range of web sites by phishing the password of just one site (i.e. a *common password attack*). In practice, those passwords also tend to be quite weak, mostly consisting of common words or phrases, which makes them susceptible to dictionary attacks.

Thus, the second major design choice for the wallet was to replace the user's passwords with new passwords that are, on the one hand, unique to each web site and, on the other hand, stronger than the usual user passwords. While changing the passwords automatically (as proposed in [31]) would be desirable from a security perspective (this way the user could not omit the password changing process), this approach fails due to the diversity of web site structures and technologies.

In practice, the user has to initiate the password changing process herself. Consequently, the user could decide not to change her password but let the wallet only handle her known password. A common reason could be the inability to perform a login from other computers without the wallet (at least in the current implementation). Secure migration of wallet data could improve this situation, however, even in this case, a secure wallet is needed on all platforms from which the user wants to log in. While user-initiated password change is conceptually less secure than letting the wallet change the passwords, the wallet still provides a great deal of protection against a wide range of attacks (also see the security analysis below). It should be possible to enforce the decision to let the wallet change the passwords by a suitable user training, which is a point for future work, though.

The password changing process does not require the user to type any passwords into wallet. The previously stored password is already known to the wallet and the new password is generated by the wallet and should not be known to the user. Thus, the password changing dialog just provides two options for filling in the old and the new password into the corresponding fields of the web form.

Protection against Malware Phishing Attacks

Providing isolation

A conventional system model is not sufficient to protect against malware phishing attacks. The wallet will use a modified architecture based on a security kernel in order to protect itself against malware attacks.

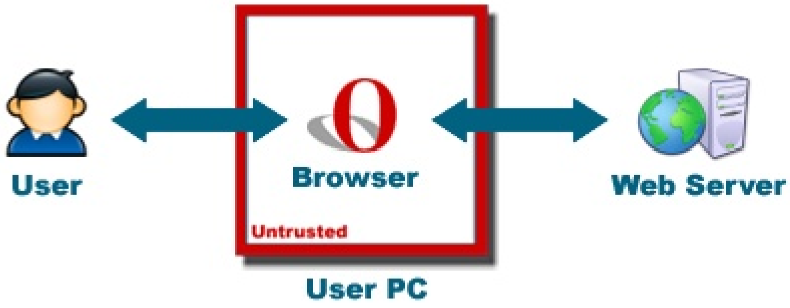


Figure 7: The Conventional System Model

Figure 7 shows the (simplified) conventional system model found in most desktop PCs with regard to internet access through a web browser. The user utilizes her web browser to connect to remote web servers and download web pages which can be viewed or modified in the browser. Everything done inside the browser could possibly affect the user's system, e.g. the user could download and execute malicious applications or active content. Such applications could launch malware phishing attacks against the user and log all her inputs to the browser or modify the browser's appearance to deceive her. Whenever the user enters confidential information, such malware could intercept it.

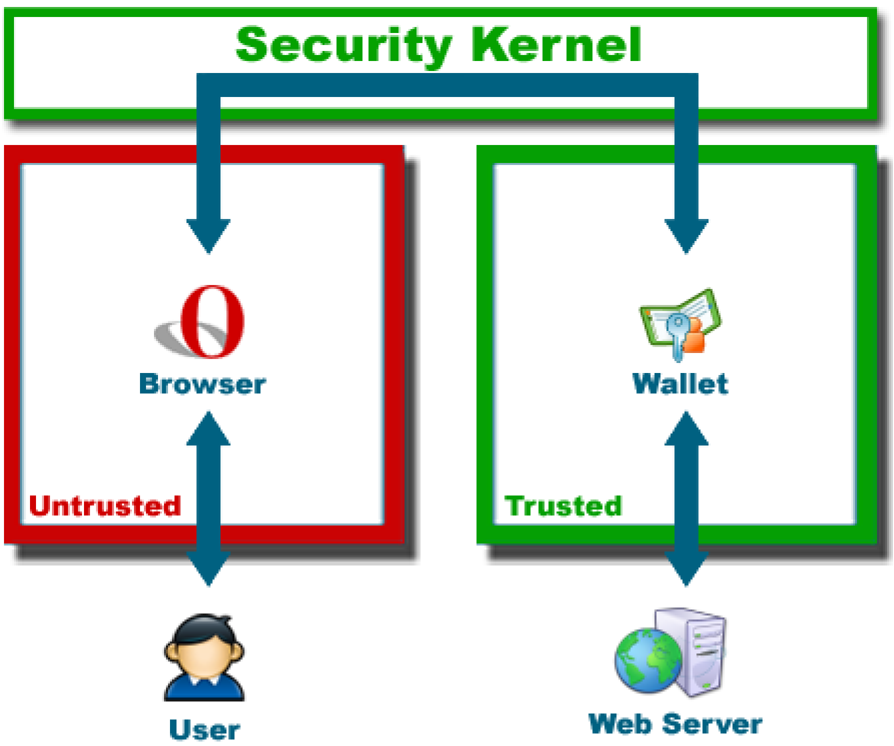


Figure 8: The Secure Wallet System Model

In order to counter those threats and achieve the security objectives described above, a modified system model will be employed as shown in Figure 8. The user PC in

Figure 7 corresponds to the red box in Figure 8 which is marked as *Untrusted*. This box, hence called *compartment*, represents a separated part of the user's system, isolated from other such compartments. Inside that untrusted compartment, all security-uncritical applications are executed, including the web browser. Applications that have an impact on security will be executed in other isolated, *trusted* compartments. No malicious software executed in the untrusted compartment should have any access to security critical applications running in other compartments. To achieve this, a security kernel is used to coordinate access between compartments and provide basic security services.

To prevent malware from gaining access to the wallet's data, i.e. to prevent malware phishing attacks, it will run in such a trusted compartment, thereby being completely isolated from the untrusted user compartment. In contrast to existing solutions implementing a password manager as a browser plugin, this approach restricts communication between the browser and the wallet to a single communication channel controlled by the security kernel. The wallet is set up as the browser's proxy server and effectively becomes the new communication endpoint, i.e. the browser is reset to its role as a graphical user interface, while the wallet handles all credentials and login operations. Thus, credentials never pass into or out of the browser and no malicious code running in the untrusted compartment can intercept them. To prevent malicious code from *using* the user's credentials, the secure wallet might be extended with transaction confirmation [40].

Trusted Path

In order to access the wallet directly for entering or retrieving credentials, the user has to initiate a trusted path which is also supplied by the security kernel. The trusted path ensures that all input and output is handled by the wallet compartment and cannot be intercepted by malicious software in other compartments. Note that this is not possible with a legacy system (e.g. Windows or Linux). Malware could forge input dialogs to imitate the wallet's user interface and trick the user into entering her credentials. Windows or Linux provide no inherent way to set up a trusted path to prevent such attacks.

We use a secure graphical user interface, called mGUI (as developped within OpenTC workpackage 5), to provide a trusted path between the user and the secure wallet. A secure attention key – in the current implementation F12 – can be used to switch between compartments. No compartment or application other than the mGUI can intercept this key. Moreover, the topmost part of the screen is used by the mGUI to display the compartment the user is interacting with (in our case, either the user Linux or the Secure Wallet compartment). No application or compartment can overwrite this section of the screen.

Trusted Computing

Virtualisation and a security kernel alone do not protect against malware attacks sufficiently. An attacker could still mount offline attacks against the wallet compartment or the security kernel itself (e.g. by booting a different operating system from CD-ROM) and try to install malicious code.

To prevent this kind of attacks, the security kernel is executed on top of hardware supporting Trusted Computing functionality based on a Trusted Platform Module. Such hardware is already shipped by several manufacturers and can be assumed to be available. User credentials are encrypted with a sealed key that never leaves the TPM and which is bound to the platform configuration at the time of sealing. If malicious software alters binaries in the chain of trust, the TPM will refuse to unseal the credentials that were stored using the original trustworthy system configuration. This way, the wallet can only access the credentials if the integrity of its compartment is preserved and the environment is secure (cf. Objective 2).

Realization

An important requirement for realizing the wallet is the preservation of existing service providers and infrastructures, i.e. they should not require changes to accommodate the wallet. Without this requirement, the wallet's chance of being deployed and commercially used would be very low. Where changes to the user's system have to be made, they should not require high costs for the provider and the client.

The wallet itself is written in Java and is as such platform-independent. In order to filter HTML web pages and HTTP requests, the Paros web proxy [8] is used, which is also a Java application. Both components in conjunction provide protection against classical phishing attacks and can be used on an arbitrary platform supporting Java.

To protect against malware phishing attacks, the system architecture in Figure 8 is realized by using the system developped within OpenTC workpackages 4 and 5. The framework uses virtualisation techniques to provide several instances of legacy operating systems running concurrently but each with its own set of virtual resources. Each instance will represent a single compartment, although a compartment generally does not need to include a complete operating system to work. The ability to use existing operating systems supports the preservation of existing infrastructures. Thus, the untrusted user compartment will contain a legacy operating system (i.e. L4Linux [4] in the case of this work).

2.5 Security Analysis

This chapter discusses all attacks that might be mounted against the Secure Wallet or any of its associated components or procedures. It will show that all threats introduced in Section 2.1 can be countered effectively with the wallet. As already pointed out before, there are two categories of phishing attacks: classical phishing attacks and malware phishing attacks. Both categories will be handled separately since they require different protection mechanisms.

Figure 9 shows an abstract overview of the system model employed by the wallet. The four involved entities are the user U, her system S, a remote web server P that U wants to communicate with and a phishing server A set up by an adversary to gain access to U's credentials. Several communication channels exist between those entities. The channel US_{in} is the user's input channel into S while she receives output over the channel US_{out} . SP_{in} is used by S to send HTTP requests to P and returned HTML pages are received over SP_{out} . The adversary uses SA_{out} to send fake messages or emails to S and receives HTTP requests from S on SA_{in} .

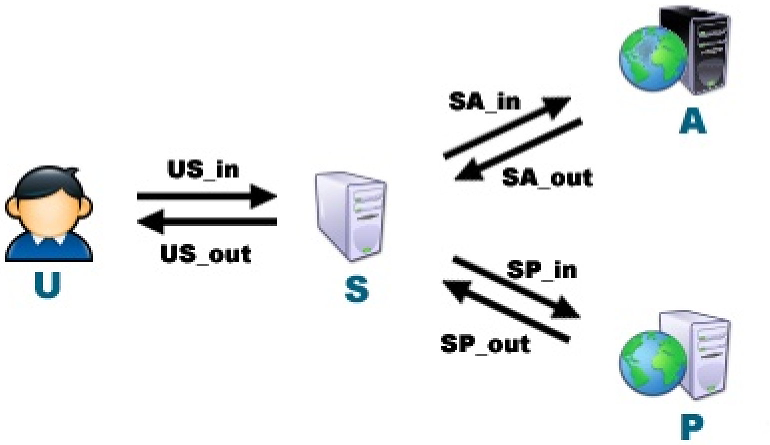


Figure 9: Simplified system model for the Secure Wallet

2.5.1 Attacks

The adversary can either directly target one of the entities or mount an attack on one of the communication channels. He can especially eavesdrop on and modify all of the network channels but cannot directly attack the user channels US_{out} and US_{in}. Attacks on an entity always use one or more of the illustrated channels to send and receive messages. Furthermore, the phishing server A can be an arbitrary machine on the internet except S and P and is just noted as a single machine for convenience.

Above, a list of potential threats for the user's credentials was given. Each of those threats corresponds to a specific class of attacks in the system model shown above. Threat 1 (*Identity Theft through Faked Web Sites*) is an attack directly on U. Threat 2 (*Malware Identity Theft*) can target the entities U (e.g., by showing a message that tricks the user into revealing her credentials) and S, the network channels and indirectly the user channels as well. Thus, it is the most extensive threat in the system model. Threats 3 (*Credential Theft*) and 4 (*Configuration Modification*) only target the entity S, while Threat 5 (*Fake Dialog Attack*) targets both entities U and S.

To show that those threats are ineffective and the security objectives have been met, it is sufficient to show that attacks on each channel or entity are countered by the wallet.

Attacks on U

Attacks on U in the scope of Threat 1 can be categorized as classical phishing attacks, which are a subclass of social engineering attacks where A sends fake messages to U in order to trick her to disclose credentials. For example, A creates a fake email that imitates a mail originating from P but contains a link to A and uses SA_{out} to deliver it to S. The user receives and reads that email using the channel US_{out} and (if deceived by it) acts upon the email using the channel US_{in} to access A, i.e. S uses SA_{in} for an HTTP request instead of SP_{in}. Other attacks on U involving the entity S as well are discussed in the next paragraph. An analysis of classical phishing attacks is provided below.

Attacks on S

Attacks on S attempt to gather or steal credentials on the user's system instead of trying to trick U to disclose credentials to a phishing site directly. Such an attack might either occur offline, e.g. by attempting to modify the system or to read the credential store directly. Or it might occur online, i.e. by actively installing malicious software on S while the system is running. Installation of such malware can occur by exploiting a known security weakness of an application running on S or the adversary might employ additional social engineering attacks to trick U to install the malware willingly.

Depending on the kind of malicious software, it might attack the channel US_{in} to eavesdrop on credentials entered by the user (keylogger), or it might attack the entity U and the channel US_{out} by displaying a fake dialog where the user enters her credentials, thereby redirecting US_{in} as well (fake dialog attack). Alternatively, the malware can target a specific system component or a communication channel between two of those components. Those online attacks, and also offline attacks, will be discussed in detail below.

Attacks on P

The adversary can also mount an attack on the remote web server P by breaking into the system in order to steal credentials directly from P's database. Since this work focuses on client-side defence against phishing attacks, this kind of attacks is out of scope and will not be discussed further.

An even stronger attack is setting up an own web server (independent of P) and letting the user register to it. This way the adversary either receives the original user password (possibly re-used at P as well) or at least a wallet-generated password derived from this original password. With that information, A can mount a dictionary attack against the user's password and attempt to guess the password used for P. Attacks against the user's passwords are discussed below.

Attacks on the channels

The channels US_{in} and US_{out} cannot be attacked directly by the adversary. He can only attack them indirectly through attacks on one of the endpoints of those channels, i.e. by attacking U or S. Those attacks have already been described above.

In contrast, A can attack the channels SP_{in} and SP_{out} directly since A can by definition be any machine on the internet apart from S and P. The adversary might either try to eavesdrop on those channels in order to passively read transmitted credentials, or he could modify the communication. In addition, he could redirect the channels so that SP_{in} is replaced by SA_{in} and SP_{out} by SA_{out} without S noticing the redirection.

Eavesdropping on and modification of an SSL-protected channel can be assumed to be unfeasible as long as the SSL protocol and its implementation are secure. Unprotected channels could be tapped at any point during the transport, though, and thus they are inherently insecure. As a result, if the user transmits credentials over a plain HTTP connection, the adversary can eavesdrop on those credentials, regardless of whether she uses the wallet or not. But even if the adversary gains the credentials for P in this way, the wallet helps to confine the loss of credentials because each web site has its own unique password generated by the wallet previously. A cannot gain access to other servers than P with the stolen credential even if the user initially used the same passwords for different web sites.

A redirection of the channels can be seen as a form of classical phishing attack because even if the user does not notice that the channel has been redirected (e.g. she enters the URL of P into her browser), she still expects to see the familiar web pages of the original web server P, i.e. the adversary needs to fake the web site just like in a normal classical attack. Therefore, redirection attacks are discussed as part of the classical phishing attacks below.

2.5.2 Assumptions

Besides the assumptions introduced above, the security analysis suggests two additional assumptions. On the one hand, we assume that the user is trained to recognize the system's trusted path indicator (e.g. a red or green bar at the top of the screen) and acts upon it accordingly, i.e. she does not enter any confidential information if the trusted path indicator is red. On the other hand, we assume that the user always changes the password for a web site after she has set it up in the wallet, i.e. she does not know the password thereafter.

2.5.3 Protection against Classical Phishing Attacks

Classical phishing attacks are based on the user U attempting to access a web site on web server P but instead arriving at a rogue web server A created by an adversary. U may arrive in one of two ways at A. Either she enters the address of the fake site directly into her browser or she enters the address of P and is redirected to the phishing server A by a redirection attack. In both cases she is presented a faked web site and might be persuaded to enter her credentials for the original site that has been faked. The difference between those two attacks is in the way the wallet handles them. In order to meet Requirement 3 (*Information Flow*) with regard to classical phishing attacks, it is sufficient to show that the adversary cannot gain access to the user's credentials if she uses the wallet.

Fake Site Attack

If the adversary uses a faked SSL certificate, the attack is detected because the wallet verifies all received SSL certificates and rejects sites with invalid or faked certificates. If he uses a legitimate SSL certificate $cert_a$ issued to the fake host address or uses no SSL at all, the web site is handed over to the browser for display but the password fields of the login form are disabled. According to Assumption 3 (*Ordinary User*), we assume that U does not detect the phishing attempt by verifying the browser's security indicators. Thus, the user clicks on the submit button to log in. Now the attack is also detected because the wallet has stored credentials $C_{u,p}$ for the host address of P and not $C_{u,a}$ for the host address of A. Therefore, the wallet now runs the setup for A instead of using the credentials of P to log in.

Even if U decides to run the setup for A using the credentials $C_{u,a}$, the adversary will still not gain the credentials $C'_{u,p}$ because the wallet updates the entered credentials to $C'_{u,a} \neq C'_{u,p}$. The hash function used to generate $pw'_{u,a} \in C'_{u,a}$ is a one-way function and thus, a computationally bounded adversary is not able to deduce $pw'_{u,p} \in C'_{u,p}$.

Unlocked Password Forms

The wallet locks the password fields of each web form by inserting the disabled attribute into the corresponding <input> tags. Thus, the user can no longer enter values and cannot submit the form with valid content. Yet, it is also easy for an adversary to counter this. Each element of an HTML form is exposed through the Document Object Model and has a disabled property. This property can be accessed with JavaScript and edited while the page is displayed. Thus, an attacker who is aware of the wallet and wants to counter the wallet's locking mechanism after it has locked the password fields for his phishing site, could include a script that unlocks all login form elements either in the OnLoad event or after some arbitrary timespan. Since there is an almost endless number of possibilities for the attacker to execute this JavaScript code, it cannot be countered effectively. Basically every transformation the wallet applies to the login form could be reversed with JavaScript code. Even if the wallet removed the form elements completely, they could be added dynamically at runtime again, provided that the attacker knows the wallet's transformation algorithm. Besides using JavaScript, the adversary could also employ malware installed in the browser compartment to unlock locked password forms, i.e. this attack is not confined to a JavaScript attack. An adversary targeting users with security knowledge far below the average could even decide to include simple text fields instead of password fields into his login forms so that the wallet would not lock them in the first place.

As a result of all those considerations, the locking of password forms is not a security enhancement since there is no way to guarantee that a form will stay locked. The mechanism merely serves as a reminder for the user to use the Secure Wallet and not the web form itself to login. If the adversary manages to unlock the password form, the user might be tempted to enter her credentials into it, especially if she is not yet accustomed to using the wallet. Because she does not know $pw'_{u,p}$, she enters $pw_{u,p}$ into the password field and sends it to A. Thus, the adversary does not receive the current credentials for P but outdated ones. If U uses $pw_{u,p}$ for other web sites not protected by the wallet as well, A might gain access to those sites, but the main objective being the preservation of the confidentiality of the user's credentials is fulfilled with respect to P and other sites protected by the wallet.

Redirection Attack

A redirection attack in the wallet model (see Figure 9) is an attack that attempts to replace the channels SP_{in} and SP_{out} with SA_{in} and SA_{out}, respectively. Since the wallet uses the host name of a web site to find the corresponding stored credentials, only redirection attacks that preserve the original host name of P are relevant to this discussion. A common example for this kind of attack is the DNS spoofing attack [19]. Other forms of redirection attacks targeting lower layers of the TCP stack, e.g. ARP spoofing [68], have the same result as far as the wallet is concerned, i.e. the traffic is routed to the rogue server A while the wallet receives P as the host name. Note that although this attack is discussed as part of the classical phishing attacks, it can also appear as a form of malware phishing attack if the redirection occurs inside of the user's machine. The implications are the same, though.

If the adversary uses a legitimate SSL certificate $cert_a$ issued to the fake host name

A, the attack will be detected immediately because the host name in the certificate does not match the original host name of P. All other cases where the adversary presents a certificate with the original hostname are countered by comparing the digital fingerprints of the stored certificate and the certificate received during the current SSL handshake.

There are several possible cases where the fingerprints do not match. If the adversary manages to obtain a valid certificate for the host address of P in spite of Assumption 4 (*Trustworthy PKI*), the attack is detected as long as the received certificate contains another public key than the stored certificate. Should the adversary be able to steal the private key of the stored certificate, the attack will not be detected. It can only be detected if the key has been revoked because the wallet should check certificate revocation lists (CRLs) every time the fingerprints do not match. The case where the adversary can steal an active, unrevoked key is excluded by Assumption 5 (*Private key protection*), though.

As already pointed out above, the client is unable to detect a redirection attack if the connection is unprotected. Thus, the wallet will disclose the user's credentials if the adversary redirects a plain HTTP connection. Protecting against this kind of attacks is out of scope of this work. A service provider can provide protection by using the SSL protocol.

2.5.4 Protection against Online Malware Phishing Attacks

A malware phishing attack attempts to steal credentials on the user's system, preferably without the user noticing the theft. Installation of malware can occur in two different ways. Either it may be installed *online*, i.e. while the machine is running, or *offline*, i.e. an adversary boots another operating system (e.g. from CD-ROM) and installs the malware. This section deals with the online attacks. Offline attacks are discussed in Section 2.7.5.

Confinement to the Untrusted Compartment

Most of the user's work takes place in the untrusted compartment. This untrusted compartment represents the legacy system, i.e. a system without the security kernel and the wallet. Thus, malware can be installed in this compartment in the same way as on a legacy system. To meet Requirement 1 (*System Integrity*), it must be shown that online malware attacks can only affect the untrusted compartment and cannot be installed outside of this compartment.

The security kernel and all other compartments are not designed to offer any mechanisms to install software at runtime. They are installed once and need not to be changed afterwards. Ideally, the security kernel has been formally verified and contains no security vulnerabilities. Since the kernel is based on a microkernel, it has a very small size, which makes it easier to formally verify any security properties. Moreover, it was developed with special care and focused on the security tasks it provides. Thus, it will statistically have less security vulnerabilities and a smaller attack surface than legacy systems and hence, it is reasonable to assume that no malware can successfully target the kernel itself.

Assuming that the security kernel provides isolation for the different compartments (i.e. it meets Requirement 2 (*Isolation*)), malware installed in one compartment cannot affect another compartment in any way. If the untrusted compartment contains any malware, it has no effect on the wallet compartment or the virtual network compartment. Although the current implementations for those trusted compartments use a full Linux system including the kernel and numerous libraries and are as such vulnerable to various attacks, they are just prototype implementations. A release implementation could realize those compartments as native L4-services. This would reduce their size and lower their attack surface significantly and we can assume that they cannot be direct malware targets just as the security kernel itself.As a consequence, we can assume that the proposed system architecture only allows installation of malicious software in the untrusted compartment and thus meets Requirement 1 (*System Integrity*). The concrete attacks against the untrusted compartment are discussed in the next section.

Attacks against the Untrusted Compartment

Numerous malware attacks against the untrusted compartment are imaginable, since this compartment represents a legacy system. Therefore, all attacks targeting a legacy system could be mounted against the untrusted compartment as well. In fact, we can assume that the whole compartment can be modified by an adversary in any way. Figure 10 shows that the untrusted compartment has two primary communication channels, $C_{u,utrust}$ being user input and output and $C_{utrust,kernel}$ being the connection to the security kernel. To prove that the adversary can still not gain access to the user's credentials, it is sufficient to show that the credentials are (i) never sent over $C_{utrust,kernel}$ and (ii) never entered directly into the untrusted compartment over $C_{u,utrust}$.

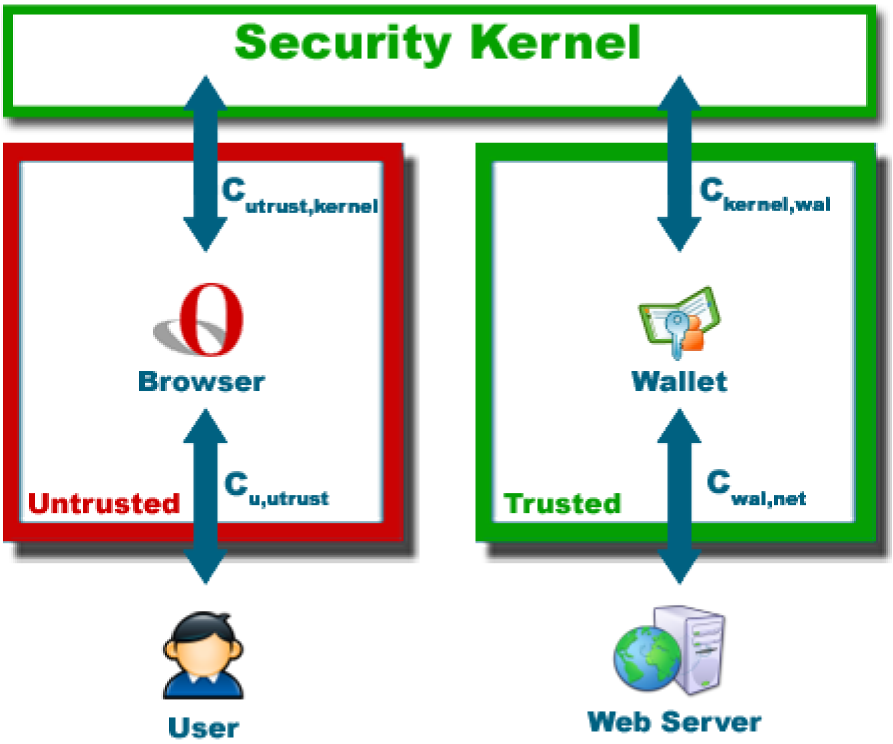


Figure 10: The Internal Communication Channels

The wallet discloses the user's credentials only as part of a HTTP POST request, i.e. the variables contained in the request body are replaced with stored values. This POST request, which is completely processed in the trusted wallet compartment, is never sent back to the untrusted compartment but directly to the intended remote server using $C_{wal,net}$ or to another trusted compartment dedicated to network access using $C_{kernel,wal}$. This also holds true if the POST request never reaches the wallet, e.g. if the adversary prevents the requests from being sent to it. In this case the request is never modified by the wallet and can receive no credentials. As a result, credentials are never sent to the untrusted compartment or even forwarded through it. No modification of the untrusted compartment can affect the wallet or the network connection in such a way that the adversary receives the user's credentials over $C_{utrust,kernel}$.

Nevertheless, the adversary can attempt to receive credentials from the user directly. Since we assume that he can modify the untrusted compartment in any way, he can also fake any user interfaces and persuade the user to enter credentials using $C_{u,utrust}$. But even if the user is tricked by those faked user interfaces, the adversary still receives no current credentials because the user does not know them anymore. When the user set up the web site in the wallet, she also lets the wallet change her password afterwards, i.e. the only credentials she actually knows of are the outdated ones she used before. Thus, current credentials can never be sent to the untrusted compartment using $C_{u,utrust}$.

In the following paragraphs some attacks that have been effective on legacy systems in the past are discussed. These are (i) the installation of a key logger and (ii) the display of fake dialogs to trick the user to enter her credentials. A third category of potential attacks covers attacks on the browser to (iii) unlock forms previously locked by the wallet or to (iv) remove the wallet's proxy assignment completely.

Trusted Path

Both the installation of a key logger and the display of a fake dialog are uncritical if Requirement 4 (*Trusted Path*) is met and Assumption 6 (*Single Credential Storage Mechanism*) holds true. Thus, for both cases it is sufficient to show that the trusted path requirement is satisfied.

Assuming that the user enters credentials only into the wallet she has to somehow access it. Since it resides in a separate compartment, in the current implementation the user has to press the F12 key to switch compartments. The F12 key is intercepted by the SecureGUI and cannot be received by any compartment. Therefore, no malware in the untrusted compartment can prevent the user from switching compartments. After the user has switched to the trusted wallet compartment, the untrusted compartment is made inactive and the wallet compartment is now the active one. The SecureGUI asserts that all user input is received only by the active compartment, i.e. the malware in the untrusted compartment never receives any keyboard events as long as the untrusted compartment in inactive. As a result, a keylogger never gains access to any credentials entered into the wallet.

The display of faked dialogs, which is an attack commonly employed by trojan horse programs, can be constrained to dialogs resembling the wallet interface because of Assumption 6 (*Single Credential Storage Mechanism*). When malware displays a dialog imitating the wallet in the untrusted compartment, the trusted path indicator still shows a red bar at the top of the screen and clearly indicates that entering credentials is not secure. A trained user will notice this and be suspicious of the unexpected dialog because she knows that she normally has to press the F12 key to invoke the wallet and that the wallet does not share its screen with her untrusted applications. Moreover, the Linux running in the untrusted compartment has no access to the trusted path indicator and therefore, no malware can paint over the indicator or even read its state because it resides beyond the accessible screen region.

Configuration Modification

By using the Secure Wallet, two new potential threats specific to the implementation arise. Malware can try to re-enable locked password fields after they have been locked by the wallet and it can attempt to disable the wallet at all. The first attack was already discussed in the course of the fake site attack. Independently of the method with which the adversary unlocks the password fields, i.e. by using JavaScript or by installing malware on the user's system, he cannot gain current credentials for the site he is phishing passwords for.

The second attack attempts to prevent the wallet from protecting the user's credentials by removing the browser's proxy assignment. As a result, the wallet no longer receives the browser's HTTP requests and can neither lock password fields nor perform automatic login operations. The user will eventually notice that the wallet is inactive. Assuming that she does not know how to repair this issue, she will not be able to log into sites for which the password change has been completed because she does not know the passwords. The adversary does not learn her current credentials but at most her outdated ones if she tries to log in with those credentials.

An advanced implementation might even redirect traffic to the wallet compartment independent of the actual source. This would render a manual proxy assignment in the browser unnecessary and the adversary could not disable the wallet in this way. However, for this to work, the wallet compartment must be able to determine for all network traffic if it should be allowed or denied, in order to prevent the adversary from circumventing the wallet. Future research is needed to decide if such an approach can be used to support arbitrary web-based logins without giving the adversary the possibility to disable the wallet, e.g., by tunneling web traffic through other protocols.

2.5.5 Protection against Offline Attacks

Offline attacks denote attacks where the user's system S is not running and the adversary has physical access to it. For offline attacks, we can assume that booting the machine himself and trying to impersonate the user is ineffective for the adversary. However, he can still try to attack the hardware or modify the system in order to break its security.

General Attacks

If the adversary has physical access to the system, he can directly attack a hardware component. He might either replace or modify a component or just take the credential store (i.e., the hard drive) with him and try to read it out on a less secure system.

Replacement or modification of a security-relevant component will be detected during the next boot process since the TPM will yield different hash values in its PCR registers and thus not be able to decrypt the credentials sealed to the previous hardware configuration.

Due to the same reason, reading the credential store directly fails, e.g. by removing the hard disk and mounting it in another system. The credentials are sealed to the hardware and software configuration present at the time of storing. Thus, without restoring the initial configuration which in turn also restores the system's security properties, the credentials cannot be unsealed.

The key used to encrypt the credentials is stored in the TPM permanently. Thus, a conceivable attack is to attack the TPM itself in order to read out the encryption key. This attack is out of scope of this work, though. The TPM has to provide built-in protection mechanisms against this kind of attacks.

Offline Malware Attacks

Besides attacking the hardware, the adversary might also attempt to modify the software configuration of the system. Due to the system's protection mechanisms this is only possible in very limited ways while the system is booted. Thus, it might be more feasible to modify critical components (e.g. the security kernel or a trusted compartment) while it is offline. A simple way to do this would be booting the machine from an alternative medium, e.g. from CD-ROM, and accessing and modifying the hard drive afterwards.

Nevertheless this attack is also detected or at least ineffective depending on the modifications applied. If the adversary modifies components inside of the untrusted compartment he gains nothing as described above. If he modifies components that are part of the trusted computing base, e.g. the security kernel, this attack will be detected as described in the previous section. The TPM will compute different hash values while booting and not be able to unseal the user's credentials since they were encrypted with a different system configuration. Therefore, offline attacks are also insufficient to gain access to the user's credentials.

2.5.6 Attacks on the Passwords

Common Password Attack

Instead of attacking the user or her system directly, the adversary may also attempt to guess her password. Most users choose weak passwords or re-use a single password for several or even all web sites. The adversary can capitalize on that by phishing the password for a low-security site (e.g. a site without SSL protection) and testing this password for the user's other accounts on high-security sites. This is also known as a *Common Password Attack*.

Without the wallet, this attack has a high chance to succeed. By using the wallet, however, the user can no longer re-use a single password for multiple sites because the wallet changes the user's password and incorporates the domain name and a random value into it. Thus, even if the user still uses the same password for several sites, the wallet will generate a distinct password for each site and provide an effective countermeasure against the common password attack.

Dictionary attack without information

Still, the adversary can attempt to mount a dictionary attack against a phished password because each wallet-generated password is a hash of the original user password:

$$pw'_{u,p} = hash(pw_{u,p} : domain(id_p) : rand) \qquad (2.1)$$

In order to perform the dictionary attack, the adversary has to guess $pw_{u,p}$ as well as $rand$ while the domain name is known to him. $rand$ is an x bit salt value and it will likely make guessing the password infeasible if x is large enough. The next paragraph discusses the recommended value for x.

Dictionary attack with an old password

There are some scenarios in which the adversary may get hold of an old user password $pw_{u,p}$. For example, the adversary might have managed to disable the wallet by removing the proxy assignment in the browser as discussed above. When the (unskilled) user now attempts to log into the adversary's phishing site, she might be tempted to enter her old password.

If the adversary is in possession of an old user password $pw_{u,p}$, the dictionary attack becomes more feasible because the only unknown value in equation (2.1) is now $rand$. Since it is a random value, the adversary has to mount a brute force attack on it. To prevent him from finding the correct salt value, it must be large enough to make a brute force search infeasible.

A modern dual-core CPU is able to compute several million SHA-256 hashes per second [44]. Assuming an average of 2^{22} hashes per second, which corresponds to about 2^{38} hashes per day and CPU, a brute force search for a salt value with 64 bits would take about 2^{18} years on a single CPU. Even with clustered processors this should be sufficient to prevent dictionary attacks using a known original password. The time required for a dictionary attack can also be further increased by slowing the hash function, a technique described in [35].

2.5.7 Discussion

Assumptions

Above, two additional assumptions were made for the security analysis. In practice, it is not clear whether those assumptions actually hold true or whether the user acts against them. Still it can be argued that the assumptions are weak compared to those assumptions usually applied when not using the wallet.

The first assumption, being that the user recognizes the simple trusted path indicator and acts upon it accordingly, is quite realistic and much weaker than the assumption that the user is able to decide whether input into an application is secure, e.g. whether a dialog displayed to her belongs to malicious software. Of course, this assumption has to be confirmed by a representative user study.

The second assumption is probably less realistic in practice. Users might be tempted to keep possession of their passwords to be able to log into web sites from other machines without using the wallet. Yet, this decision is prone to several attacks described in the course of the security analysis. For example, the user might ignore the trusted path indicator and enter her credentials into a fake dialog or the adversary removes the wallet proxy assignment and unlocks all browser forms so that the user is tempted to log in using the traditional way.

All of those cases lead to disclosure of the user's credentials if the user has not changed the passwords before. This shows the importance of a thorough user training. It is important for users to realize that not letting the wallet change their passwords leaves room for potential phishing attacks.

Metatag Approach

If the assumption that users let the wallet change their passwords turns out to be too strong in practice, additional steps must be taken to automate the password changing process so that the user cannot avoid it. Providing metatags is a possible solution for this problem. If the wallet has enough information about a web site to trigger the password changing process itself, it can be integrated into the setup process and the user has no choice but to let the wallet change the passwords.

While this is the optimal solution from a security standpoint, this approach has the significant drawback to require specialized metatags for each supported web site. Consequently, if the wallet has no metatags for a given web site, it cannot store the user's passwords for it and offers no protection at all.

Password Knowledge

This work generally assumes that the user does not know the passwords for her web sites after the wallet has changed them. Although the wallet does not initially display the changed value, the user could still use the wallet's GUI to find out the new password. Thus, certain classical phishing attacks might still be feasible at first thought.

Yet, it can be argued that the passwords generated by the wallet are hard to remember. Most users re-use their (often simple) passwords across many different sites (the author cannot even absolve himself from that). This shows that remembering many different passwords is hard for most users. Taking into account that the wallet makes full use of the available password length and generates pseudo-random passwords (e.g. Xc7f3h2IK12u instead of mypassword23), it can be assumed that most users are not able to permanently remember the wallet-generated passwords even if they explicitly review them. However, as long as the user can still view the password, it is impossible to prevent the disclosure completely (e.g., apart from memorizing passwords, the user could also write them down).

2.5.8 Other Attacks

Transaction Generators

Due to the automation of login operations, the user loses a certain degree of control over the browser's actions. A modified browser, aware of the wallet, could take advantage of the fact that no user interaction is necessary to log into a specific web site and carry out an arbitrary amount of transactions impersonating the user without her noticing it. Such attacks called *Transaction Generators* have already been described by Jackson et al. [40].

This kind of attacks is not specific to the Secure Wallet but rather a generic problem with transactions that can be committed without user interaction. A user without the wallet is susceptible to this attack after having logged into a web site in the same way as a wallet user. Therefore, it is out of scope of this work to present a countermeasure. Transaction confirmation (as described in [40]) could be implemented in addition in the wallet compartment.

2.6 Architectural Overview

In this section, we sketch the architecture on a PC, describe an architecture for a mobile platform, and propose a “hybrid” architecture for a demo-prototype, where functionalities are split between a PC and a mobile (X-GOLD™ 208-based) platform.

Section 2.7 will then discuss the X-GOLD™208-based demonstrator prototype in more detail. General information on this mobile platform can be obtained in [74].

For the PC-based prototype, the Security Services developed within OpenTC Workpackage 5 could be re-used.

2.6.1 Architecture on a PC

shows the architecture, as it is currently implemented on PC hardware.

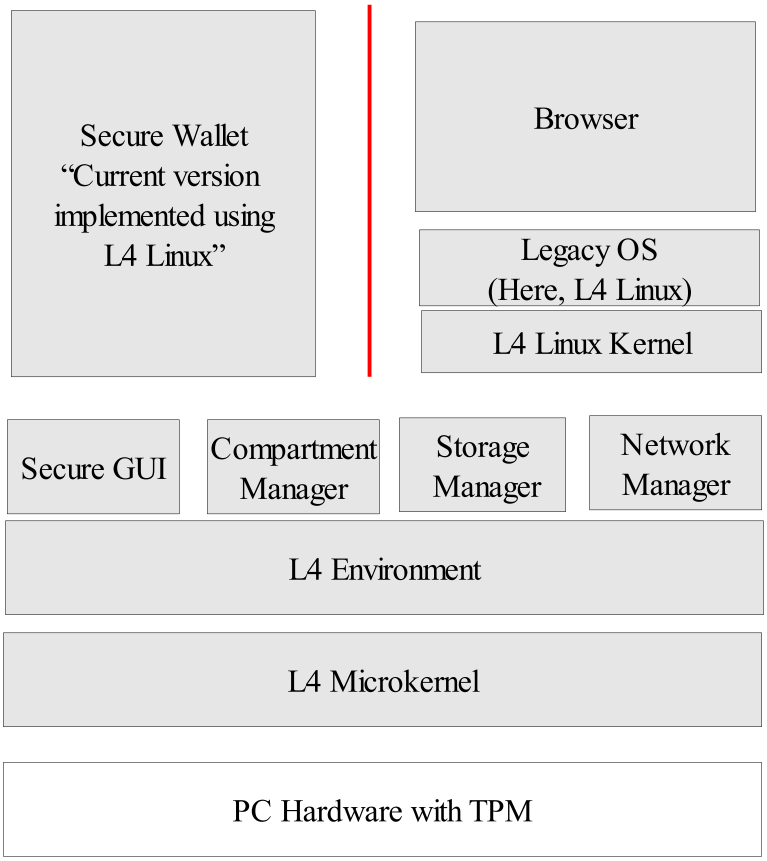


Figure 11: System architecture for PC hardware.

We use TrustedGRUB as bootloader. TrustedGRUB measures the microkernel, L4env and the security services (Compartment Manager etc.), and extends the PCRs.

The Compartment Manager measures and starts the Secure Wallet and other L4-Linux compartments. These measurements are not written into PCRs, but stored in memory only. In this manner, the Compartment Manager extends the authenticated boot. To verify the integrity of a compartment, a verifier has to rely on the conventional TCG chain of trust to verify the basic system (up to the Compartment Manager), and additionally, the measurements of the compartment (as provided by the Compartment Manager) have to be checked.

2.6.2 Storage Manager

This section describes the implementation of the Storage Manager *SM* that enables other compartments to persistently bind their local states to their actual configuration while preserving integrity, confidentiality and freshness. A prototype of the Storage Manager has been implemented within OpenTC Workpackage 5, which is re-used here. The freshness requirement is not important for the secure wallet use case because replay attacks are not an issue. However, in other use cases, freshness may be required. Thus, it should be considered in the design of the Storage Manager as a generic security service. We first give an short overview and then describe the realisation of secure storage that will be extended by an additional freshness layer to provide *trusted* storage. At the end of this section, we briefly describe the protocols for the initialisation of *SM*, as well as for storing to and loading from trusted storage (using *SM*).

Overview: The Storage Manager is invoked by a compartment to store a data object persistently preserving confidentiality and integrity – optionally with additional restrictions *rest* (e.g., freshness, certain user id). *SM* invokes the Compartment Manager to retrieve the actual configuration of the respective compartment and to bind the data object to that compartment configuration *cmp_conf*. *SM* creates/updates a metadata entry for the corresponding data object with the data object identifier d_{ID}, its freshness detection information *f*, i.e., the actual cryptographic hash value, and all relevant access restrictions *rest*[3] with its index i_{SM}. *SM* extends the data object with integrity verification information, synchronises its monotonic counter c_{SM}, encrypts the data object and the updated index using the key k_{SM} and writes it on untrusted persistent storage. Since i_{SM} is the base of security for *SM*, i_{SM} is sealed to *SM*'s configuration via the sealed key k_{SM}. Thus only the same, trusted Storage Manager configuration is able to unseal and use k_{SM} again. On a load request, *SM* again uses the Compartment Manager to compare the invoking compartment configuration with the one of the compartment that has stored the respective data object before. On a successful verification, *SM* reads and decrypts the data object from the untrusted persistent storage and verifies its integrity. Before the data object is committed to the requesting compartment, *SM* also verifies possibly existing additional restrictions such as freshness or a certain user id.

Trusted Storage: *SM* offers trusted storage to bind the data of a compartment to the compartment while preserving integrity and confidentiality. Therefore, *SM* uses a cryptographic hash function[4] to calculate the data object's hash value and a symmetric cipher[5] with its internal cryptographic secret key k_{SM} bound to its configuration to encrypt data objects together with their actual hash values. Then *SM* writes the encrypted blob to untrusted persistent storage providing at least availability. The key k_{SM} in turn is sealed to the configuration of *SM,* using functionality of the TPM so that only the same, trusted Storage Manager configuration is able to unseal and use the key again. During a load operation, the data object is decrypted and verified for integrity using the appended hash value.

3 Further access restrictions can be a certain user id, group id or date of expiry.
4 Our implementation currently uses SHA-1.
5 Our implementation currently uses AES.

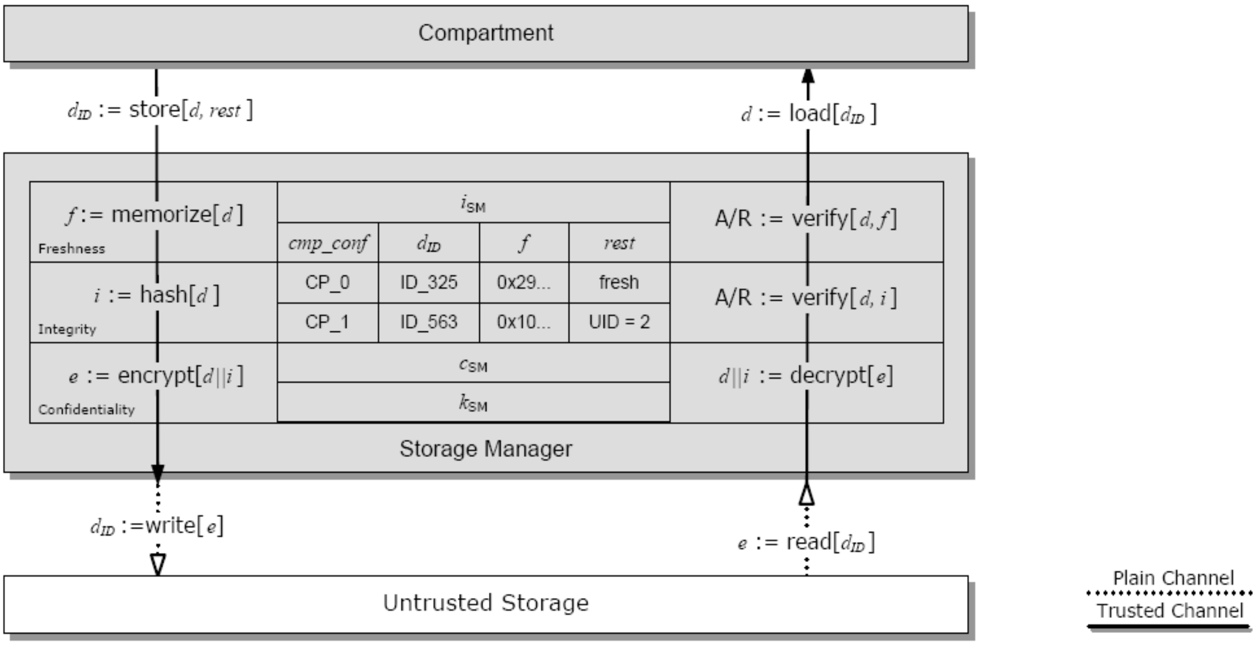


Figure 12: Implementation of the Storage Manager

Figure 12 depicts our trusted storage implementation. Our trusted storage compartment basically offers two trusted channels *load[]* and *store[]* while the storage compartment itself uses two untrusted channels namely *read[]* and *write[]* from an untrusted storage compartment to persistently write, respectively read, data (however, the untrusted storage should provide availability).[6]

If *SM* receives a data object *d* via *store[d, rest]*, *SM* internally creates or updates the object's metadata[7] and calculates its hash value *i* to verify integrity. Then the data together with *i* is encrypted with the internal cryptographic secret key k_{SM} using the function $e := encrypt\ [d \ || \ i]$ (to provide confidentiality). The encrypted data *e* will afterwards be written on untrusted storage using $d_{ID} := write[e]$ that returns the object identifier d_{ID}. Conversely, if *e* is read from the untrusted storage via $e := read[d_{ID}]$ it will be decrypted to *data* and *i* via *decrypt[e]* using k_{SM}. Before returning *d* to *load[]*, *SM* verifies the integrity of *d* and further access restrictions (e.g., a certain user id) based on the corresponding metadata in *SM*'s index using the function *verify[d, i]* .

In order to provide fresh trusted storage, we enhance *SM* by an additional layer for managing freshness of data objects. This extension consists of a (currently abstract) function *f* := *memorize[d]* that updates the internal data structure *FRESH* with the freshness value *f*. Afterwards, data will be stored persistently ensuring confidentiality and integrity using secure storage. On *load[]* from secure storage, the function

6 For the realisation of availability we suggest solutions based on high redundancy, i.e., by the utilisation of multiple distributed storage locations (e.g., USB sticks or online sites) assisted by an appropriate RAID system. In case of failure of a particular storage device, it is still possible to retrieve data from alternative storage mirrors.
7 More details on storage metadata are given at the end of this section.

verify[d, f] additionally verifies that the received data object *d* is the last one being stored.

To provide such freshness detection, *SM* uses an additional metadata field to store the cryptographic hash value *hash(d)* that defines the last stored version of *d*. On *load[]*, *SM* calculates *hash(d)* again and checks if it matches the hash value of the last store. In order to ensure freshness of these metadata, the index of *SM* itself has to be stored fresh. We therefore analysed to what extent TPMs of version 1.1b and 1.2 can be used to realise a fresh index for *SM*.

- DI-Register: TPMs version 1.1b provide a Data Integrity Register (DIR) that can persistently store a 160 bit value. Unfortunately, access to this register is only authorised by the TPM owner secret implying that the TPM owner can always perform replay attacks. The only solution would be to distribute platforms with an activated TPM and an owner authorisation secret that is unknown to the user. This solution does not conform to the TCG specification that demands that TCG-enabled platforms have to be shipped with no owner installed.
- SRK Regeneration: An alternative way to prevent replay attacks based on TPMs version 1.1b would be to create a new Storage Root Key (SRK) before the system is shut down. Regeneration of the SRK would prevent that previously created TPM encryption keys can be used any more. Unfortunately, an SRK can only be renewed by the *TakeOwnership* function which itself requires a previously *OwnerClear* that itself disables the TPM. Therefore, an online regeneration of the SRK seems to be impossible.
- NV-RAM: TPMs version 1.2 provide a limited amount of non-volatile (NV-) RAM to which access is restricted to authorised entities. So called NV-Attributes define which entities are authorised to write to and/or read from the NV-RAM. Thus, data integrity can be preserved by storing a hash value of the data into the NV-RAM and ensuring that only the Storage Manager can access the authorisation secret.
- Secure Counter: A TPM version 1.2 supports at least four monotonic counters. Based on this functionality, the freshness of data can be detected by securely concatenating it with the actual counter value.

As a result of our previous analysis, we showed that TPMs version 1.1b cannot be used to provide fresh storage as required to enforce stateful licenses and/or to transfer licenses, as it is needed for digital rights management, for example. Therefore, we decided to realise trusted storage based on the monotonic counter functionality of TPMs version 1.2. For the secure wallet, however, freshness is not needed, hence the functionality provided by a TPM of version 1.1b is sufficient.

A monotonic hardware counter allows us to securely maintain versioning of an arbitrary data component, by keeping a software counter synchronised with one (of four guaranteed) hardware counters of the TPM. *SM* manages an internal software counter that, every time SM updates its index, is incremented synchronously with the monotonic hardware counter. If both mismatch at any time, outdated data is detected, which will be handled according to the actual security policy. However, in order to employ a TPM monotonic counter, *SM* has to be initialised correctly. On the initial setup SM uses the TPM to create its internal cryptographic key k_{SM} that then will be sealed to the actual platform configuration.

To enable freshness detection and thus trusted storage, SM creates a monotonic counter c_{SM} with authentication data *auth*, e.g., a secret password. The initial setup finishes with the creation of *SM*'s internal metadata index i_{SM} and the saving of the sealed key blob and the encrypted index on untrusted storage.

After a platform reboot, *SM* reads the key blob from the untrusted storage and asks the TPM to unseal its internal key. The TPM is able to unseal k_{SM} if the platform has the same configuration as it was at the sealing process, thus preventing a modified *SM* to access i_{SM}.

Then *SM* uses k_{SM} to decrypt its metadata index read from the untrusted storage. Finally, *SM* verifies the freshness of i_{SM} by comparing the decrypted counter of i_{SM} with the actual counter value of the corresponding TPM counter c_{SM}.

To bind a compartment's data object persistently to its actual configuration the following has to be done: After the mapping of compartment identifier to the actual compartment configuration using the Compartment Manager *CM*, *SM* updates i_{SM} with the corresponding metadata as well as the incremented software counter to enable freshness detection for i_{SM}. Afterwards, *SM* writes both, the data objects and the updated index, on the untrusted storage, encrypted with k_{SM}. Finally, *SM* synchronises its software counter with the TPM's monotonic hardware counter and returns the data object identifier.

We complete the scenario with loading a compartment's data object again: After the mapping of requesting compartment identifier to the actual compartment configuration using *CM*, *SM* reads the requested data object from untrusted storage and decrypts it using k_{SM}. Before returning data to the corresponding compartment, *SM* verifies all access restrictions (e.g., freshness, or a certain user id) given on store via *rest* based on the corresponding metadata in i_{SM} and verifies that the requesting compartment has the same configuration as it was on *store[]*.

2.6.3 X-GOLD™ 208-Based Architecture

Ideally, the architecture on the X-GOLD™ 208 platform [74] should look almost identical to the PC-based architecture. However, there are some differences:

1. The L4 microkernel, L4env, and the Security Services must be protected by the secure boot feature of X-GOLD™ 208, instead of the authenticated boot used by TCG-compliant PCs. Compartments are measured the same way as on the PC platform (i.e., it is not necessary to protect them by secure boot).
2. For the trusted storage, the mobile system must use the cryptographic functionality of the X-GOLD™ 208 instead of a hardware TPM. As in the demonstration architecture presented below, this can be achieved by using a (modified) TPM "emulator", which is implemented on top of X-GOLD™ 208 and provides a TPM (or MTM) compatible interface.

2.6.4 Hybrid Architecture for Demo-Prototype

Unfortunately, it is not possible to implement the entire system on the mobile X-GOLD™ 208 platform within the scope of the OpenTC project (for instance, porting drivers to the microkernel-based system is a substantial effort). However, some functionalities can be implemented on the mobile platform to demonstrate the concept. We propose to adapt the architecture shown in Figure 11 for a system, where some parts are still running on a PC. The result is shown in Figure 13: the PC platform communicates with the mobile platform via a serial interface.

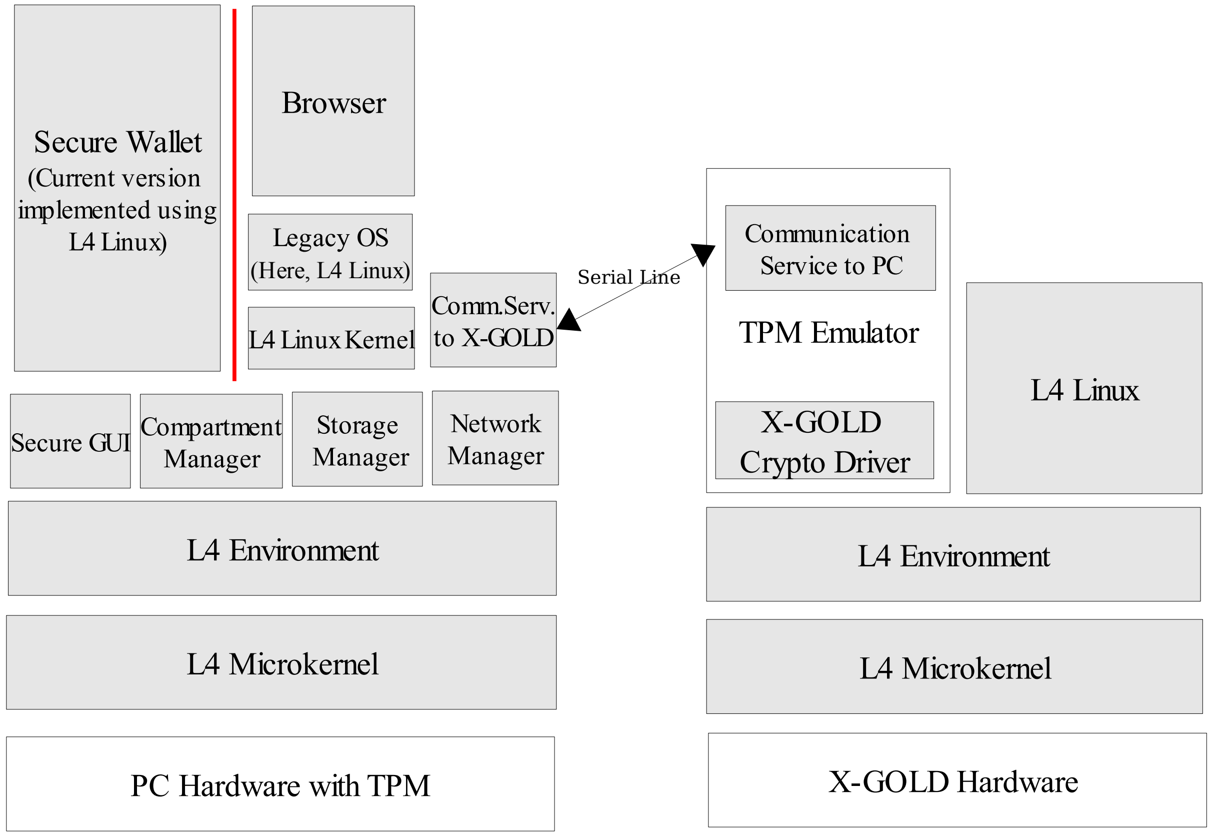


Figure 13: Architectural overview for a demo-prototype.
Only some core functionalities are implemented on the mobile platform, the rest has to be provided by the PC.

Communication between PC and X-GOLD™ 208 platform

We use a serial line for the communication between the PC and mobile platform. The functions needed by the (modified) Storage Manager for sealing will be executed on the X-GOLD™ 208 platform. For the communication, with the X-GOLD™ 208 board, a proxy is used, hence the Wallet-PC does not have to handle the serial communication directly. Instead, TCP sockets are used for the communication between the Wallet-PC and proxy (see below).

2.7 Porting and Test Concepts of the TPM emulator on X-GOLD™ 208

In this section we will focus on development and test aspects related to the implementation of the TPM emulator on the Infineon X-GOLD™ 208 (formerly called S-GOLD3™) platform. The following three components were used as a starting point:

- The L4Linux port on X-GOLD™ 208 done by Technische Universität Dresden within the OpenTC project;
- The GNU cross-compile tool chain configured for ARM cores (GCC 4.1.2, bin-tools 2.17);
- The Linux TPM Emulator developed by Mario Strasser [61], ETH Zürich.

In order to be able to test the target application using existing open-source TPM tools the following software packages were deployed:

- The TSS TrouSerS Software Stack [13,67], developed by IBM;
- The TPM toolset on top of TrouSerS, developed by IBM;
- The TPM Manager [14], an open source GUI to configure TPMs, developed by Ruhr-Universität Bochum and Sirrix AG within the EMSCB project.

Furthermore, the L4 build environment from TU Dresden was deployed to generate code images executable on the X-GOLD™-208 based platform. The entire development environment is depicted in Figure 14.

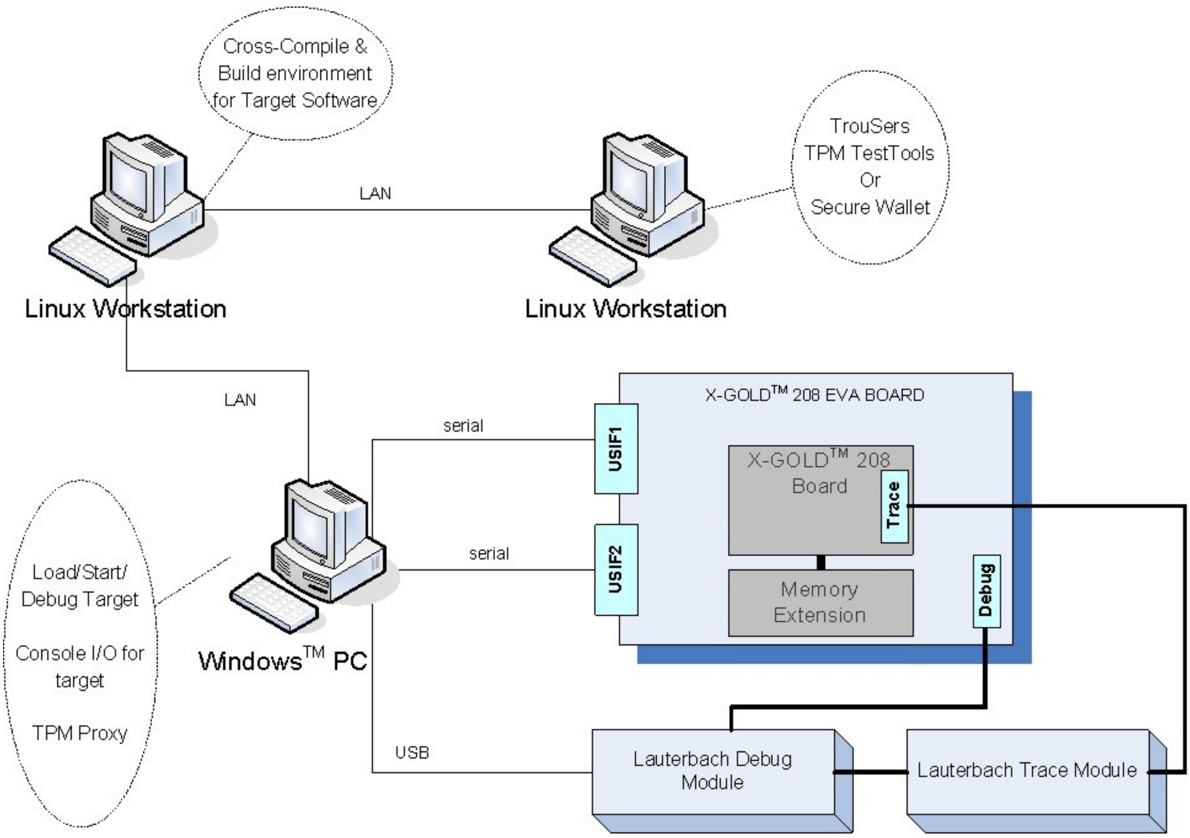
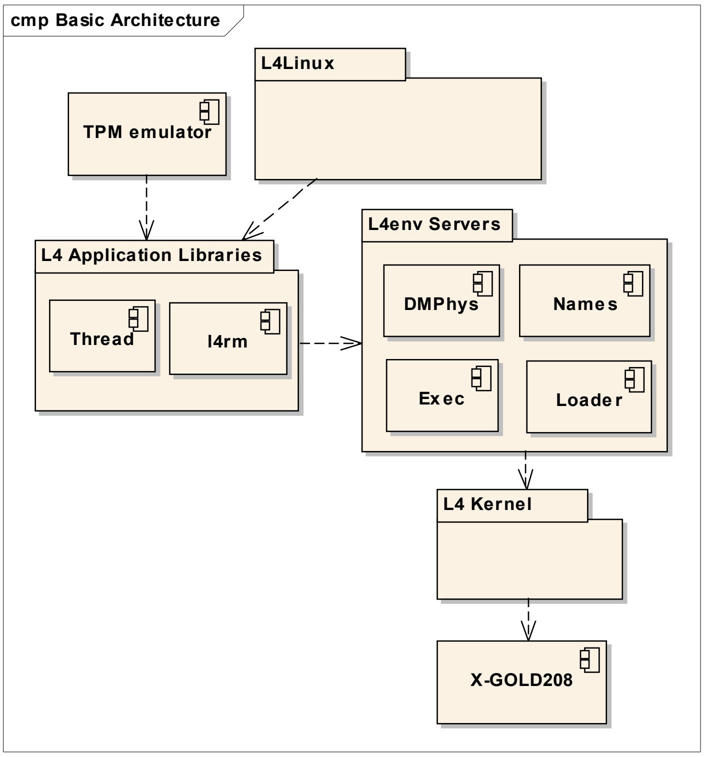


Figure 14: Development environment for TPM emulator on target

2.7.1 Porting Concepts

The basic target architecture for the TPM emulator running on the L4 platform is depicted in Figure 15.



L4 Application Layer

L4 Server + Application Library Layer

- Management of physical memory
- Loading L4 Applications
- Console I/O
- Semaphores
- ...

The L4 Microkernel

The Hardware Platform

Figure 15: Basic target architecture for TPM emulator on L4/X-GOLD™ 208

As can be seen in the diagram, the TPM emulator is configured as a dedicated L4 application which runs independently of Linux. The benefit of this architecture can be seen in the fact that it provides a fair amount of isolation which is important when considering various types of software attacks.

Since the TPM emulator was actually developed as a Linux kernel module, see ref. [61], and given the limited scope of this demonstrator, it would also have been an option to deploy a dedicated Linux compartment instead. But the practical drawback of that approach is clearly given by the fact that it requires to include the entire Linux kernel into the target application software build. Given the complex and time-consuming software build procedure and taking into account the time to load a large software image via the Debugger onto the target, this procedure would have significantly slowed down the development and test phase of the TPM emulator.

On the contrary, the chosen concept to restrict the TPM emulator to services available in the L4env environment enables to omit L4Linux from the software build and thus, keep the target software image footprint low. This benefit has to be paid with slightly increased software porting effort.

Assumptions and development constraints

In this section we will briefly address the development constraints, mainly given by the limited scope of the demonstrator:

- Only minimalistic support of TPM commands required for the secure wallet demonstrator

It is not required to support the full scope of TPM commands in order to demonstrate the use of an embedded TPM emulator for a specific secure wallet use case. Instead only a subset of commands is required. Within the WP08 work group it was suggested that a TPM sealing procedure could be a good example. On the other hand, also a sealing procedure requires the TPM to be in a certain state, e.g. a storage root key needs to be present and ownership credentials need to be known. Also the platform configuration registers need to contain a reasonable value in order to resemble a realistic scenario.

- No support of secure or authenticated boot for the software running on the target

  We saw virtually no benefit in implementing a procedure measuring the L4 software image, since the mechanism as such is already known and deployed in mobile phones (OMTP TR0 [49]). Also, it needs to be taken into consideration, that the target software build basically contains the L4/L4env and the TPM emulator application. On the other hand, the PC containing the software wallet application runs on a different architecture and includes different software images. So the measurement results on these platforms would be different which prevents a simple re-use. Furthermore, right after booting the target, the TPM emulator with its measuring capabilities does not even exist, so it would need to be preceded by other mechanisms. The results of these measurements would then need to be passed to the TPM emulator once it is started in its L4 domain.

- No software driver available for on-board storage of non-volatile data

Whereas the memory extension module of the evaluation board features a non-volatile NOR flash device, it was not considered realistic to develop a suitable driver within the L4 environment. Flash drivers usually turn out to be rather complex software components, taking into consideration the various requirements which need to be addressed: management of power-failure, wear levelling of erase units and so forth. It would also have been possible to provide a NOR flash driver in the L4Linux environment, and provide a basic file store/retrieve API towards the TPM emulator via L4. This would generally be a recommendable solution, as it avoids the problems arising from sharing peripheral ownership between different execution domains (L4Linux, TPM emulator). But, in addition to the implementation effort, a drawback of this approach is given by the fact that it requires the inclusion of L4Linux into the target software build, which we wanted to avoid, see previous section.

- Only serial interface available for communication with external host

This is not a major obstacle, since a TPM does not have to deal with large messages. The evaluation board also features connectors with higher bandwidths such as USB or MMC, but we saw little value in developing driver functionality for these devices. For that reason we stayed with using the serial interface (115 kbit/s) which is already used for the L4 console I/O and the L4 kernel debugger.

- No usage of GNU multi-precision library (GMP)

The standard Linux TPM emulator makes use of the GNU multi-precision library in order to perform big integer arithmetic. For two reasons we decided to not use this library for the emulator running on L4. First, the library is rather large and has further dependencies to other system libraries. In a realistic deployment scenario, the TPM emulator software footprint should be kept as small as possible in order to reduce weaknesses arising from complexity. Second, the X-GOLD™ 208 already features hardware acceleration for big integer exponentiation which enables the deployment of a suitable driver with a rather small memory footprint.

2.7.2 Implementation strategy

After analysing the Linux TPM emulator code structure and taking into account the restrictions listed in the previous section, the following decisions were taken:

- Replacing the software cryptographic functions of the Linux emulator with a driver using the X-GOLD™ 208 cryptographic hardware facilities.

  In particular this concerns almost all functions contained in the /crypto directory of the Linux emulator.
  - Public RSA key exponentiation
  - Private RSA key exponentiation
  - Hashing according to SHA-1
  - Generation of RSA key pairs

Whereas in a realistic scenario the driver would be implemented in an event-driven state, e.g. triggered by interrupts signalling the completion of certain hardware procedures, it was decided to go for a simpler solution, where the driver basically polls status registers. The benefit of this approach is that it has no impact on the L4 microkernel, since no interrupt routines need to be registered. The only required step for the L4 task running the TPM emulator is to map the associated peripheral address range into its own memory space and request it to be configured as non-cacheable.

In a later step the microkernel and the driver may be updated to support an interrupt-driven behavior.

- Design the TPM emulator as a dedicated L4 task communicating via a serial connection with the external PC running the secure wallet demonstrator

In Figure 16 a component diagram of the Linux TPM emulator is presented. In the

Linux user space a possible use case scenario based on the IBM TrouSerS TPM software stack is included.

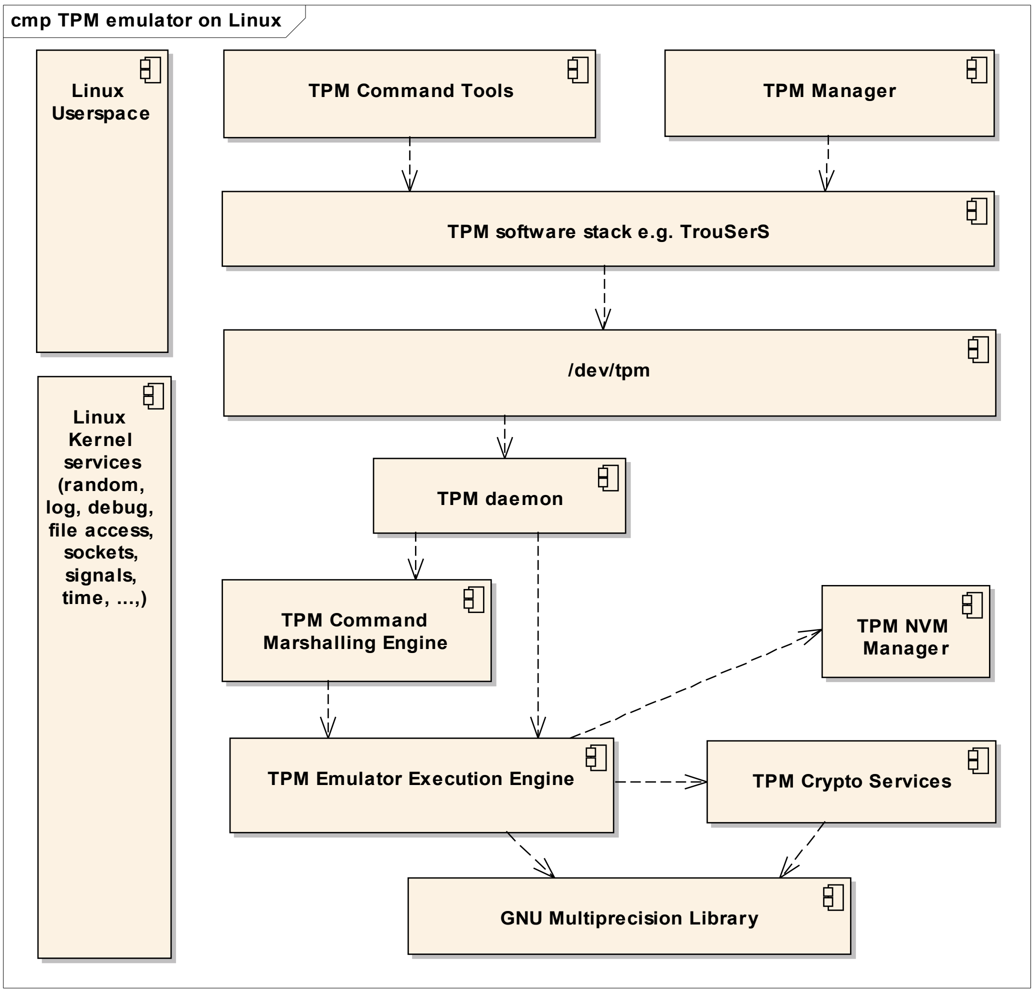


Figure 16: Linux TPM emulator architecture

In the Linux world the TPM emulator is designed as a kernel module which basically behaves as a daemon being triggered by TPM commands received via the /dev/tpm interface.

Whereas the Linux kernel provides a substantially richer set of services compared to the L4/L4env scenario, fortunately the TPM emulator core itself has only very few platform dependencies. For this reason the layer containing the Linux kernel dependent parts could be easily stripped off, so that the emulator in L4 becomes a simple task which is launched immediately after starting the target. Afterwards the emulator behaves like a server which waits for commands from the remote host.

- Deploy dedicated serial interface for exchanging TPM commands and TPM emulator control data between target and host

  The L4 already uses one Universal Serial Interface (USIF) peripheral for general console I/O and kernel debugging purposes. In order to keep this functionality independent from the TPM command/response exchange, it was

decided to use a second dedicated serial peripheral exclusively for the L4 task running the TPM emulator. As the X-GOLD™ 208 features multiple USIF peripherals and the evaluation board hosts a corresponding number of serial connectors, this was a straight-forward approach. Similar to the management of the crypto peripheral, the driver functionality was included into the emulator task and the peripheral address range was mapped into its address space. An interrupt-driven behavior may be later on added here as well.
For reliability reasons this USIF peripheral is operated using hardware flow control, which also needs to be configured at the host site.

- Use host to store and retrieve non-volatile TPM data

For a reasonable deployment the TPM emulator needs to be able to store its non-volatile data generated during a session of TPM commands and to retrieve it during initialization. In order to overcome the aforementioned problem of missing flash driver software for the L4 environment, we decided to deploy a thin protocol to be terminated by both TPM emulator on the target and the host PC. This protocol should not only carry TPM commands and their responses but as well some dedicated commands to be able to store and retrieve TPM data remotely from the host.

When it comes to storing confidential TPM data such as private key exponents or authentication credentials in a non-volatile memory device, it is apparent that appropriate protection facilities are required which address all relevant threat scenarios. The standard Linux TPM emulator does not provide any measures for this, it simply streams all data into a single large byte packet and stores it in a kernel file system. For simplicity reasons we also did not apply any explicit measures. In a real deployment scenario of course a suitable protection scheme is required. General recommendations on a secure data storage have been defined in OMTP TR1 [50].

- Remove Direct Anonymous Attestation (DAA) from the emulator

After investigating the implementation of the DAA related functions we decided to omit the related TPM commands from the target build. The reason was that the porting effort for the respective big integer arithmetic operations was considered too high and we did not have any use case within the scope of the secure wallet demonstrator.

- Use Lauterbach scripting for static configuration of on-chip peripherals

From the TPM emulator perspective, most of the X-GOLD™ 208 peripherals and system core functions can be configured statically. For example it is not necessary for the prototype to apply power measurement optimizations by changing clock settings or voltage levels. For this reason it became apparent to assemble all static configurations into a single Lauterbach script, which configures all necessary chip functions before the target software is loaded and started.

- Use a proxy at the host site for direct communication with the target

Instead of communicating directly between the target and the PC running the secure wallet application, a proxy is inserted in between. The tasks of this proxy are:

- Initiate the serial communication path towards the target;
- Set up a TCP server socket for exchange of TPM commands with the client (i.e. the secure wallet PC);
- Provide the TPM emulator non-volatile data and request its initialisation based on this data;
- Request the TPM emulator to transmit its current non-volatile data to the proxy and store it locally in a file system;
- Transparently pass TPM commands received over the TCP socket connection from the client via the serial link to the target and wait for the response;
- Transparently pass TPM responses received over the serial interface from the target, return it via the TCP socket to the client and wait for the next command from the client.

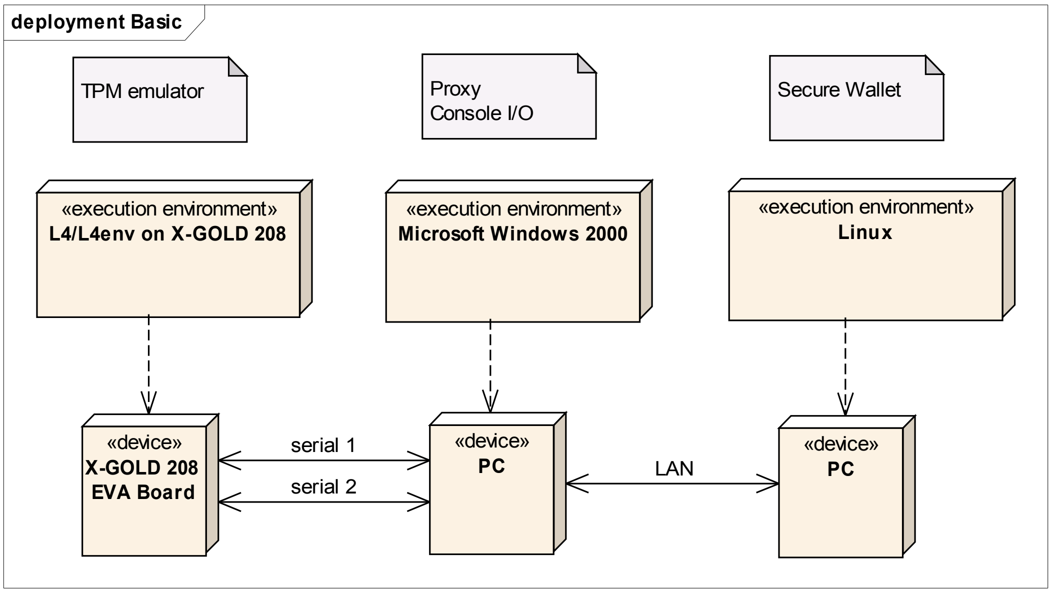


Figure 17: Basic prototyping deployment view

The benefit of this approach is that the secure wallet PC does not have to deal with setting up the TPM emulator, managing its non-volatile data and taking care of the proprietary protocol on the serial interface. From a secure wallet PC perspective, the proxy simply behaves as a remote TPM connected via a TCP socket.

As the L4 target is loaded and started via a Lauterbach Debugger application running under Windows™, and since the L4 console I/O can also be operated by a serial terminal running in this domain (e.g. HyperTerminal), it was a natural step to also implement the proxy under this operating system.

2.7.3 Architecture

In this section we will present some architectural details of the TPM emulator running under L4. A basic overview of the software components and how they are related to each other is given in Figure 18.

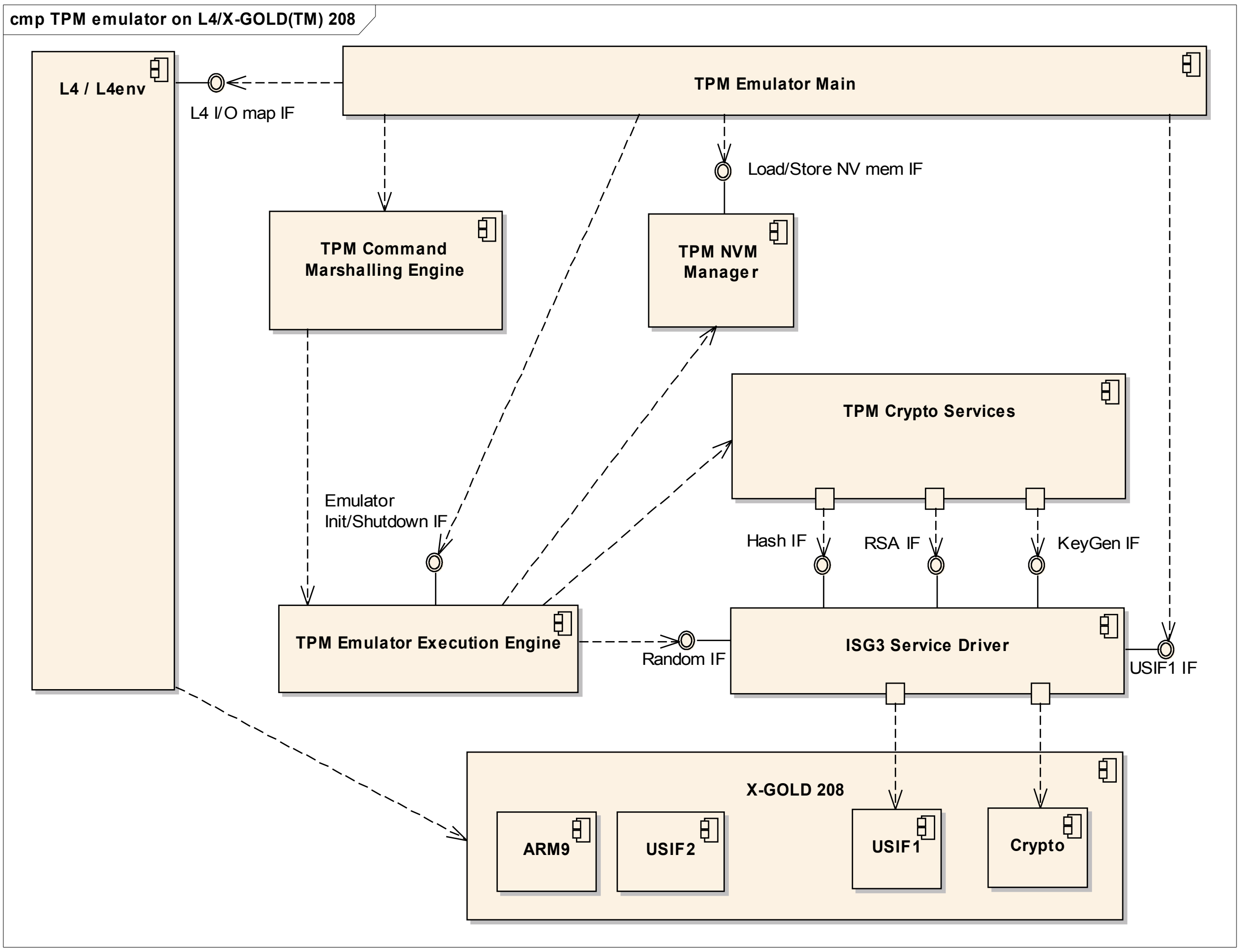


Figure 18: Component view of target software architecture

As can be seen from the diagram, the platform specific services are integrated into a single component (ISG3-Service-Driver). This is done in order to keep the changes to the original Linux TPM emulator source components as limited as possible. The 'TPM Emulator Main' component is basically a replacement of the Linux TPM daemon. It takes care of all communication towards the proxy, initialises the emulator with non-volatile data and passes/fetches TPM commands/responses to/from the emulator core.

Note that the diagram only lists one dependency towards the L4/L4env environment, which reflects the memory mapping functionality in order to map two peripherals into the emulator task space. This is apparently a simplification, since the TPM emulator also makes use of a few other basic L4 services. An example is the console output (debug printout) which is routed via L4 kernel services to the second serial interface (USIF2) of the baseband processor.

The following Figure 19 gives an overview of the functional behavior of the TPM emulator.

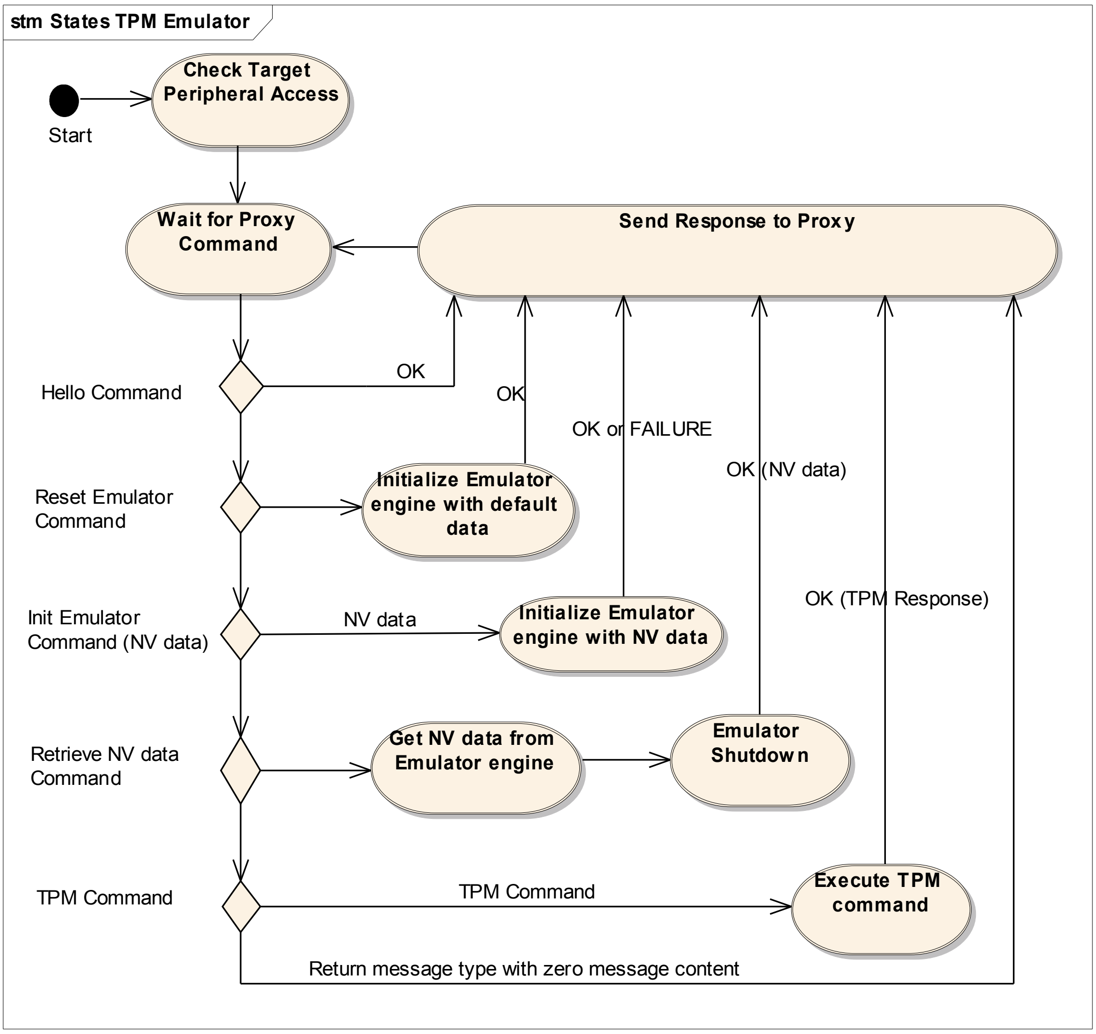


Figure 19: TPM emulator procedures on L4

The corresponding procedures of the TPM proxy running at the host site are depicted in Figure 20. In order to set up a complete processing chain, the following steps need to be executed:

1. Configure the target and load target software image via Lauterbach Debugger
2. Start of L4 kernel on target
3. Start of TPM emulator on target
4. Start of TPM proxy
5. Start of TPM client (Secure Wallet PC or patched[8] TrouSerS daemon)

8 The device driver (TDDL) layer of the TrouSerS daemon needs to be patched in order to support communication with a remote TPM connected via a TCP socket.

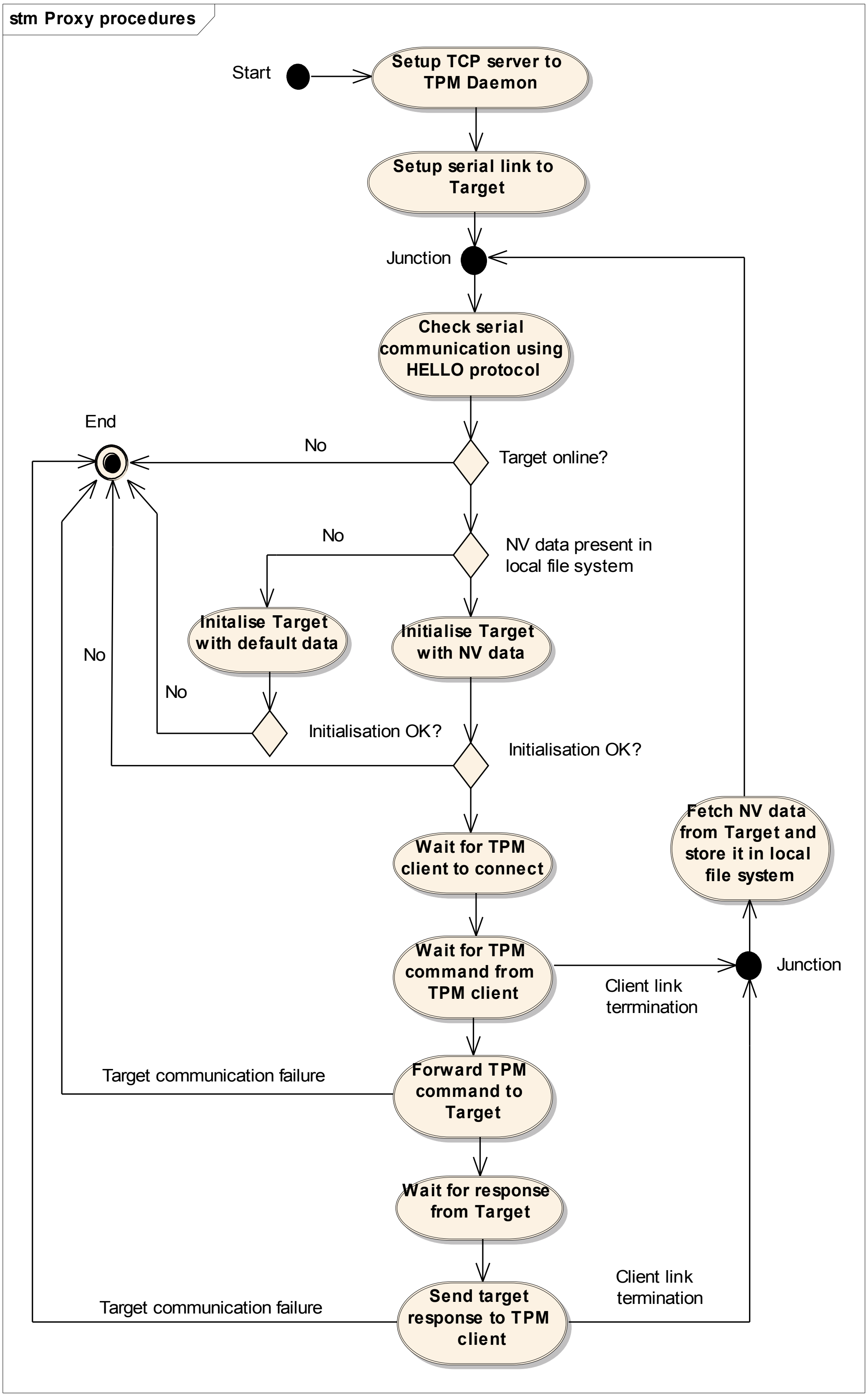


Figure 20: TPM Proxy procedures

2.7.4 Test Architecture

The entire deployment view for the test architecture is given in Figure 21. An example which visualises the message exchange between the involved nodes is given in figures 22 and 23. In the chosen scenario the TPM owner running a TPM command tool requests the public endorsement key (EK) to be read from the TPM.

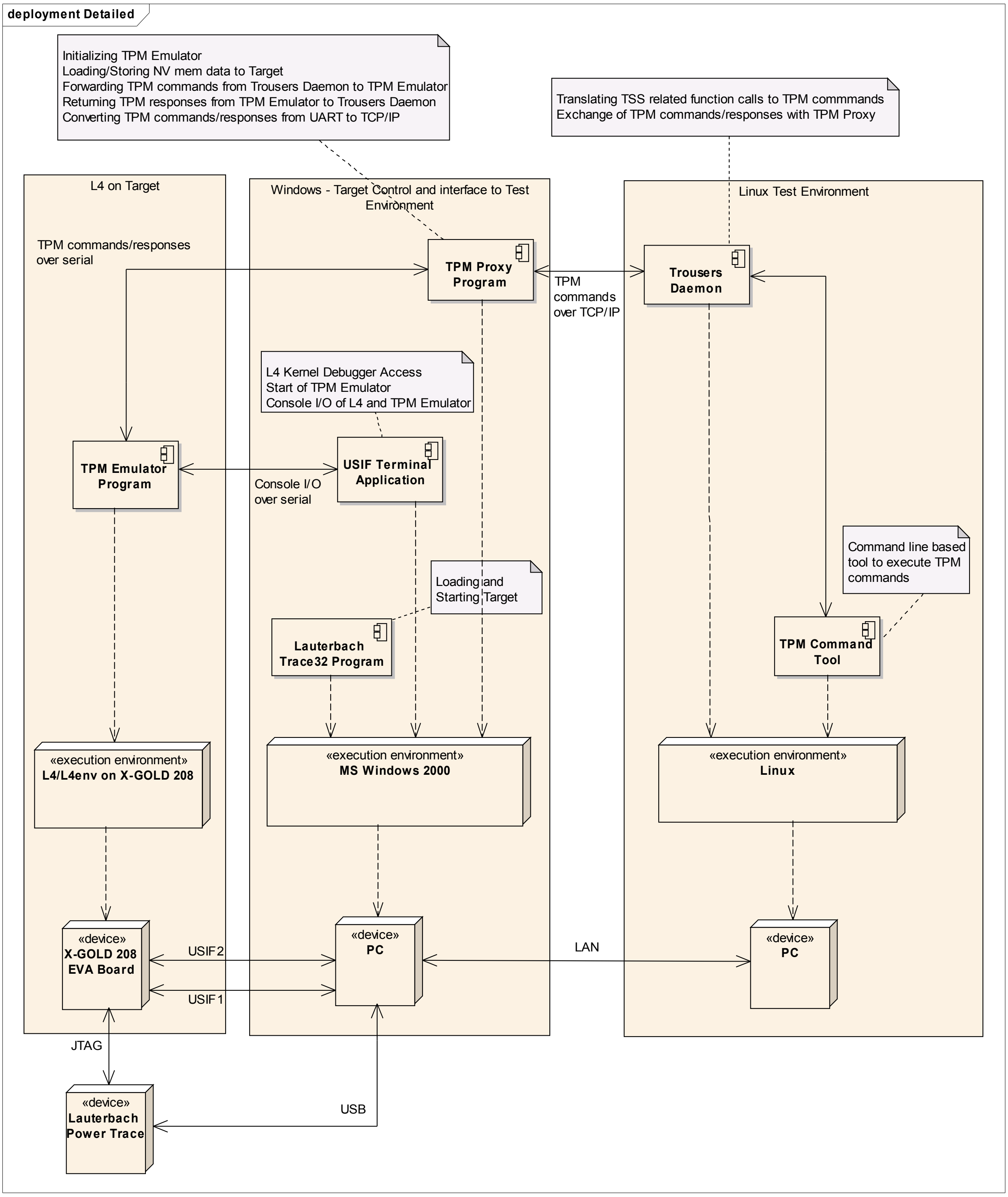


Figure 21: Deployment view used for target testing

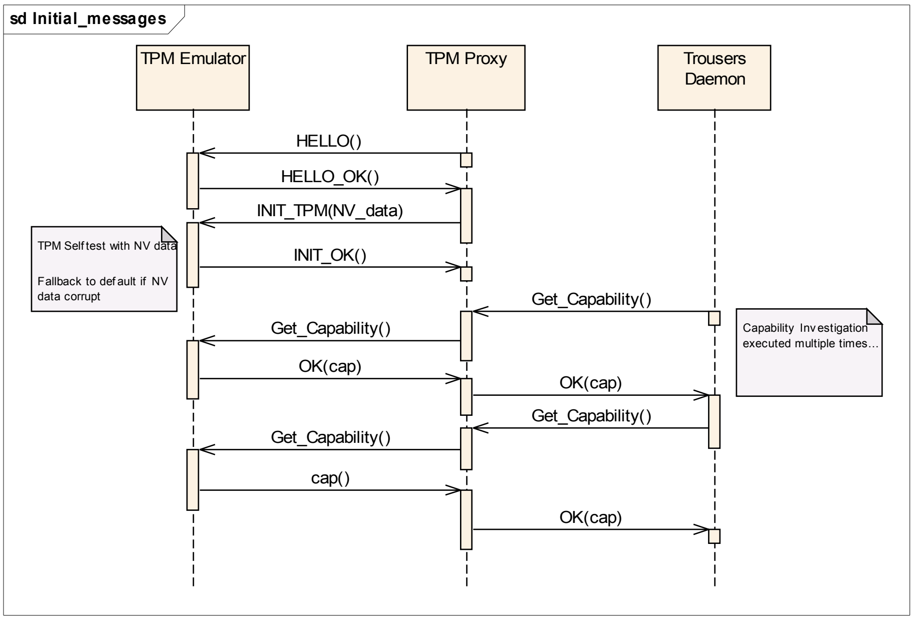


Figure 22:Message flow until start of Trousers daemon

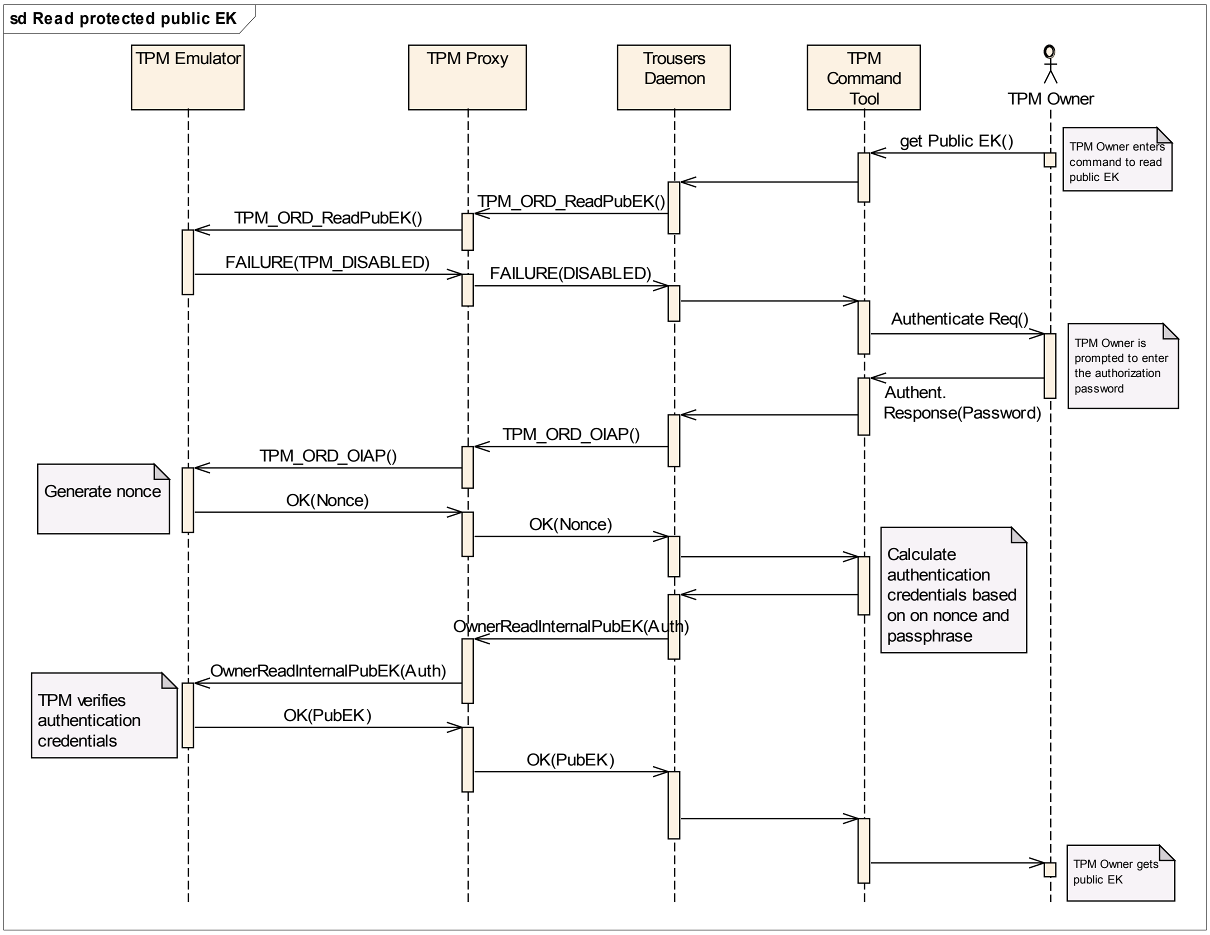


Figure 23: Example message exchange for a simple use case to read the public EK

3 TCG Support for the Secure Wallet Prototype

In this chapter we examine the secure wallet with a view to specifying what functionality is required of a Trusted Mobile Platform (TMP) if it is to facilitate a robust implementation of this mechanism. The numbered list of functional requirements accumulated is then utilised to determine the architectural components, based on the TCG mobile reference architecture [63], and the functions, as specified in the TCG MTM specification [64], which meet these requirements.

3.1 Requirements for a Robust Implementation of the Secure Wallet

Section 3.1.1 describes the process by which a secure wallet application is installed on a device. This process is analysed in order to extract any threats which may impact upon the device if the secure wallet application is not robustly implemented. Following this, the functionality required of a TMP in order to mitigate these threats is described.

Section 3.1.2 examines the fundamental steps in each of the protocols defined within the secure wallet suite described in section 2.4. Following each of the protocol descriptions, the threats which may impact upon the security of the protocols, if the secure wallet application is not robustly implemented, are highlighted. As above, the functionality required of a TMP in order to mitigate these threats is also described.

Section 3.1.3 summarises the requirements extracted throughout sections 3.1.1 and 3.1.2.

3.1.1 Secure Wallet Application Installation

Before a secure wallet application can be executed by a mobile device user, it must be installed on the mobile device. The following step, described in table 2, must be completed when installing a secure wallet application on a mobile device.

Step	Description
1	The secure wallet application code must be installed on the device.

Table 2: Secure wallet application installation

Unless the device implementation of the secure wallet mechanism is robust, a number of threats may impact on the device.

- Unauthorised modification of the secure wallet application code on installation into the device.
- Unauthorised modification of the secure wallet application code while in storage on the device.

Using the list of threats outlined above, the following requirement can be derived for a TMP, if it is to facilitate the secure installation of a secure wallet application.

1. The TMP SHALL provide a mechanism so that the secure wallet application code can be integrity-protected on installation into and in storage on the device.

3.1.2 Secure Wallet Protocol Suite

The secure wallet mechanism has been defined as a set of six protocols [47]:

- Starting the secure wallet;

- Setting a user passphrase;
- Authenticating a user;
- Changing a passphrase;
- Storing sensitive data; and
- Accessing secure storage (by an application).

3.1.2.1 Starting the Secure Wallet

There are two possible ways by which a secure wallet application can be started, as shown in tables 3 and 4.

Step	Description
1	The user clicks on the secure wallet icon or menu item.
2	The secure wallet is started.

Table 3: Starting the secure wallet

Step	Description
1	The secure wallet is started automatically at system boot.

Table 4: Starting the secure wallet (alternative)

Unless the implementation of the secure wallet mechanism is robust, the following threat may impact upon the device.

- Unauthorised modification of the secure wallet application code while executing on the device.

Using the threat outlined above, the following additional requirement can be derived for a TMP, if it is to facilitate a robust implementation of the secure wallet mechanism.

2. The TMP SHALL provide a mechanism so that the secure wallet application code can be integrity-protected while executing on the device.

3.1.2.2 Setting a User Passphrase

Once a secure wallet application has been installed, a user can set a passphrase which is used by the secure wallet application to authenticate him/her.

Step	Description
1	The user selects “passphrase”.
2	The secure wallet asks the user for a new passphrase.
3	The user enters his new passphrase twice.
4	The secure wallet stores the passphrase if both passphrases are identical.

Table 5: Selecting a passphrase

Step	Description
1	The user selects “passphrase”.
2	The secure wallet asks the user for a new passphrase.
3	The user enters his new passphrase twice.
4	The secure wallet does not store the passphrase if both passphrases are different.

Table 6: Selecting a passphrase

Unless the implementation of the secure wallet mechanism is robust, the following additional threats may impact upon the device.

- Unauthorised reading/copying of the passphrase on installation/input into the device.
- Unauthorised modification of the passphrase on installation/input into the device.
- Unauthorised reading/copying of the passphrase while in storage on the device.
- Unauthorised modification of the passphrase while in storage on the device.

Using the list of threats outlined above, the following additional requirements can be derived for a TMP, if it is to facilitate a robust implementation of the secure wallet mechanism.

3. The TMP SHALL provide a mechanism so that a passphrase can be confidentiality-protected during its installation/input.
4. The TMP SHALL provide a mechanism so that a passphrase can be integrity-protected during its installation/input.
5. The TMP SHALL provide an access control mechanism so that a passphrase can only be accessed by authorised entities.
6. The TMP SHALL provide a mechanism so that a passphrase can be confidentiality-protected while in storage on the device.
7. The TMP SHALL provide a mechanism so that a passphrase can be integrity-protected while in storage on the device.

3.1.2.3 Authenticating a User

The passphrase set by the user, as described in section 3.1.2.2, is subsequently used by the secure wallet application in order to authenticate a user attempting to gain access as described in tables 7 and 8.

Step	Description
1	The system asks the user to authenticate him/herself.
2	The user enters a passphrase.
3	The secure wallet compares the passphrase to the stored passphrase.
4	The secure wallet grants the user access.

Table 7: Authenticating a user

Step	Description
1	The system asks the user to authenticate himself.
2	The user enters a passphrase.
3	The secure wallet compares the passphrase to the stored passphrase.
4	The secure wallet denies the user access.

Table 8: Authenticating a user (alternative)

This protocol does not introduce any additional threats.

3.1.2.4 Changing a Passphrase

A user passphrase may be changed using the processes described in tables 9 and 10.

Step	Description
1	The user selects “change passphrase”.
2	The secure wallet asks for a new passphrase.
3	The user enters his new passphrase twice.
4	The secure wallet updates the passphrase if both passphrases are identical.

Table 9: Changing a passphrase

Step	Description
1	The user selects “change passphrase”.
2	The secure wallet asks for a new passphrase.
3	The user enters his new passphrase twice.
4	If both new passphrases are not identical the secure wallet displays an error message.

Table 10: Changing a passphrase (alternative)

This protocol does not introduce any additional threats.

3.1.2.5 Storing Sensitive Data

Tables 11 and 12 describe the process by which a user can store data (e.g. user credentials) using the secure wallet mechanism.

Step	Description
1	The user selects “enter secret data”.
2	The user enters the data.
3	The user presses “OK” to confirm data storage.
4	The secure wallet presents a list of applications.
5	The user may select an application which may access the sensitive data, e.g. a particular browser.
6	The sensitive data is securely stored for the chosen application.

Table 11: Storing sensitive data

Step	Description
1	The user selects “enter secret data”.
2	The user enters the data.
3	The user presses “cancel” to abort data storage and nothing is stored.

Table 12: Storing sensitive data (alternative)

Unless the implementation of the secure wallet mechanism is robust, the following additional threats may impact upon the device.

- Unauthorised reading/copying of sensitive data on installation into the device.
- Unauthorised modification of sensitive data on installation into the device.
- Unauthorised reading/copying of sensitive data while in storage on the device.
- Unauthorised modification of sensitive data while in storage on the device.

Using the list of threats outlined above, the following additional requirements can be derived for a trusted mobile platform, if it is to facilitate a robust implementation of the secure wallet mechanism.

8. The TMP SHALL provide a mechanism so that sensitive data can be confidentiality-protected during its installation.
9. The TMP SHALL provide a mechanism so that sensitive data can be integrity-protected during its installation.
10. The TMP SHALL provide an access control mechanism so that sensitive data can only be accessed by authorised entities.
11. The TMP SHALL provide a mechanism so that sensitive data can be confidentiality-protected while in storage on the device.
12. The TMP SHALL provide a mechanism so that sensitive data can be integrity-protected while in storage on the device.

3.1.2.6 Accessing Secure Storage

Tables 13 and 14 describe how data may be accessed by an application. In the current wallet implementation (which targets web logins), an http proxy that handles the authentication (see Sec. 2.4) is the only application using the wallet.

Step	Description
1	An end-user works with an application.
2	The application requires sensitive data (for example, when connecting to a banking web server).
3	The application contacts the secure wallet.
4	The secure wallet gives the application access to the sensitive data.
5	The application uses the sensitive data.

Table 13: Accessing secure storage (application)

Step	Description
1	The user works with an application.
2	The application requires sensitive data (for example when connecting to a banking site).
3	The application contacts the secure wallet.
4	The secure wallet denies the application access to the sensitive data.

Table 14: Accessing secure storage (application)(alternative)

Unless the implementation of the secure wallet mechanism is robust, the following additional threats may impact upon the device.

- Unauthorised reading/copying of the sensitive data while in use on the device.
- Unauthorised modification of the sensitive data while in use on the device.

Using the list of threats outlined above, the following additional requirements can be derived for a TMP, if it is to facilitate a robust implementation of the secure wallet mechanism.

13. The TMP SHALL provide a mechanism so that the sensitive data can be confidentiality-protected while in use on the device.
14. The TMP SHALL provide a mechanism so that the sensitive data can be integrity-protected while in use on the device.

3.1.3 Summary of Requirements

This section summarises the requirements from the secure wallet use-case.

SecureWallet1: The TMP SHALL provide a mechanism so that the secure wallet application code can be integrity-protected on installation into and in storage on the device.

SecureWallet2: The TMP SHALL provide a mechanism so that the secure wallet application code can be integrity-protected while executing on the device.

SecureWallet3: The TMP SHALL provide a mechanism so that a passphrase can be confidentiality-protected during its installation/input.

SecureWallet4: The TMP SHALL provide a mechanism so that a passphrase can be integrity-protected during its installation/input.

SecureWallet5: The TMP SHALL provide an access control mechanism so that a passphrase can only be accessed by authorised entities.

SecureWallet6: The TMP SHALL provide a mechanism so that a passphrase can be confidentiality-protected while in storage on the device.

SecureWallet7: The TMP SHALL provide a mechanism so that a passphrase can be integrity-protected while in storage on the device.

SecureWallet8: The TMP SHALL provide a mechanism so that the sensitive data can be confidentiality-protected during its installation.

SecureWallet9: The TMP SHALL provide a mechanism so that the sensitive data can be integrity-protected during its installation.

SecureWallet10: The TMP SHALL provide an access control mechanism so that the sensitive data can only be accessed by authorised entities.

SecureWallet11: The TMP SHALL provide a mechanism so that sensitive data can be confidentiality-protected while in storage on the device.

SecureWallet12: The TMP SHALL provide a mechanism so that sensitive data can be integrity-protected while in storage on the device.

SecureWallet13: The TMP SHALL provide a mechanism so that sensitive data can be confidentiality-protected while in use on the device.

SecureWallet14: The TMP SHALL provide a mechanism so that sensitive data can be integrity-protected while in use on the device.

3.2 Requirements Analysis

Requirements **SecureWallet1** and **SecureWallet2** necessitate that the integrity of software (i.e. the secure wallet application) can be checked, and, that if unauthorised modification is detected, that appropriate action is taken.

In order to meet requirement **SecureWallet1** an authenticated boot mechanism in combination with a secure storage mechanism could be used.

- An authenticated boot mechanism facilitates the reliable measurement and storage of the software state of a TMP; and
- A secure storage mechanism ensures that security sensitive information, such as a user passphrase, cannot be accessed and/or utilised if a specified platform component, for example, the secure wallet code, has been modified in an unauthorised way.

Alternatively, in order to meet requirements **SecureWallet1** and **SecureWallet2**, a secure boot mechanism could be deployed to ensure that only legitimate and authorised software can be loaded at boot time. Run-time integrity protection and/or verification mechanisms could then be used in conjunction with a secure boot mechanism in order to ensure that the software environment remains in a trustworthy state after boot.

- A secure boot mechanism enables the reliable measurement and verification of a TMP's software state at start-up. Any unauthorised, yet successful, attempt to modify a protected software component should result in one of the following three scenarios [23] at boot time.
  - The system could continue booting as normal but issue a warning. This approach gives little protection against attack. Malicious or corrupted software components can still be executed.
  - The system could opt not to execute the component whose integrity is compromised. This, however, leaves the system open to denial of service attacks.
  - Finally, the system could attempt to recover and correct the inconsistency using a trusted source before executing or using the component.
- A runtime integrity-checking mechanism facilitates the accurate measurement and verification a TMP's software state while it is in operation. Any unauthorised yet successful attempt to modify a protected software component, for example, the secure wallet application code, during runtime, should result in one of the following two scenarios.
  - The system could continue as normal but issue a warning. This approach, however, gives little protection against attack. Attacks may still be successfully executed against software components running on the platform.
  - The system could make the majority of its services unavailable if the integrity of a software component is compromised. The platform would then have to be rebooted in order to transition back into a trusted state. This, however, leaves the system open to denial of service attacks.
- Alternatively, a mechanism, such as software isolation, which aims to prevent an attack impacting the runtime integrity of the platform could be adopted.

Requirements **SecureWallet3** to **SecureWallet14** can be summarised as follows.

- A mechanism is required so that data may be input into the TMP, where either its:
  - Integrity; or
  - Integrity and confidentiality must be protected (i.e. a trusted path is required).
- A mechanism is required so that data stored on the TMP is protected with respect to its:

    - Integrity; or
    - Integrity and confidentiality.
- A mechanism is required so that confidentiality and integrity-protected data can only be accessed by authorised entities, for example the secure wallet mechanism running as expected.
- A mechanism is required so that data in use on the TMP is protected with respect to its:
    - Integrity; or
    - Integrity and confidentiality.

Protected storage functionality, which enables data to be protected on input into, while in storage on and while in use on a device is necessary so that requirements **SecureWallet3** to **SecureWallet14** can be met.

3.3 TCG Mappings

In this section we consider whether and how the functional requirements summarised in section 3.1.3 can be met assuming a TMP as defined by the TCG Mobile Phone Working Group (MPWG) in [63] and [64] which also incorporates an isolation layer (namely, an L4 microkernel).

In section 3.3.1 the model defined in section 2.4.2 is re-examined and modified to support a TMP. This section also describes the properties of a TMP, as defined in the previous paragraph, and assumed for the remainder of this section. Section 3.3.2 explores the fundamental command runs which need to be completed on any TCG compliant MTM before its security mechanisms can be utilised. Sections 3.3.3 and 3.3.4 examine authenticated and secure boot mechanisms. Section 3.3.5 examines runtime integrity protection and verification mechanisms. Section 3.3.6 shows how secure storage can be provided. Section 3.3.7 describes the process by which an entity can demonstrate knowledge of an authorisation value/secret bound to a key object, data object, or an 'owner authorised command' so that access to the object or use of an 'owner authorised command' can be permitted by an MTM. We conclude in section 3.3.8.

3.3.1 Revised Architectural Model

We now revisit the secure wallet use-case architectural model described in section 2.4.2. We require the addition of a new functional component, namely a TMP, in place of the mobile device shown in figure 24.

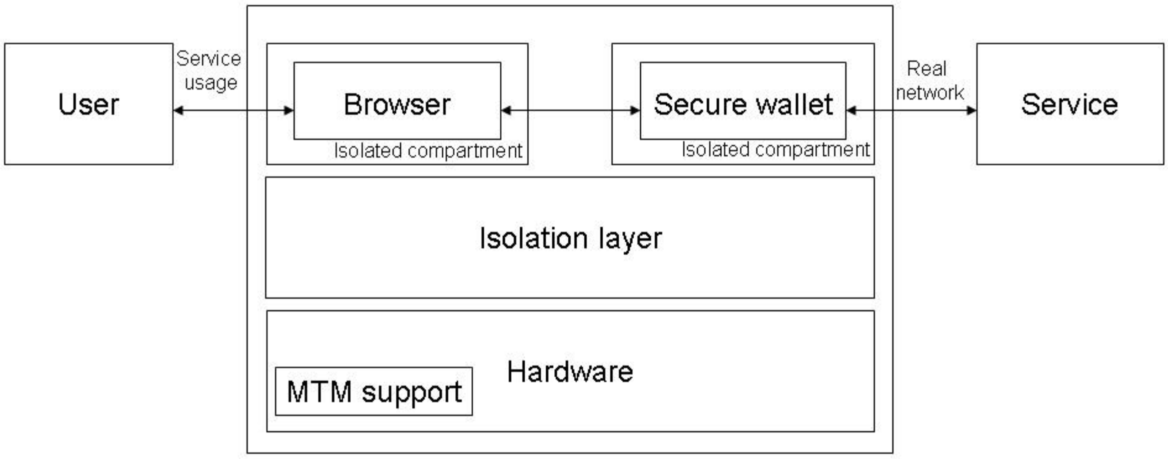


Figure 24: Secure wallet architecture

A TMP, as defined by the TCG [63,64] is comprised of a set of engines, whereby an engine is described as a construct capable of manipulating data, providing evidence that it can be trusted to report the current state of the host platform and providing evidence about the host platform's current state. Each trusted mobile platform stakeholder has its own engine, where the principal stakeholders in a mobile phone include the device manufacturer, network operator, service providers and users. Each engine provides platform services on behalf of its stakeholder and also incorporates functionality similar in many ways to a traditional TCG PC platform. Each engine [63]:

- has protected capabilities and shielded locations such that trusted services, which must not be subverted, can be implemented;
- can use attestation identities to prove that information originated from a trusted platform;
- has access to a set of 'roots-of trust' such that 'normal services' provided by the engine can be measured and those measurements reported;
- has access to protected storage functionality, with a Storage Root Key and its subsequent hierarchy; and
- may implement other TCG functions depending on the intended functionality of the engine's 'measured normal services' (see bullet three above).

TMP engines may be categorised as either mandatory or discretionary.

- A mandatory engine provides the prerequisite functionality of a TMP, for example that required to comply with regulations which govern the operation of mobile platforms in cellular radio systems. Mandatory engines must be supported by a Mobile Remote owner Trusted Module (MRTM), which supports secure boot and does not permit a local operator to remove the stakeholder from the engine.
- A discretionary engine provides services that may be added, removed and turned on/of without the consent of any external service provider. Discretionary engines must be supported by a Mobile Local owner Trusted Module (MLTM), which is not required to support secure boot and permits a local operator to remove the stakeholder from the engine.

The device manufacturer and device owner define the mandatory engines which may exist on their platforms. A device owner may also list the discretionary engines permitted.

An engine may be implemented using trusted and/or measured resources. In order to construct a trusted resource, namely a 'root of trust', a trusted entity must vouch for a specific instantiation of that resource [63]. Alternatively, in the case of a measured resource, a reliable entity measures an instantiation of a resource and a second reliable entity provides a trustworthy reference measurement for comparison [63]. A TMP, as defined here, is also assumed to enable isolated execution of software.

There are numerous scenarios which may result in the implementation of a secure wallet mechanism as described in section 2.1. The secure wallet may, for example, be provided by a third party service provider and implemented by a TMP end-user who may be the device owner. Such a service is non-essential and therefore provided on the device by a service provider discretionary engine. This particular service provider engine would be listed in the DeviceOwner_discretionaryEngineList and is supported by an MLTM. In this case, the local operator/end user of the device would be permitted to remove the service provider from the engine at any stage.

Alternatively, we can envisage a scenario in which a corporate entity is the device owner and requires all device operators (namely employees) to use the secure wallet mechanism. In this case, the device owner may list the agent installer engine which provides the secure wallet functionality in the DeviceOwner_mandatoryEngineList. This implies that the engine would be supported by an MRTM and would not permit a local operator to remove the stakeholder from the engine.

In short, we can imagine scenarios in which the engine providing the secure wallet mechanism is discretionary and supported by an MLTM and, equally, scenarios in which the engine is mandatory and therefore supported by an MRTM.

In the remainder of this chapter, we investigate whether the trusted computing mechanisms provided by discretionary and mandatory TMP engines meet the requirements described in section 3.1.3. If a particular mechanism is provided by a TMP, we examine the architecture components and commands required to leverage it.

3.3.2 Fundamental MTM command runs

Before we examine the MTM commands, which can be used to fulfil authenticated boot, secure boot and secure storage requirements, as described in section 3.2, we review a number of MTM commands which need to be executed in order to initialise an MTM for use.

3.3.2.1 MTM Permanent Flags

Firstly, in table 15, we define a number of MTM permanent flags the use of which is discussed in this chapter. MTM permanent flags are used to maintain the state information for the MTM [65]. The values of these commands are not affected by the *TPM_Startup* command.

Name	Description
TPM_PF_READPUBEK	This flag may be set to *TRUE* or *FALSE*. It indicates whether the public endorsement key can be read with or without owner

Name	Description
	authorisation. The default value is *TRUE*.
TPM_PF_DISABLE	This flag may be set to *TRUE* or *FALSE* and indicates whether MTM is disabled or enabled. The default value is *TRUE*.
TPM_PF_OWNERSHIP	This flag may be set to *TRUE* or *FALSE* and indicates whether or not an entity can be take ownership of the MTM. The default value is *TRUE*.
TPM_PF_DEACTIVATED	This flag may be set to *TRUE* or *FALSE* and indicates whether the MTM is deactivated or activated. The default value is *TRUE*.

Table 15: MTM permanent flags

3.3.2.2 MTM Initialisation

The MTM must be first be initialised. *TPM_Init* is a physical method of initialising the MTM. This command puts the MTM into a state where it waits for *TPM_Startup*, a command which specifies the type of the initialisation required. The MTM initialisation command is shown in table 16. This command must be implemented in both an MRTM and an MLTM.

TPM_Init

Table 16: MTM initialisation

3.3.2.3 MTM Start-up

After MTM initialisation the MTM must be started up. The *TPM_Startup* command is always preceded by *TPM_Init*. This command must be implemented in both an MRTM and an MLTM. An MTM can startup in one of three possible modes. The chosen mode depends on the event that caused the reset and the operations on the MTM that need to be completed in response to the event. The 3 modes include: *clear* start, *save* start and *deactivated* state. For an initial engine start up, a *clear* start would normally be used, where all variables go to their default or non-volatile values. During a *save* start the MTM recovers and restores variable values saved on a prior *TPM_SaveState*. During a *deactivated* start an MTM turns itself off and requires another *TPM_Init* before the MTM will execute in a fully operational state. A *clear* start is permitted by an MRTM and an MLTM. A *save* start is dependent on the implementation of *TPM_SaveState*, which is an optional command on both an MRTM and an MLTM. A *deactivated* start must not be supported by an MRTM and may be optionally supported by an MLTM. The *TPM_Startup* command is shown in table 17 and the T*PM_SaveState* is shown in table 18.

TPM_Startup

Table 17: MTM start-up

TPM_SaveState

Table 18: MTM save state

3.3.2.4 MTM Self-testing

During the initialisation process, there are a minimal set of self tests completed by the MTM. In order to ensure a more thorough self test the commands shown in table 19 may be executed. Results of self tests are held in the MTM and can be retrieved using the command described in table 20. These three commands are required in both an MRTM and an MLTM.

Continue self-test process:	
TPM ContinueSelfTest	This command causes the MTM to test the MTM internal functions not tested at initialisation.
Complete a full self-test:	
TPM_SelfTestFull	Requests that the MTM completes a full self test.

Table 19: Self testing

TPM_GetTestResult

Table 20: Retrieving self test results

3.3.2.5 Endorsement Key Generation

The endorsement key pair is defined as optional in a TMP MRTM and mandatory in a TMP MLTM. If an endorsement key pair is used however, the command set which enables its handling must be implemented. An endorsement key pair may be generated using an external key generator. Alternatively, an endorsement key pair may be generated using either of the commands shown in table 21. The *TPM_CreateEndorsementKeyPair* command may be optionally implemented in an MRTM but is required in an MLTM. The *TPM_CreateRevokableEK* command, which causes a revocable endorsement key pair to be generated, may also be implemented on an MRTM and an MLTM as it is considered optional for both.

Before generating an endorsement key pair, calls may be made to the *TPM_GetCapability* to determine whether or not an endorsement key already exists.

TPM_CreateEndorsementKeyPair
TPM_CreateRevokableEK

Table 21: Creating an endorsement key pair

3.3.2.6 Accessing a Public Endorsement Key

Table 22 shows how a public endorsement key can be accessed. Access to the public endorsement key is necessary before an entity can take ownership of an MTM as it is used during the take ownership process in order to input data into the MTM securely. *TPM_ReadPubek* is required in an MRTM if indeed the *TPM_CreateEndorsementKeyPair* has been implemented. Otherwise, the command is unnecessary. The *TPM_ReadPubek* command is required in an MLTM. The *TPM_OwnerReadInternalPub* is optional in an MRTM (as was the case for

RPM_ReadPubek; its implementation will be dependent on the implementation of *TPM_CreateEndorsementKeyPair*) and required in an MLTM.

Open access to the public endorsement key:

TPM_ReadPubek

Disable the public read of public endorsement key:

Often by default, once the MTM has acquired an owner, the flag which indicates whether or not open access to the public endorsement key is allowed, *TPM_PF_READPUBEK*, is set to *FALSE* so that the public endorsement key can only be read by the MTM owner. This flag may however be changed using the optional *TPM_SetCapability* command which requires owner authorisation.

TPM_SetCapability

MTM owner read of public endorsement key:

TPM_OwnerReadInternalPub

Table 22: Accessing the public endorsement key

3.3.2.7 Enabling an MTM

The MTM must be enabled; that is the *PM_PF_DISABLE* flag must be set to *FALSE*. It is assumed that an MRTM is always enabled. In the case of an MLTM, this may be achieved using the required commands shown in table 23.

TPM_PhysicalEnable	The MTM owner must enable the platform before any MTM commands can be utilised.

Table 23: Physically enabling an MTM

In order to physically disable the MLTM before it has acquired an owner, the commands shown in table 24 can be executed.

TPM_PhysicalDisable

Table 24: Physically disabling an MTM

Once an MLTM has acquired an owner, he or she may also enable or disable the MTM using the required *TPM_OwnerSetDisable* command which changes the state of the *TPM_PF_DISABLE* flag to either *TRUE* or *FALSE*. This command is shown in table 25.

TPM_OwnerSetDisable	Used to change the status of the *TPM_PF_DISABLE* flag.

Table 25: Enabling/Disabling an MTM

3.3.2.8 The Ownership Flag

In order for a user to take ownership of an MTM, the ownership flag, *TPM_PF_OWNERSHIP* flag must be set to *TRUE* using the commands shown in table 26. In an MRTM the default value for this flag is *TRUE*, so this command is excluded and in an MLTM this command is required.

TPM_SetOwnerInstall	Used to set the value of the *TPM_PF_OWNERSHIP* flag to *TRUE* so that an entity can take ownership of an MTM.

Table 26: Setting the state of the '*TPM_PF_OWNERSHIP*' flag

3.3.2.9 Taking Ownership of an MTM

In an MRTM the *TPM_TakeOwnership* command is optional. This command may not be necessary if there is no endorsement key pair and an AIK and SRK have been pre-installed. In order for an entity to take ownership of an MLTM, the following steps must be completed.

1. The public endorsement key must be accessed, as described in table 22.
2. MTM owner authorisation data must be input into the MTM.
3. An SRK must be generated inside the MTM.
4. The authorisation data for the SRK must be input (if required) into the MTM.
5. A tpmproof must be generated. A tmpProof is a 160-bit secret that is generated by the MTM when the *TPM_TakeOwnership* command is executed. This secret is associated with non-migratable objects so that an MTM can identify the objects which it has created.

Steps 2 to 5 can be completed using the take ownership command shown in table 27.

TPM_TakeOwnership

Table 27: Taking ownership of an MTM

3.3.2.10 MTM Activation

Finally, an MTM must be activated; this will result in the *TPM_PF_ACTIVATED* flag being set to *FALSE*. It is assumed that an MRTM is always activated. In the case of an MLTM, this may be achieved using the required command shown in table 28.

TPM_PhysicalSetDeactivated

Table 28: Activating an MTM

3.3.3 Authenticated Boot Process

SecureWallet1 to **SecureWallet14**, as described in section 3.2, may be partially met through the deployment of an authenticated boot mechanism, where an authenticated boot is defined as the process by which the state of a platform engine can be reliably measured and stored.

An authenticated boot is supported by both a mandatory and a discretionary TMP engine as defined in [63]. In order to support such a mechanism an engine must comprise of a Root of Trust for Measurement (RTM) and a Root of Trust for Storage (RTS).

- A RTM is required to accurately measure at least one integrity measurement in an engine, and report the integrity measurement to the RTS. This may be accomplished using the MTM PCR extension command, *TPM_Extend*.

- A RTS is required to accept integrity measurements and record them. Both an MRTM and an MLTM, which incorporate the RTS in a mandatory and a discretionary engine respectively, are required to have a set of Platform Configuration Registers.

It is envisaged that an authenticated boot process for a TMP engine will closely resemble that of a PC platform. Very basically, an engine RTM may for example measure its own configuration and the configuration of img1 (the next software component to be loaded and executed on the platform engine), saving the measurement to an MTM PCR and a summary of the measurement to a log file stored on the engine. Measurement functionality integrated into img1 continues the measurement process, saving the measurement of img2 (the next software component to be loaded and executed on the platform engine), to an MTM PCR and a summary to the log file. It then passes control to img2. This process continues until all the specified software in the engine has been reliably measured. Measurements stored during the authenticated boot process may be utilised in secure storage and attestation mechanisms. The exact process by which a trusted mobile platform is booted, its integrity measured and its integrity measurements stored, needs to be specified for each TMP architecture, just as for the PC client in [66].

3.3.4 Secure Boot Process

SecureWallet1 and **SecureWallet2** as defined in section 3.2, may be met through the deployment of a secure boot mechanism, where a secure boot is defined as the process by which the state of an engine can be reliably measured, verified and stored.
A secure boot mechanism must be supported by a mandatory device manufacturer engine, should be supported by all other mandatory engines and may be supported by discretionary engines. In order to support such a mechanism an engine must incorporate a RTM, a RTS and a Root of Trust for Verification (RTV).

- A RTM is required to accurately measure at least one integrity measurement in an engine, and report the integrity measurement to the RTV.
- A RTV is required to accept an integrity measurement from the RTM and verify it against the corresponding reference integrity measurement before reporting it to the RTS. This is accomplished using the *MTM_VerifyRIMCertAndExtend*.
- A RTS is required to accept integrity measurements from the RTV and record them. Both an MRTM and an MLTM, which incorporate the RTS for a mandatory and a discretionary engine respectively, are required to have a set of PCRs.

Before an engine can be securely booted, it must be provisioned with an asymmetric public key called a Root Verification Authority Identifier (RVAI). The RVAI must be integrity-protected within an MTM. For example, an integrity check sum for the asymmetric public key may be stored in an MTM shielded location. Alternatively, the asymmetric public key may be signed using a private key associated with the MTM.

The corresponding RVAI private key is securely stored by the engine's stakeholder. The root verification authority, i.e. the engine's stakeholder, may use the private key to either sign:

- a certificate which contains a reference integrity measurement for a particular software component, namely a RIM_Cert; or
- a Rim_Auth_Cert, in which the public key of another authority (a so-called

RIM_Auth) is authorised to create/sign RIM_Certs.

A RIM_Cert may be classified as external or internal. External RIM_Certs are generated outside the MTM, may be valid for a number of platforms and are signed by RIM_Auths. Internal RIM_Certs are generated from external RIM_Certs and authorised by the engine itself. Internal RIM_Certs are integrity protected using an engine's internal verification key, a secret unique to the engine's MTM.

An MTM which enables a secure boot must also support two monotonic counters:

- *counterBootstrap*, which is used in order to verify the validity of the first executable image; and
- *counterRIMProtect*, which is used to protect internal RIM_Certs from re-flash attacks.

To summarise, in table 29, we define the MTM permanent data associated with an engine's secure boot mechanism.

Name	Description
counterBootstrap	This field contains the current value of the counterBootstrap monotonic counter.
counterRimProtectId	This field contains the current value of the counterRIMProtect monotonic counter.
integrityCheckRootSize	This field indicates the length of the data held in the *integrityCheckRootData* field in bytes.
integrityCheckRootData	This field contains an immutable cryptographic binding of a single MRTM instance to (a) RVAI(s) in the case of a mandatory engine or an immutable cryptographic binding of a single MLTM instance to (a) RVAI(s) in the case of a discretionary engine.
internalVerificationKey	This field contains a secret unique to an MTM used in the creation (i.e. authorisation and integrity protection) of internal RIM_Certs from external RIM_certs.

Table 29: MTM permanent flags

A RVAI and a Rim_Auth_Cert are represented in an MTM by the *TPM_VERIFICATION_KEY* structure which is composed of the parameters defined in table 30.

Name	**Description**
tag	This field contains the value '*TPM_TAG_VERIFICATION_KEY*'.
usageFlags	This field define the capabilities associated with the key.
parentId	This field contains an identifier for the key's parent key, if indeed one exists.
myId	This field contains an identifier for the key defined in the structure.
referenceCounter	This field defines the name and the value of

	the counter to which the key structure is bound.
keyAlgorithm	This field contains an algorithm identifier for the key.
keyScheme	This field defines the manner by which the *integrityCheckData* field can be validated using the *keyData*.
extensionDigestSize	The length in bytes of the *extensionDigest* field
extensionDigest	A buffer containing a hash of the proprietary extension data.
keySize	The length of the *keyData* field.
keyData	The verification key, be it a RVAI or indeed a RIM_Auth key.
integrityCheckSize	The length of the *integrityCheckData* field.
integrityCheckData	An integrity check of the *TPM_VERIFICATION_KEY.*

Table 30: *TPM_VERIFICATION_KEY* structure

A Rim_Cert takes the form of a *TPM_RIM_CERTIFICATE* structure which is composed of the parameters defined in table 31.

Name	Description
tag	Must be set to *TPM_TAG_RIM_CERTIFIC*ATE
label	A proprietary label.
rimVersion	A version number for the RIM certificate.
referenceCounter	This field defines the name and the value of the counter to which the key structure is bound.
state	This field contains the expected values of the engine's PCRs at the time of certificate use. Unless the value in this field matches that of the engine's PCRs the certificate will not be accepted.
measurementPcrIndex	This field specifies the PCR that is to be extended with *measurementValue* using the *TPM_VerifyRIMCertAndExtend* command.
measurementValue	This field contains the value to be extended into the PCR – '*measurementPcrIndex*'.
parentId	The identity of the key of the *TPM_VERIFICATION_KEY* used to verify the structure.
extensionDigestSize	The length in bytes of the *extensionDigest*.
extensionDigest	This field contains a hash of the proprietary extension data.
integrityCheckSize	The length of the data in the

	'*integrityCheckData*' field.
integrityCheckData	An integrity check on the *TPM_RIM_CERTIFICATE*.

Table 31: *TPM_RIM_CERTIFICATE* structure

In order to enable a secure boot process, RIM_Certs must initially be installed in an engine. The command used for RIM installation is shown in table 32. This command is used to generate internal RIM certificates from external RIM certificates. During this conversion:

- all fields of the external RIM_Cert input are written to the structure for an internal RIM_Cert.
- the *counterReference* -> *counterSelection* field is set to *MTM_COUNTER_SELECT_RIMPROTECT.*
- the value of the permanent data field counterRIMProtectId +1 is inserted into the *counterReference* -> *counterValue* field.
- the *integrityCheckdata* for the internal RIM_Cert is generated using the *TPM_Internal_Verification_Key* as a HMAC key and written to *rimCertOut* -> *integrityCheckData*.
- The size of the *integrityCheckData* is written into the *rimCertOut* -> *integrityCheckDataSize*.

TPM_InstallRIM

Table 32: RIM installation

The resultant internal RIM_Certs can be checked using *TPM_VerifyRIMCert* as shown in table 33.

TPM_VerifyRIMCert	When this command is called the RIM_Cert syntax, verification key, counter value and integrityCheckData are validated.

Table 33: RIM_Cert verification

The *TPM_LoadVerificationKey* command, shown in table 34, is used to load verification keys into an MTM (including the RVAI). Verification key loading can be authorised using one of the following means.

1. The key may be loaded into the MTM before integrity checking has been enabled, i.e. the *MTM_STANY_FLAG* -> *loadVerificationrootKeyEnabled* = *TRUE*.
   This enables a verification root key (namely a RVAI) to be loaded when the MTM is first manufactured or customised for a particular engine.
2. A cryptographic hash or equivalent may be embedded in *MTM_PERMANANT_DATA* -> *integrityCheckRootData* in the MTM.
3. The loading may be authorised by the MTM owner.
4. The key to be loaded may be signed by an authentic, authorised and already loaded *TPM_VERIFICATION_KEY.*

TPM_LoadVerificationKey

Table 34: Loading a verification key

The *TPM_LoadVerificationRootKeyDisable* command, as shown in table 35, disables the functionality to load a verification root key as described in step 1 above.

TPM_LoadVerificationRootKeyDisable	This command sets loadVerificationrootKeyEnabled = FALSE

Table 35: Disabling the loading of a root verification key

The *TPM_IncrementBootstrapCounter* command increments *MTM_Permanent_Data –> CounterBootstrap*. In order to execute this command a RIM_Cert containing the incremented counter value and signed using as *TPM_VERIFICATION_KEY* whose usage flags have *TPM_VERIFICATION_KEY_USAGE_SIGN_RIM_CERT* and *TPM_VERIFICATION _KEY_USAGE_INCREMENT_BOOTSTRAP* set must be input.

TPM_IncrementBootstrapCounter

Table 36: Incrementing a bootstrap counter

The *TPM_SetVerifiedPCRSelection* command is used to set MTM_PERMANANT_DATA -> verifiedPCRs. This field lists the PCRs into which only verified measurement values can be written. This command may be called when *MTM_STANY_FLAG -> loadVerificationrootKeyEnabled = TRUE*, else it requires MTM owner authorisation.

TPM_SetVerifiedPCRSelection

Table 37: Setting verified PCRs

As stated above, the *TPM_VerifiyRIMCertAndExtend* command is used to verify a measurement against a RIM contained in the corresponding RIM_Cert and, given a successful validation, to extend the PCR listed in the RIM_Cert with the measurement.

TPM_ VerifiyRIMCertAndExtend

Table 38: Measurement verification and PCR extension

Given the scenario in which a corporate entity is the device owner who requires all device operators (namely employees) to use the secure wallet mechanism and assuming therefore that the device owner has listed the service provider engine which provides the secure wallet functionality in the *DeviceOwner_mandatoryEngineList*, and that the service provider engine is supported by an MRTM, the secure boot of this engine may proceed as follows.

Prior to a secure boot:

1. A service provider RVAI must be loaded using *MTM_LoadVerificationKey*.
2. Once the RVAI has been loaded, the flag which enables a *TPM_VERIFICATION_KEY* to be loaded without the completion of any integrity checks, must be set to false, *MTM_STANY_FLAGS -> loadVerificationrootKeyEnabled = FALSE*, using the *MTM_LoadVerificationRootKeyDisable* command.
3. MTM permanent data must be set:
   MTM_PERMANENT_DATA ->
   counterBootstrap = the current value of the Bootstrap counter
   counterRIMProtectId = the current value of the RIMProtect counter
   integrityCheckRootSize = the size of an integrity value for the RVAI

integrityCheckRootData = the value of an integrity value for the RVAI
internalVerificationData = the engine's internal verification key
verificationAuth = the *verificationAuth* used to authorise *MTM_InstallRIM* and updates of the *counterRIMProtect*.

4. While the RVAI may be used either to sign a RIM_Auth_Certs or sign a RIM_Cert it is considered best policy to use the RVAI for signing RIM_Auth_Certs only.
   For this use-case we therefore require the generation and upload of a second public key pair which is then used in order to protect secure wallet data using *MTM_LoadVerificationKey*.
5. The private key from this newly loaded RIM_Auth key is then used by the service provider to sign an external RIM_Cert for the secure wallet application. This RIM_Cert must then be installed on the service provider engine using *MTM_InstallRIM*.
6. Once an internal RIM_Cert has been created it may be verified within the engine using the *MTM_VerifyRIMCert* command.
7. Finally, the MTM owner must specify the PCR which is to be extended with a verified secure wallet application measurement using the *MTM_SetVerifiedPCRSelection* command.

Following this the RTM, i.e. the first measurement agent running within an engine, can retrieve a list of components to be measured (for simplicity sake, we assume that the secure wallet is the only component within this engine to be measured and verified) and measures the first component. The RTV, i.e. the first verification engine agent running within an engine, then retrieves the expected value of the measured component and calls *MTM_VerifyRIMCertAndExtend* which results in the comparison of the calculated measurement against the expected software component's measurement. The measurement is then stored to an MTM PCR by the RTS and a summary of the measurement stored to a log file in the engine. If at any point the expected value of a software component cannot be located or indeed an expected value does not match the measured value then the boot process is aborted.

The exact process by which a trusted mobile platform is securely booted, its integrity measured, verified and its integrity measurements stored, needs to be specified for each TMP architecture, just as for the PC client in [66].

3.3.5 Maintaining Integrity

As stated in the previous section, TMP engines (with the exception of the device manufacturer engine) are not required to support a RTV. An engine which does support a RTV, and therefore a secure boot mechanism, may also support a mechanism which enables the integrity of an engine to be maintained after boot.

Within the mobile reference architecture [63] three engine states are described, namely *initialisation*, *success* and *failed*:

- An *initialisation* state indicates that the RTS is not fully operational and that since start-up no software measurements have yet been verified.
- A *success* state represents the state of an engine when the RTS is operational and all software measurements which require verification have been matched to their corresponding RIMs.
- A *failed* state indicates that the RTS is not operational (and cannot become so) or that, since start-up, some integrity measurement which required verification

has failed to a match its expected RIM.

Ideally, a platform would remain in a *success* state during run-time. In order to achieve this a preventative approach is required to run-time integrity maintenance. Suggested mechanisms which enable an engine to remain in a *success* state include but are not limited to the following.

- The protection of critical functions using hardware. In this case program code or critical data could be stored in Read Only Memory (ROM) or one-time programmable memory, for example.
- Software may be isolated using hardware mechanisms (whereby critical MTM functionality is implemented on a separate chip for example) or, indeed, software mechanisms (through the use of a trusted execution environment or full virtualisation).
- Software may be simplified. By reducing the complexity and size of software it becomes easier to make it error free and verify it as such.
- The installation of particular types of software may be heavily restricted. For example, the installation of native software may not be permitted. Alternatively, an operating system may enforce strong access controls which restrict the installation of certain software.
- Certain security checks may be completed on software at installation, for example, verification of integrity checks, public key certificates, digital signatures and the code itself. Given a failed integrity check, certificate revocation, a failed digital signature verification or indeed if on examination code contains the signature of known malware, the application will not be loaded onto the device.

Alternatively, a platform may transition from a *success* state to a *failed* state. In this case, the transition must be detected and the consequences of such a transition limited. A reactive approach to run-time integrity is comprised of two elements: a detection element and a reaction element.

The detection element described within the mobile reference architecture is essentially an extension of the secure boot mechanism. It requires a Primary Run-time Measurement/Verification Agent (PRMVA) which must reliably measure and verify at least one software component running on the host engine. A secondary RMVA, which is measured and verified by the PRMVA may also exist if the PRMVA is unable to perform all the necessary checks alone.

The expected runtime RIM of a software component may be different to the expected boot time RIM. Therefore, run-time measurements are verified against run-time RIMs contained within RIM_run Certs. A RIM_run Cert may be classified as external or internal and may be in the form of a RIM_Cert or indeed in a proprietary format. An external RIM_run Cert may be created by the engine's stakeholder and input into the device. Alternatively, RIM_run Certs may be generated by the engine itself by measuring each code image just after it has been launched. It is pivotal, however, that every effort is made to ensure that false negatives between run-time software component measurements and RIM_run Certs are avoided. In order to achieve this a software image may be loaded into the same memory location each time, for example, or the static part of a software component may be measured as opposed to the entire component.

An engine's stakeholder specifies how often and/or under what conditions runtime measurement and verification occurs. Policies for run-time measurement and verification essentially fall into one of two classes, time-based checks which are completed at regular intervals or alternatively, event-based checks.

3.3.6 Secure Storage

Requirements **SecureWallet3** to **SecureWallet14** can be partially met through the deployment of a secure storage mechanism.

3.3.6.1 Key Hierarchy

Each TMP stakeholder can incorporate his own key hierarchy. Here the focus is on the secure wallet provider. A sample key hierarchy from a secure wallet provider engine is represented in figure 25.

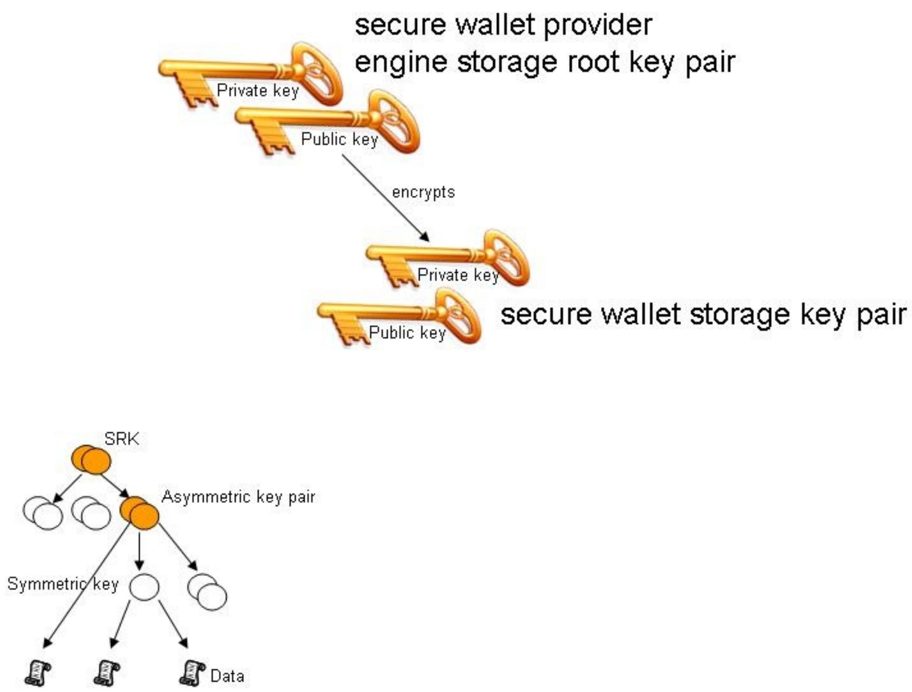


Figure 25: A sample key hierarchy from a secure wallet provider engine

3.3.6.2 Installing Integrity and Confidentiality Sensitive Data

In order to import sensitive data into a secure wallet for protection, a secure transport session can be set up with the engine's MTM so that all input parameters into the secure storage commands described below can be protected while being communicated to the MTM.

Transport security enables the establishment of a secure channel between the MTM and secure processes, offering confidentiality and integrity protection of commands sent to the MTM. It also provides a logging function such that all commands sent to the MTM during a transport session can be recorded.

Session establishment involves the generation of 20 bytes of transport authorisation data by the caller, for use between the caller and the MTM. This transport authorisation data has two purposes:

- It is used to generate a secret key for use in encrypting commands from the application to the MTM; and
- It is also used to generate a secret HMAC key to provide origin authentication and integrity protection for the *TPM_ExecuteTransport* command.

The authorisation data is generated by the caller and encrypted under a public key whose corresponding private key is available only to the MTM. The key used is pointed to in the *encHandle* field of the *TPM_EstablishTransport* command.

A transport session is established, used and terminated using the commands shown in table 39.

Establish transport session:
TPM_EstablishTransport
Execute transport session:
TPM_ExecuteTransport
Close transport session:
This command completes the transport session, and if logging is switched on, a signed hash of all operations completed during the session is output. In order to complete this command run, a signing key must have been created for this purpose and its handle communicated as input to the:
TPM_ReleaseTransportSigned

Table 39: A transport session

If an inherent confidentiality-protected channel exists between the MTM and its RTM and RTV transport session functionality is considered optional on both an MRTM and an MLTM. Else this functionality is required in both cases.

3.3.6.3 Secure Storage of and Access Control to Sensitive Data

Data which needs to be both integrity and confidentiality protected, may be MACed and encrypted using cryptographic functionality provided for by a TCG independent Cryptographic Infrastructure (CI) implemented on the platform. This CI may then utilise the MTM so that a *TPM_Seal* can be called and the MAC and encryption keys stored securely, where the sealing mechanism can confidentiality protect the symmetric keys and ensure that they are only accessible by the legitimate application, namely the secure wallet application.

Alternatively, sensitive data which needs to be both integrity and confidentiality protected, may be directly sealed by the MTM such that it is only accessible to a particular legitimate secure wallet application.

Integrity protection is not explicitly provided by the sealing mechanism. In order to integrity protect sealed data, 20 bytes of authorisation data needs to be associated with it. This authorisation data then needs to be sealed to a particular application (or PCR values which represent a trustworthy platform environment in which a correctly functioning version of the particular application is running). In this way, only the correctly functioning application can unseal the authorisation data and then unseal the protected data. Data protected in this way can only be unsealed if knowledge of the correct authorisation data is demonstrated and the current platform environment is represented by the PCR values bound to the data when it was sealed.

In order to protect data input to the secure wallet, a key hierarchy as described above must initially be set-up and then the data sealed to the appropriate PCRs using the 'Secure Wallet Storage Key (SWSK)' (a non-migratable storage key) such that it can only be accessed by the secure wallet application.

1. Load the secure wallet provider SRK and obtain a handle to the SRK.
2. The secure wallet storage key needs to be created under the secure wallet SRK, as shown in table 40.

TPM_CreateWrapKey

Table 40: Creating a wrap key

3. Load the SWSK, as shown in table 41.

TPM_LoadKey2

Table 41: Loading a key

4. Finally, seal the secure wallet sensitive data or, indeed, the symmetric keys used to confidentiality and integrity-protect the secure wallet sensitive data, using the SWSK, as shown in table 42.

TPM_Seal

Table 42: Sealing data using a storage key

Secure storage functionality, as described by the TCG, cannot prevent the unauthorised deletion of stored data. Both an MRTM and an MLTM are required to implement the commands shown in table 40, 41 and 42.

3.3.6.4 Security of the Secure Wallet Sensitive Data While in Use

The PCRs which represent the execution environment into which the secure wallet data can be released are presumed to represent be a secure and trustworthy environment. Isolation techniques described in chapter 2 can be used to protect sensitive secure wallet data while in use on the platform.

3.3.7 Demonstrating Privilege

In order to demonstrate the level of privilege required to execute various MTM commands:

- An entity may demonstrate physical presence at the platform; or, alternatively,
- An entity may demonstrate knowledge of the required authorisation data.

There are three particular occasions where demonstration of physical presence at the platform may be necessary in order to execute particular MLTM commands. These occasions include the operation of commands that control the MLTM when the MLTM owner has lost cryptographic authorisation information; to authorise an MLTM command in a way that can not be subverted by rogue software; or to temporarily deactivate an MLTM.

Physical presence must not, however, be supported in an MRTM as the entity who is in control of the engine is assumed to be absent and the operator of the phone is not considered to be in control of the phone. In conjunction with this, owner authorised commands may not be implemented on a mandatory engine and if owner authorised commands are implemented it is assumed that the owner-authorisation data is backed-up remotely.

As an alternative to physical presence, cryptographic authorisation mechanisms may be used to authenticate an owner to their MTM, or to authorise the release and use of MTM protected objects. An authorisation value must be 20 bytes long, for example, a hashed password or 20 bytes from a smartcard. It must always be treated as shielded data and only ever used in the authorisation process.

Many of the MTM commands described throughout this chapter (specifically the MTM owner authorised commands) may require knowledge of the required authorisation data to be demonstrated before access to either an MTM owner authorised command, a key or even a data object is permitted. A variety of authorisation data is held by an MTM, including:

- Unique MTM owner authorisation data, input of which is required before any 'owner-authorised MTM command' may be executed;
- MTM object usage authorisation data, input of which is required before an object protected by the MTM may be accessed; and
- MTM object migration authorisation data, input of which is required before an MTM key object can be migrated.

In order to demonstrate knowledge of the relevant authorisation data to the MTM, an entity may deploy one of two challenge-response protocols, namely the Object Independent Authorisation Protocol (OIAP) or the Object Specific Authorisation Protocol (OSAP).

OIAP is the more flexible and efficient of the two challenge-response authorisation protocols. Once an OIAP session has been established, it can be used to demonstrate knowledge of the authorisation data associated with a particular MTM object or MTM command.

For example, if the MTM owner wishes to read the public endorsement key knowledge of the owner authorisation data must be initially demonstrated, in order to gain access to the public endorsement key, as shown in table 43.

TPM_OIAP

TPM_OwnerReadInternalPub

Table 43: Authorising an MTM owner read of the public endorsement key

The second protocol defined in the TCG specifications is OSAP. This protocol allows for the establishment of a session to prove knowledge of the authorisation data for a single MTM object, and minimises the exposure of long-term authorisation values. It may be used to authorise multiple commands without additional session establishment but, as we discuss below, the *TPM_OSAP* handle specifies a single object to which all authorisations are bound.

During this protocol an ephemeral secret is generated (via the HMAC of the session nonces exchanged at the beginning of the protocol, with the target MTM object's authorisation data used as the HMAC key) by the MTM and the caller, which is used to prove knowledge of the MTM object authorisation data.

This particular protocol must also be used with operations that set or reset authorisation data, e.g. sealing or creating a wrap key. In order to input the required authorisation data a number of steps must be followed:

1. The *TPM_OSAP* command must be called. *TPM_OSAP* creates the authorization handle, the shared secret and generates *nonceEven* and *nonceEvenOSAP*.
2. The required MTM command is called.
3. The shared secret which is generated can be used not only to authorise use of the parent object but also to input the authorisation data for a newly created child object, for example a new key or sealed data object.
4. Once this has been completed, the OSAP session can be kept open in order to authorise another command which is bound to the same parent object.

We will now re-examine the load key command run shown in table 41, where we assume that the key, SWSK, is to be loaded by the input of a wrapped key blob. It is also assumed that the engine's SRK is loaded and its handle is available, and that the parent key, the engine's SRK, requires authorisation.

In order to load the SWSK, knowledge of the SRK authorisation data must be demonstrated. When the SWSK has been loaded, a seal command, as described in table 42, is called. Use of the SWSK must also be authorised.

In this case, the user can demonstrate knowledge of the parent wrapping key (the SRK) authorisation data when loading the non-migratable key, SWSK, using an OIAP, for example. When sealing the secure wallet data using the SWSK, knowledge of the SWSK authorisation data can be demonstrated and the authorisation data for the sealed data inserted using the shared key established during the initial steps of the OSAP. This process is shown in table 44.

Assume we have the handle of the engine's SRK
TPM_OIAP
TPM_LoadKey2

Now we have the handle to SWSK seal data:

TPM_OSAP

TPM_Seal

Table 44: Authorising a load key and an object seal

3.3.8 Conclusions

We have utilised the requirements extracted in section 3.2 from the analysis of the secure wallet use-case designed by RUB in order to examine which architectural components, based on TCG mobile reference architecture [63], and which functions, as specified in the TCG MTM specification [64], could be used to facilitate its robust implementation. The components and functionality required in order to implement the secure wallet mechanism will be used in specifying and analysing the methods by which a subset of MTM functionality can be provided given an X-GOLD™ 208/a generic OMTP TR1 device.

Table 45 summaries the subset of MTM commands required in order to enable this use-case. Regardless of whether the secure wallet mechanism is implemented on a mandatory or a discretionary engine, an authenticated boot mechanism is required. In order to implement an authenticated boot mechanism, the TMP must incorporate:

- A RTM; and
- A RTS (including PCRs).

If the secure wallet mechanism is implemented on a mandatory engine, a secure boot mechanism may be leveraged. In order to implement a secure boot mechanism, the TMP must incorporate:

- A RTM;
- A RTV;
- A RTS (incorporating PCRs).
- A RVAI;
- A list of keys authorised to sign RIM_Certs;
- An internal verification key;
- Two monotonic counters:
  - counterRIMProtect
  - counterBootstrap
- Platform component RIM_Certs;
- A policy for platform recovery; and
- Policies for RIM certificate revocation and update.

In order to maintain integrity after boot, a number of preventative and reactive approaches may be deployed. We assume the use of software isolation through the deployment of virtualisation technology (namely, an L4 microkernel).

In order to implement this use-cases, it is also required that the TMP engine can be taken ownership of. In conjunction with this, basic functionality, such as self testing, is also needed. Secure storage and command authorisation functionality is also mandatory in order to robustly implement the secure wallet mechanism.

Table 45: MTM commands required in an MLTM and an MRTM in order to implement the secure wallet mechanism

MLTM	MRTM
TPM_Init	TPM_Init
TPM_Startup	TPM_Startup
TPM_SelfTestFull	TPM_SelfTestFull
TPM_ContinueSelfTest	TPM_ContinueSelfTest
TPM_GetTestResult	TPM_GetTestResult
TPM_SetOwnerInstall	This command may not be required in an MRTM as it may be pre-installed with an SRK and an AIK.
TPM_OwnerSetDisable	An MRTM can never be disabled.
TPM_PhysicalEnable	An MRTM is always enabled so this command is not required.
TPM_PhysicalDisable	An MRTM can never be disabled.
TPM_PhysicalSetDeactivated	An MRTM can never be deactivated.
TPM_TakeOwnership	This command may not be required in an MRTM as it may be pre-installed with an SRK and an AIK.
TPM_Seal	TPM_Seal
TPM_CreateWrapKey	TPM_CreateWrapKey
TPM_LoadKey2	TPM_LoadKey2
TPM CreateEndorsementKeyPair	An MRTM may not contain an endorsement key pair so this command is considered optional.
TPM_ReadPubek	An MRTM may not contain an endorsement key pair so this command is considered optional.
TPM_OwnerReadInternalPub (optional)	An MRTM may not contain an endorsement key pair so this command is considered optional.
TPM_Extend	TPM_Extend
TPM_OIAP	TPM_OIAP
TPM_OSAP	TPM_OSAP
TPM_EstablishTransport (required if no inherent confidentiality-protected channel exists between the MTM and the RTM/RTV)	TPM_EstablishTransport (required if no inherent confidentiality-protected channel exists between the MTM and the RTM/RTV)
TPM_ExecuteTransport (required if no inherent confidentiality-protected channel exists between the MTM and the RTM/RTV)	TPM_ExecuteTransport (required if no inherent confidentiality-protected channel exists between the MTM and the RTM/RTV)
TPM_ReleaseTransportSigned (required if no inherent confidentiality-protected channel exists between the MTM and the RTM/RTV)	TPM_ReleaseTransportSigned (required if no inherent confidentiality-protected channel exists between the MTM and the RTM/RTV)
TPM_ReadCounter	TPM_ReadCounter
-	TPM_InstallRIM
-	TPM_VerifyRIMCert
-	TPM_LoadVerificationKey
-	TPM_LoadVerificationRootKeyDisable
-	TPM_IncrementBootstrapCounter
-	TPM_SetVerifiedPCRSelection
-	TPM_VerifyRIMCertAndExtend

4 OMTP TR1 and the Secure Wallet Prototype

In this section we consider the secure wallet prototype in the context of the recently published OMTP (Open Mobile Terminal Platform) TR1 Advanced Trusted Environment recommendations document [50]. We will consider a final architecture where the secure wallet has been completely ported to the X-GOLD™ 208.

First of all we briefly summarize the main features of the OMTP TR1 document. For details, the reader is advised to consult the original document.

4.1 OMTP TR1 Summary

OMTP TR1 is a successor to the OMTP TR0 Trusted Environment document [49]. OMTP TR1 has been aligned with current threats and business requirements. Although TR1 is concerned with mobile equipment security, which means the handset, it also acknowledges that a UICC (Universal Integrated Circuit Card) would in many cases meet, and exceeds the security requirements defined in the TR1 recommendations document. The UICC is the chip card used in mobile phones on GSM and UMTS networks. It is best known as the location of the SIM application. It can also host other applications. Many of the OMTP TR1 Security Enabler requirements and the TR1 use cases make reference to the UICC.

Where as OMTP TR0 defines a basic threat model, TR1 has a much more detailed threat model, and all requirements reference the threat model where relevant. Two security profiles called profile 1 and profile 2 are defined. Profile 1 is a subset of profile 2, and these profiles define which threats have to be defended against. Profile 1 assets must mostly be only defended against software attacks and some basic hardware attacks. Profile 2 assets must be defended against software attacks and more advanced hardware attacks.

The document is partitioned into two parts. Part 1 consists of security enablers. Part 2 consists of some example use cases.

4.1.1 Security Enablers

In this section we summarize the security enablers defined in the TR1 document.

- Trusted Execution Environment (TEE)

This is an execution environment for executing security sensitive programs. It meets a defined set of security requirements, resists a defined set of threats, and within this scope ensures that a program executes as it was designed to execute.

- Secure Storage (SST)

The secure storage facility helps the TEE to handle security sensitive objects. It stores the sensitive objects in a way that the security properties of the objects are maintained within the scope of a defined set of threats.

- Flexible Secure Boot (FSB)

FSB requirements ensure the integrity of the ME (Mobile Equipment) code base at boot time, and also defines requirements for securely updating the code image via an external connection to the ME. Again these requirements are within the scope of a defined set of threats.

- Generic Bootstrap Architecture (GBA)

3GPP GBA is a generic method which can be used by arbitrary application functions in the mobile network to authenticate users and establish a shared secret. It is based on the fact that both network and USIM share a 128-bit secret key K_i. The MNO (Mobile Network Operator) stores the secret keys for all subscribers in a Authentication Center (AUC), which is connected to the Home Location Register. The secret keys never leave the AUC and SIM domain.

An AKA (Authentication and Key Agreement) protocol is executed between the USIM/ ISIM and the mobile network in order to generate a confidentiality session key (CK) and integrity session key (IK). An ISIM is a further application which can run on the UICC. It is part of the IMS (Internet Protocol Multimedia Subsystem), which is a framework for delivering IP Multimedia over GSM/UMTS mobile networks. In the case of ME based GBA , upon successful network verification, the USIM/ISIM delivers the confidentiality and integrity keys CK and IK to the mobile station, where they are used to generate the shared secret with the target network application function.

The GBA requirements are concerned with which level of TEE the sensitive GBA software should run on the ME. There are also requirements regarding protection of the confidentiality and integrity of the CK and IK if delivered to the ME. There are also further requirements regarding access restriction for applications running on the UE (User Equipment) which request access to the GBA functions on the USIM. These access controls are not specifically supported by any additional cryptographic mechanisms, and would therefore need to be by supported access control mechanisms built into the software architecture of the ME. Most of the OMTP requirements are based on references to the relevant 3GPP specifications.

- Run-Time Integrity Checking (RIC)

TR0 was mostly concerned with boot time security when considering platform integrity. Where as TR0 did make references to run-time checking, there were no detailed requirements. The purpose of RIC is to check system integrity, post of boot. The RIC requirements do not define what must be checked by the RIC, but rather the robustness rules for the RIC mechanisms.

Some important principles are laid out. For example the RIC may be a hardware mechanism or could also be software mechanism in a TEE. The RIC cannot be used to check resources upon which it relies. For example, if the RIC is executed within a TEE, it cannot be used to check the integrity of that TEE. Also, it must not be possible for less trusted software to manipulate this TEE or other RIC assets. All the requirements are made with reference to the threat model.

What is actually checked depends on the system. This could be the main OS. Access Control Lists or other sensitive system assets. The specification also considers a primary and secondary RIC. The secondary RIC could be a software mechanism used by the main OS. TR1 states that the primary RIC must verify the integrity of the secondary RIC.

- Secure Access to User Input/Output Facility (SUIO)

The SUIO requirements are concerned with the input and output of data between the user and the TEE where a trusted application is executing. SUIO assets are only required to be defending against software attacks. The IO facilities here could be a keyboard, touch-screen, display etc.

- Secure Interaction of UICC with Mobile Equipment (SUM)

The SUM requirements are concerned with creating and maintaining a secure channel between the ME and the UICC. The required function is that the UICC can authenticate the ME, or perhaps a specific TEE running in the ME, and a secure channel can be created between the ME (or TEE) and the UICC. This allows a secure application to be partitioned between the ME and the UICC.

4.1.2 Threat Model

As already mentioned TR1 has a much more detailed threat model than TR0. Seven threat groups have been defined.

4.1.2.1 Group 1 (Hardware Modules used for Accessing Memories)

These are threats which are based on misuse of on chip bus master modules, other than the main CPU, which could be used to access security sensitive memory ranges for example. These types of attacks are considered, especially since master modules usually do not have any MMU type hardware built into them.

4.1.2.2 Group 2 (CLCD (Color LCD Controller) used for displaying memories and interfering with displayed data)

These threats are similar to group 1, but allow any accessed sensitive data to be displayed.

4.1.2.3 Group 3 (Bypass security by removal of battery power or removal of external memory card)

These threats are concerned with putting the ME in an unknown state, or preventing it from completing a sensitive operation by power removal. Memory card is included as if sensitive information were stored on it, it may be possible to manipulate the handset behavior with respect to these sensitive objects by removing the memory card.

4.1.2.4 Group 4 (Attack by replacement of flash when power is off (pre-boot))

A secured handset which does not allow the code image in flash to be altered could still be attacked by de-soldering the flash and replacing it with hacked code.

4.1.2.5 Group 5 (Extract secret via bus monitoring)

Confidential data could be extracted from the ME if it passes between the main processor and external flash or DRAM, by probing the connections between these components.

4.1.2.6 Group 6 (Mod chip attacks on data in external RAM)

These are quite advanced threats. They are concerned with the use of additional hardware built into the ME which can be used to manipulate data or code at runtime, as it is in transit between the main CPU and external memory. This could alter the behaviour of the ME.

4.1.2.7 Group 7 (Attack by replacement of flash when power is on (post-boot))

This threat is based on a physical attack on the handset. The handset is modified with additional logic (and perhaps memory components) so that the memory image is swapped post boot, with modified code.

4.1.2.8 Software Threats

Software threats are handled as a set of best practices.

Software Quality Measures

Improving the quality of the software is concerned with removing security vulnerabilities which could be exploited. The types of measures which are advised include special attention to validation of security code, external review, reduce size of the security code, and use of an execution environment with reduced instruction set (Java for example).

Definition of API Related Coding Techniques

Techniques are described which avoid problems due to poorly designed APIs. These include separation of security APIs from other APIs, isolation of security code from other code so that a different boundary is crossed when calling security APIs than when calling standard APIs, and use type safe APIs on the security boundary.

Definition of buffer overflow techniques

Buffer overflow attacks are a common method used to attack systems. TR1 describes some techniques to counter such attacks. They include use of type safe API (which keep track of buffer sizes), and using verification tools which analyse source code for buffer overflow vulnerabilities, prevent areas used for stacks and heaps from being executable.

Definition of execution isolation techniques to address software attacks

These techniques are concerned with isolating the scope of an attack. This means that if a vulnerability is found, it does not mean that the whole system is vulnerable. Methods including hardware isolation, and use of microkernel architectures, can be used to achieve this security goal.

Definition of concurrent processing threats

This is concerned with vulnerabilities due to race conditions in the operating system. Possible ways to combat these types of attacks is to use a simple thread model in the the security software domain.

4.1.3 TR1 Core Requirements

TR1 has a set of requirements which are valid throughout the whole document for all Security Enabler and use case requirements. It starts by defining asset grouping. These are split into sensitive TR1 code assets, data assets, hardware assets, and key assets.

TR1 then defines some base requirements for software threats, and hardware threats, and specifies which for profile 1 and 2 which threats must be defended against.

4.1.3.1 Requirements to protect against software threats

For both profile 1 and profile 2, TR1 requires use of the techniques proposed in ‘Definition of software Quality Measures’, ‘Definition of API Related Coding Techniques, ‘Definition of Buffer Overflow Protection Mechanisms’.

Only profile 2 is required to defend the TR1 asset’s security properties against the threats described in ‘Hardware Modules used for Accessing Memory’ and ‘CLCD used for Displaying Memories and Interfering with Displayed Data’.

Further, only profile 2 is recommended to make use of methods described in ‘Definition of Concurrent Processing Threats’, and ‘Definition of Execution Isolation Techniques to Address Software Attacks’.

4.1.3.2 Requirements to protect against hardware threats

The security properties of TR1 profile 1 and 2 code, data, and key assets are required to be protected against attacks based on battery or card removal (threat group 3), and attacks based on the removal of flash when the mobile phone is not powered (threat group 4).

Only profile 2 TR1 confidential assets are required to be defended against bus probing threats (threat group 5), and only profile 2 TR1 Key Assets are required to be protected against ‘Mod chip attacks on data in external memory’ (threat group 6), and ‘Attack by replacement of flash when power is on’ (threat group 7).

4.1.3.3 Debug Requirements

The debug requirements refer to the TR0 debug requirements, but are a little more specific regarding threat profile. The most important point is that debug assets which are used to debug a profile 2 TEE must also be of profile 2.

4.1.3.4 Cryptographic Requirements

TR1 also defines a set of cryptographic requirements. These are quite similar to TR0 HUK (Hardware Unique Key) requirements. Some changes are that the RSA key length was increased from 1024 to 2048 bit, and the SHA digest length was also increased from SHA1 (160 bit) to SHA-256 for protecting authenticity.

4.1.4 Asset Protection

Each TR1 enabler or Use Case description has an asset table. Each asset has its type defined (data, code, keys etc.), and the security property required for this property is defined. All the TR1 enablers and Use Cases specifically refer to an HUK as an asset. The security properties which are defined are integrity, confidentiality, authenticity, and non-replay. Often the requirement for defending a property is very specific to the use case.

4.1.5 Trusted Execution Environment

In this section we look at the TEE is a little more detail since this is one of the most important security enablers for TR1. TR1 begins by introducing the concept of an Execution Environment (EE), being a set of hardware/software components.

Further, TR1 describes a typical set of core components for the execution environment itself. These are a processing unit which define the EE Instruction Set Architecture (ISA), a set of connections (buses for example), physical memory for storing data and code, a mechanism for initializing the boot process, and the EE code, data and keys.

The EE has a set of facilities which it makes available to Applications.

The applications need some form of interface. This could be an API or an ISA.

EEs will vary in complexity, they may provide dynamic management of code (thread management, task switching, the possibility to load and unload applications etc.). Further, the code may be natively executed or interpreted.

The environment may also provide memory management. This allows areas of memory to be allocated/de-allocated, and control access to memory depending on what application is currently running in the environment. Other facilities such as storage and retrieval of data in non volatile memory may also be provided.

The EE may also offer facilities which allow an application to communicate with the external world. This could be to something local such as keyboard and display, or something remote such as a network connection.

As already mentioned more than one application may execute in an EE. The EE may provide facilities to allow the applications to communicate with each other. The EE may also provide facilities to install, upgrade and generally manage applications. This may include identifying users and processes, and assign them credentials and permissions so that access control policies may be enforced.

A system may contain multiple Execution Environments, and they may share resources, or have resources allocated to a particular EE. In this case, the resource must be protected from other EEs. TR1 assumes that some of the EEs will have access to a Hardware Unique Key as defined in TR0. TR1 also assumes that a TEE will always have access to secure storage facilities.

Applications running in an EE could be a service to a user, or to another application. An application running in an EE could be another EE. Example of EEs are a CPU, an Operating System, a Virtual Machine or a UICC.

TR1 considers two sets of security requirements (profile 1 and profile 2) as already mentioned. If an EE meets these security requirements of a particular profile, it can then be referred to as a TEE of this profile.

4.1.5.1 Open Trusted Execution Environment

TR1 also defines an Open Trusted Execution Environment. This type of TEE is quite specific to operator requirements. An Open TEE is a TEE which allow the MNO to install applications into it ‘post manufacturing’. Further, an Open TEE must support a UICC secure channel, the Generic Bootstrap Architecture, and secure user IO.

4.1.5.2 Trusted Execution Environment Requirements

The TR1 TEE requirements are partitioned into groups. These are:

- TEE Core Requirements

These are generally concerned with TEE HUK requirements

- TEE Cryptographic Requirements

These are concerned the level of cryptographic support required by a TEE

- TEE Keys

This is a set of requirements concerned with key handling within the TEE.

- TEE Facilities

These requirements are concerned with the facilities required for the different types of TEE. Examples of required facilities are SUIO, SST and SUM.

- TEE Application Lifecycle

These requirements are concerned with the rules for installing applications within a TEE.

- TEE Application Requirements

The requirements are mostly concerned with isolation of applications within a TEE, and also checking the authenticity/integrity of applications before letting them run.

- TEE Self Protection Requirements

These requirements are mostly concerned with securely booting the TEE, and make references to the FSB facility.

- TEE Isolation Requirements

These requirements are mostly concerned with protecting the TEE and its resources from others EEs.

- Inter-Execution Environment Communications

This is a set of requirements which are concerned with how TEEs and EEs can securely communicate with each other.

One of the basic TEE requirements is access to a Secure Storage facility. We will look at the OMTP T1 Secure Storage structures and requirements when we analyse the Secure Wallet prototype architecture.

4.1.6 Use Case Overview

TR1 includes three use cases. These are Broadcast Service Protection, Trusted Device Management, and Mobile Commerce. We will briefly look at them here, and summarize which of the TR1 security enablers are made use of for each of them.

4.1.6.1 Broadcast Service Protection

The broadcast service protection use case concentrates on the Open Mobile Alliance (OMA) BCAST Smart Card Profile. OMA BCAST is concerned with content broadcast services which are encrypted in order to control the consumption of these services.

In the Smart Card profile much of the security is centered on the use of a UICC. As TR1 points out, the UICC has a Trusted Execution Environment like facility with on chip card secure storage. The UICCs are generally designed to defend against threats which are often out of scope for a mobile phone baseband controller. OMA BCAST

Smart Card Profile defines that the long term keys are stored on the UICC.

The TR1 Broadcast requirements mostly deal with the protection of the keys which are in the ME. These are short terms keys, such as traffic keys, or binding keys for binding the UICC to the ME. The requirements reference the TR1 SUM (Secure Interaction of UICC with Mobile Equipment). The Broadcast Service Protection requirements also define the use of TEEs and SSTs in order to protect the key objects. This also means that the FSB requirements must be met for this use case.

OMA BCAST also makes use of GBA for key distribution, so the TR1 GBA requirements are also relevant.

4.1.6.2 Trusted Device Management

The Trusted Device Management use case is concerned with the requirements for a secure TR1 implementation of the Open Mobile Alliance Device Management protocol. This use case is divided into two sub use cases.

These are:

- Trusted Firmware Management (Update)

Firmware refers here top the basic software of the ME including device drivers.

- Trusted Software Management

This refers to any software other than the firmware. The types of functions required are installation, update, removal, activation and deactivation.

In OMA Device Management, the firmware/software on a device is managed by a management server.

The Access Control List is one of the most security sensitive assets. This defines for each management server what types of management commands can be executed on the device. If the Access Control List is manipulated, then the device can be compromised by an attacker.

The actual requirements are centred on the protection of a device management key. This is classified as a sensitive object which must be handled by an SST facility. The requirements also define that the security properties of the device management keys shall be protected, and that the key is only accessible by the appropriate firmware or software management code.

The download and update management code must be verified before execution. This could be at boot, in which case this can be managed by the secure boot. The Trusted Device Management use case also has some optional requirements for Secure User IO. TR1 does not go into this in detail, but one possible reason would be so that the end user can safely make a decision on whether to carry out a software update based on the information displayed on the screen.

Requirements for handling of a download package are handled by referring to the

Flexible Secure Boot security enabler. Further, if the downloaded application is to be installed into a TEE, then the installation process must follow the TEE Lifecycle Requirements.

4.1.6.3 Mobile Commerce

The mobile commerce use case referred to by TR1 is quite specific. It focuses on proximity payment where the most sensitive part of the application is in the UICC. The ME provides a User Interface (UI) to the payment application.

The ME has a browser which communicates with a web server situated on the UICC via an HTTP connection. This partitioning is based on the proximity payment architecture as recommended in the GSM Association NFC (Near Field Communication) technical guidelines.

The use case is broken up into two parts

1. The user has an application activated in her UICC by holding it close to a Point of Sale. The mobile commerce application indicates to the user that a transaction is pending. The user enters a PIN so that the transaction can complete.

2. The user has an application activated in her UICC by holding it close to a Point of Sale. The mobile commerce application indicates to the user that a transaction is pending. The user is only required to enter a PIN if the amount of money involved is above a certain limit.

The main assets involved in this use case are:

- a mobile application certificate used to allow the mobile application to authenticate itself to the UICC, and a root certificate for authenticating the mobile application certificate.
  - Each with the security properties integrity and authenticity

- The mobile application code, data, and keys.
  - All with security properties integrity and authenticity plus confidentiality for the keys.
- Data exchanged between the user and the mobile application via the keyboard and display.
  - With security properties integrity, authenticity, non-replay plus confidentiality for the keypad interface.
- A session key for creating a secure channel between the mobile application and the UICC.
  - With security properties integrity and confidentiality.
- A PIN for activating the payment service
  - With security properties integrity, confidentiality and non-replay.

Threats to the Mobile Commerce Application

The mobile commerce application code, data, and certificates need to be protected from

- Bypass security by removal of battery power or removal of external memory card
- Attack by replacement of flash when power is off (pre-boot)

This is for profile 1 and profile 2 applications.

To recap, only profile 2 mobile commerce application code, data, and certificates need to be protected against threats

- Hardware Modules used for Accessing Memories
- CLCD used for displaying memories and interfering with displayed data
- Extract secret via bus monitoring
- Mod chip attacks on data in external RAM
- Attack by replacement of flash when power is on(post-boot)

Further, only profile 2 mobile commerce application keys need to be protected from

- Extract secret via bus monitoring
- Mod chip attacks on data in external RAM

The mobile commerce use case also specifically has requirements for secure user IO for keyboard and display for both profile 1 and profile 2. But it must be noted that TR1 only defines a profile 1 SUIO.

There are also requirements for a secure storage utility if PIN and session key data are to survive for more than one session.

The certificates that are used must also be integrity protected. Although not stated in the TR1 requirements document, this could be managed by including them in the secure boot, or secure application loading mechanisms and then isolating them in a TEE.

The mobile commerce application must be checked at installation. It is advised to check it prior to execution, and optionally it can be checked at run time using a RIC.

Although not specifically stated, the mobile commerce use case could make good use of a TEE, SST, FSB.

4.2 Secure Wallet Architecture in the context of TR1

In order to understand the secure wallet architecture in the scope of the TR1 recommendations document, we will briefly compare it with one of the TR1 use cases. The mobile TV and the device management use cases are too dissimilar to the secure wallet use case, and we will not discuss them further. The TR1 mobile commerce example is the closest use case to the secure wallet mobile application, so we will now contrast and compare them.

Both use cases are concerned with a form of payment, but they are still quite different. The TR1 mobile commerce use case is very UICC centric, where as the secure wallet, in its final form would be completely implemented on the baseband controller.

Although the TR1 use case makes intensive use of the UICC security capabilities it also does place security requirements on the baseband controller, as does the secure wallet.

The TR1 mobile commerce application makes use of the security enablers Secure User IO, Trusted Execution Environment, Secure Storage, and the basic trust in the platform is established by a secure boot. In the following sections we show that the Secure Wallet also has these requirements, and we will map the the basic architecture of the secure wallet to TR1 security enablers. The TR1 security enablers, Generic Bootstrap Architecture and Secure Interaction of the UICC with the Mobile Equipment are not relevant to the secure wallet use case, and will not be considered further.

Before we begin this it should be stated that the secure wallet is defined to defend against software attacks. For this reason we consider the architecture in terms of a TR1 profile 1 requirements.

4.3 Proposal of the final porting of the secure wallet to the X-GOLD 208

In the current prototype, a TPM emulator, which makes use of the X-GOLD™ 208 cryptographic hardware, has been ported to the X-GOLD™ 208, see section 2.7. In a final architecture, the complete secure wallet prototype would be ported to the X-GOLD™ 208.

In this final prototype, the L4 microkernel and L4 environment would run on top of the X-GOLD™ 208 hardware. There would be seven L4 applications running in the L4 environment. These would be the secure GUI, the Compartment Manager, the Storage Manager, the Network Manager, the TPM emulator, the wallet application, and the legacy browser.

The TPM emulator would make use of the X-GOLD™ 208 hardware as it currently does, but in addition, the Storage Manager could also make use of the X-GOLD™ 208 hardware. The X-GOLD™ 208 has a hardware key which can be used by the AES hardware in order to encrypt and decrypt sensitive objects.

The L4 microkernel would also provide isolation between the L4 applications. Some form of policy manager would be required so that only authorized communication between the L4 applications would be possible.

As in the current prototype, two versions of the L4 Linux could be ported. One would contain the secure wallet application, and the other would be the legacy OS in which all the ‘non-secure’ software could run. This scenario is depicted in Figure 26.

4.4 Platform Integrity and Authenticity

One of OMTP TR0 and TR1’s most basic requirements is the establishment of platform integrity through a secure boot. Platform integrity and authenticity can be provided by the X-GOLD™ 208 secure boot.

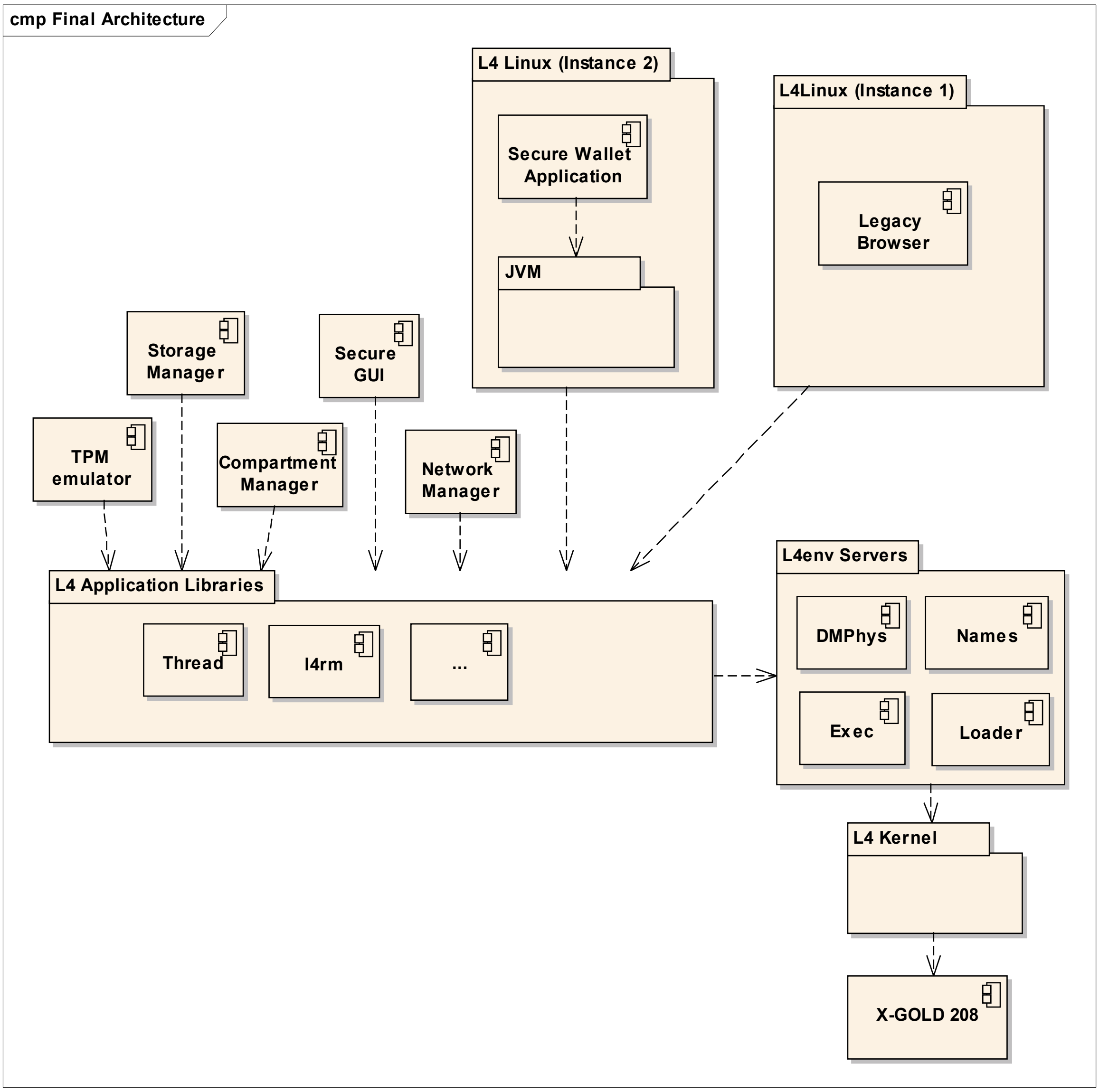


Figure 26: Proposed architecture for final secure wallet prototype

In this architecture, the X-GOLD 208 secure boot would be used as the first stage of a boot process which securely instantiates an 'immutable' Root Trust of Enforcement (RTE), as defined in the Trusted Computing Group Mobile Reference Architecture. This RTE would then build further Roots of Trusts in the platform. These Roots of Trust would then be used to establish the integrity and authenticity of the L4 microkernel, the L4 environment, and the L4 applications including the TPM emulator. Although not shown here, a measurement agent could then make use of the TPM in order to verify the integrity of the the rest of the software as it was loaded. This would possibly be handled by the compartment manager.

4.4.1 Trusted Execution Environments

The secure wallet prototype is actually a set of communicating Trusted Execution Environments.

We list the TEEs in the architecture below.

- L4 microkernel: This is the most basic TEE in the system. All other TEEs run on top of this TEE.
- L4 environment: This is the TEE in which all the L4 applications run. The L4 microkernel provides the isolation between these TEE applications.
- L4 Linux for secure wallet: The L4 Linux is also a TEE since it is isolated from the legacy Linux which would be open to untrusted applications.
- JVM running in trusted L4 Linux: The JVM is also a TEE. In this application only the single secure wallet application runs in the JVM, but the JVM could offer isolation for other secure applications.

Authorized Communication between the TEEs can be provided by the L4 Environment as long as a policy manager is implemented. In this architecture, if we consider the secure application to be running in the JVM, then it would have access to secure storage, and cryptographic services (possibly provided by the TPM emulator) via the L4 environment.

4.4.2 Secure Storage

In this section we look at the secure storage utility of the secure wallet prototype. We also briefly look at some OMTP TR1 Secure Storage requirements.

The Secure Wallet prototype architecture makes use of two types of secure storage.

- Secure storage as part of the TPM emulator
  - Hardware support provided by the X-GOLD™ 208 cryptographic hardware
  - The TPM emulator only offers asymmetric cryptographic operations as TPM commands
- Secure storage used by the storage manager
  - This would also make use of the X-GOLD™ 208 cryptographic hardware, and could make direct use of the symmetric encryption/decryption hardware.

We consider the storage manager first. The storage manager runs in its own compartment. Its purpose is to store components whilst preserving their integrity and confidentiality.

We briefly review the operation of the Storage Manager before we look at out it mpas to the TR1 definition of SST. When the Storage Manager is invoked to store data by a compartment, the storage manager calls the compartment manager in order to get the configuration data of the invoking compartment. The Storage Manager stores a data object with an index value, which contains the meta data belonging to the data object. This includes a hash of the invoking compartment, and possibly access restriction rules for this data object.

The index value is critical to the security properties of the stored object. The stored object and its index value are encrypted using the storage manager symmetric key k_{SM}. We will consider the k_{SM} later.

If a compartment makes a request to the Storage Manager to retrieve an object, the Storage Manager checks that this particular compartment has the rights to retrieve this object. It does this by invoking the compartment manager to compare the index value of the calling compartment (which will have been measured and stored at system boot), with the index value stored with the retrieved object. The storage manager may also check the user id of the calling entity from within the calling compartment. The retrieved object is only delivered to the calling compartment if the index check passes, and if the user requesting the object is authorized to receive the retrieved object.

The retrieved object and index value are decrypted using the $k_{SM.}$ k_{SM} is sealed to the storage manager. This is done using the TPM sealing function. k_{SM} can only be unsealed by the TPM if the configuration of the storage manager matches that of the storage manager which sealed it in the first place. A modified storage manager would therefore not be able to access the k_{SM}.

We consider now how the secure wallet Storage Manager maps to the structures defined in the OMTP TR1 Secure Store requirements. OMTP TR1 SST defines a key manager which is responsible for handling secure storage keys. In the case of the secure wallet prototype, the key manager is partitioned between the TPM emulator and the Secure Storage compartment. The Secure Storage root key is protected by the TPM emulator. TR1 refers to this key as the SST key manager key. It should be noted that even in a profile 1 system, the key manager key has to be protected against all of the defined hardware threats, as well as the profile 1 software threats. Care would have to taken with the final implementation, if these requirements were to be met. Further, the storage manager key needs to be securely passed from the TPM emulator to the storage manager compartment. OMTP TR1 places requirements on inter TEE secure communication when sensitive objects need to passed between TEEs.

OMTP TR1 SST also defines an Applications Assets Manager. The Application Asset Manager is the heart of the SST utility. It is the Application Asset Manager which calls the SST Key Manager. OMTP TR1 defines that only the Application Asset Manager must have access to the SST Key Manager. In the Secure Wallet Prototype, the Application Asset Manager roughly maps to the secure wallet prototype's Storage Manager. As the key manager runs inside the storage manager compartment, access to the key manager can be controlled by the storage manager. The TR1 SST requirements can then be met as long as the compartment manager ensures that only the key manager has access to the Secure Storage root key.

In the OMTP TR1 Secure Storage requirements, it is suggested that the Application Assets Manager could store the security properties and access policies for a sensitive object. The secure wallet prototype's Storage Manager implements these functions through the use of the index value which is stored with the sensitive object.

OMTP TR1 places additional requirements on the Application Asset Manager. Two of the fundamental requirements are

1. The Application Asset Manager must be able to bind the identity of an application supplied by a TEE or EE to a sensitive object, and limit access to the sensitive object to this particular application.
2. The Application Asset Manager must also maintain an access control policy for the sensitive objects under its control.

The secure wallet prototype can meet these requirements. It achieves this through the process of binding objects to the configuration of the compartments which use the secure storage utility. This functionality is not concentrated in the secure wallet prototype storage manger. The storage manager provides this functionality through the use of the compartment manager.

TR1 SST also has requirements which state that an application should not be able to compute the storage key of another application. Again this is achieved in the secure wallet prototype through the use of the configuration checking capabilities of the compartment manager.

4.4.3 Secure User IO

As previously mentioned, the SUIO requirements are concerned with the input and output of data between the user and the TEE where a trusted application is executing.

This fits quite well with the secure wallet architecture.

The architecture defines a trusted path between the secure GUI, the keyboard and the secure wallet application, which is running in a TEE. The secure wallet prototype provides such a trusted path. The security and isolation of the trusted path is enforced by the L4 environment.

4.4.4 Software Threats

We already mentioned that the secure wallet has been defined to be resistant to software threats. This generally aligned to a TR1 profile 1 security level. TR1 Secure Storage key management requirements are an exception and TR1 still require protection from hardware threats.

The profile 1 software required software measures are covered by ‘Definition of software Quality Measures’, ‘Definition of API Related Coding Techniques, ‘Definition of Buffer Overflow Protection Mechanisms’.

These can only be met by careful coding, code reviews, and especially careful design of TEE interfaces. The secure wallet architecture assists in the implementation of these measures by concentrating the security facilities in isolated Trusted Execution Environments.

In fact, the secure wallet prototype architecture implements the security measure proposed in TR1 by the 'Definition of Execution Isolation Techniques to Address Software Attacks'. This is a profile 2 requirement, but the secure wallet architecture makes extensive use of these techniques. This locates the TR1 security classification of the secure wallet prototype software architecture somewhere between a profile 1 and profile 2.

4.5 Summary

In Section 4, we first summarized the OMTP TR1 recommendations. We selected the OMTP TR1 security enablers and use cases which were most relevant to the secure wallet prototype architecture. These were the security enablers Trusted Execution Environment, Secure Storage, Secure Access the User Input/Output facility, Flexible Secure Boot/Secure Boot, and Runtime Integrity Checking. Generic Bootstrap Architecture and Secure Interaction of the UICC and Mobile Equipment were not considered as these UICC centric security enablers were not relevant to the secure wallet prototype.

We compared the Secure Wallet use case with the OMTP TR1 mobile commerce use case, and although we found some similarities, there were also many differences. The security enablers were seen as more promising for our work.

An initial and non-exhaustive analysis was carried out in order to judge how the secure wallet prototype architecture mapped to the TR1 requirements. The implemented prototype was not used for the analysis. Instead we considered a theoretical successor to the secure wallet prototype, where the complete system had been ported to the X-GOLD™ 208.

We found that the basic platform security for OMTP TR0 and TR1 are based on a secure boot. The X-GOLD™ 208 can also provide general platform integrity through its secure boot feature. One of the most important security enablers of TR1 is the TEE. We saw that the secure wallet prototype architecture can be viewed as a set of communicating Trusted Execution Engines. The prototype also provides a Secure Storage and Secure Access to User Input/Output facility generally in line with an OMTP TR1 profile 1 classification. The secure storage was made possible due to the hardware cryptographic functions and unique key provided by the X-GOLD™ 208 hardware.

The major security strength of the prototype was due to the strong isolation provided by the compartment manager. This isolation is generally only found in an OMTP profile 2 architecture. The prototype would not meet all profile 2 requirements, as it was not defined to protect against all of the OMTP TR1 physical threats.

Areas for further work would be a more detailed analysis of the secure wallet prototype and the OMTP TR1 requirements.

5 Conclusions

In this deliverable, we proposed the *Secure Wallet* as a countermeasure against identity theft and examined the use case from different points of view. In particular, the realization of such a solution on a mobile platform and its deployment with respect to relevant mobile standards have been considered.

A PC-based prototype of the Secure Wallet has been implemented, whereas the realization of the demonstrator described in Section 2.7 is still ongoing. Given that the TCG Mobile Trusted Module (MTM) specification was published when much of the work for our prototype was already in progress, and since the sealing functionality (which is the major Trusted Computing functionality needed for the Secure Wallet) provided by MTMs does not deviate from the TPM 1.2 specification, it seems reasonable to use a modified TPM emulator – equipped with a driver for accessing the existing security chip – to provide Trusted Computing functionality for the demonstrator. However, it is anticipated that in the future MTMs (possibly based on a similar mechanism to access vendor-specific mobile hardware) will be employed instead.

In our theoretical work, we addressed the most relevant and recent standards relating to the implementation of a trusted mobile platform. We examined which architectural components, based on the TCG mobile reference architecture [63], and which functions, as specified in the TCG MTM specification [64], could be used to facilitate a robust implementation of the secure wallet mechanism. The components and functionality required in order to implement the secure wallet will be used in specifying and analysing the methods by which a subset of MTM functionality can be provided given an X-GOLD™ 208/a generic OMTP TR1 device. We also examined the secure wallet use case in light of OMTP TR1.

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