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1 Introduction

This explanatory document provides additional information regarding secure design for the AUTOSAR standards. This document is currently limited to the AUTOSAR Adaptive Platform. Support for the AUTOSAR Classic Platform may be added in a future release of this document.

1.1 Objectives

This document explains security features which could be utilized within the AUTOSAR Adaptive Platform. The motivation is to provide standardized and portable security for Adaptive Applications as well as the whole AUTOSAR Adaptive Platform.

1.2 Scope

This document shall be explanatory and help the security engineer to identify security related topics within Adaptive Applications and the AUTOSAR Adaptive Platform.

The content of this document will address the following topics:

- Protection against memory corruption attacks.
- Isolation of software components between each other.
- Isolation of the operating system from software components.
- Existing security solutions

2 Definition of terms and acronyms

2.1 Acronyms and abbreviations

All acronyms used are included in the AUTOSAR TR Glossary.

3 Related Documentation

3.1 Input documents & related standards and norms

[1] Explanation of Adaptive Platform Design
AUTOSAR_AP_EXP_PlatformDesign

[2] SoK: Eternal War in Memory

[3] C++ Core Guidelines of May 11, 2024
https://github.com/isocpp/CppCoreGuidelines/blob/50afe02/CppCoreGuidelines.md

[4] The SPARC Architectural Manual, Version 8
http://sparc.org/wp-content/uploads/2014/01/v8.pdf.gz

[5] OpenBSD-3.3 announcement, public release of WX
http://www.openbsd.org/33.html

[6] Smashing The Stack For Fun And Profit
http://phrack.org/issues/49/14.html

[7] The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86)

[8] Jump-oriented Programming: A New Class of Code-reuse Attack

[9] On the Expressiveness of Return-into-libc Attacks

[10] Code-Pointer Integrity

[11] ARM Pointer Authentication
https://lwn.net/Articles/718888/

[12] PaX ASLR (Address Space Layout Randomization)

[13] Control-flow Integrity

[14] AMD64 Architecture Programmer's Manual Volume 2: System Programming
http://support.amd.com/TechDocs/24593.pdf

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https://www.ibm.com/developerworks/systems/library/es-archguide-v2.html

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http://public.dhe.ibm.com/software/dw/library/es-ppcbook3.zip

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[27] Secure Element Protection Profile
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[28] Cryptographic Algorithm Recommendations
https://globalplatform.org/specs-library/globalplatform-technology-cryptographic-algorithm-recommendations/

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[30] Secure Element Management Service
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[32] Factoring using 2n + 2 qubits with Toffoli based modular multiplication
https://www.microsoft.com/en-us/research/wp-content/uploads/2017/05/1611.07995.pdf

[33] RFC 5246, The Transport Layer Security (TLS) Protocol Version 1.2

[34] The Transport Layer Security (TLS) Protocol Version 1.3
https://tools.ietf.org/html/rfc8446

[35] RFC 6066, Transport Layer Security (TLS) Extensions: Extension Definitions

[36] Datagram Transport Layer Security Version 1.2
https://ietf.org/rfc/rfc6347.txt

[37] Explanation of IPsec Implementation Guidelines
AUTOSAR_AP_EXP_IPsecImplementationGuidelines

[38] RFC 4301, Security Architecture for the Internet Protocol

[39] RFC 4302, IP Authentication Header

[40] RFC 4303, IP Encapsulating Security Payload (ESP)

[41] RFC 7296, Internet Key Exchange Protocol Version 2 (IKEv2)

[42] Requirements on IPsec Protocol
AUTOSAR_FO_RS_IPsecProtocol

[43] Specification of MACsec Key Agreement
AUTOSAR_CP_SWS_MACsecKeyAgreement

4 Security Overview

4.1 Protected Runtime Environment

4.1.1 Introduction

Vulnerabilities in software programs lead to unauthorized system manipulation and access when they are exploited by runtime attacks. Unauthorized system manipulations are, for instance, arbitrary code execution, privilege escalation, or persistent manipulation of storage. The cause of the vulnerabilities are mostly programming mistakes and design flaws. Although design rules and guidelines might be followed during the development process or quality assurance processes like static code analysis or fuzzing are performed, vulnerabilities exist statistically in nearly all projects. These measures can be specified only qualitatively by the AUTOSAR `Adaptive Platform` specification. However, there are technical countermeasures on the operating system level to harden a system against such attacks. Note that the term harden includes that there is still no guaranteed system security but the effort for a successful attack can be raised to a higher level.

The hardening measures are combined as the term *Protected Runtime Environment* (PRE) in the context of AUTOSAR `Adaptive Platform`. A PRE includes the most important, basic protection mechanisms for a complex software environment. Without it, any other security mechanism will be circumventable, as any compromised process or service will be able to compromise any other running process on a system. The goal of a protected runtime environment is to protect the integrity of a process's control-flow during runtime and to limit the impact of a successful attack. So, two strategies of hardening are considered for AUTOSAR `Adaptive Platform`: proactive protection that should mitigate the exploitation of vulnerabilities and ”post-mortem” measures that isolates an untrusted process.

The present document is a guidance for integrators and implementers who are going to develop an automotive system that is compliant to the AUTOSAR `Adaptive Platform` specifications. It contains recommendations and hints to fulfil the desired security requirements listed in this document. The actual implementation of a specific measure is yet to be defined and may depend on the concrete system at hand, or may be a combination of multiple measures.

Section 4.1.2 introduces exploit mitigation approaches and presents related integration options. Afterwards, Section 4.1.7 discusses the isolation aspects that limits the action scope of a compromised or untrusted process. In each chapter the general attack and mitigating techniques are detailed and existing countermeasure implementations are presented. Further, technical prerequisites for the integration are highlighted.

4.1.2 Protection against Memory Corruption Attacks

Unmanaged languages, such as C or C++, enable programmers to implement their code with a high degree of freedom to manage resources. As such, code can be optimized for runtime performance or memory consumption and access to low level functions of the operating system is possible. However, programmers are fully responsible for bounds checking and memory management since C/C++ is memory-unsafe. In practice, this often leads to the violation of the *Memory Safety* policy or memory errors, as the manual management of memory is very error prone.

Memory errors in turn can be utilized to cause memory corruption, the root cause of nearly all vulnerabilities in software components. If the vulnerabilities are exploited by an attacker the possible impact is, for example, arbitrary code execution, privilege escalation, or the leakage of sensitive information.

The language of choice in the AUTOSAR `Adaptive Platform` is C++14 as proposed in platform design explanatory document [1, Section 2.3.1]. As such, the designated programming language for `Adaptive Applications` (AA), AUTOSAR Runtime for `Adaptive Applications` (ARA), as well as Functional Clusters on the `Adaptive Platform` Foundation or the `Adaptive Platform` Services is unmanaged, resulting in a large attack surface. One goal of a PRE is the minimization of this attack surface.

This chapter is structured as follows. Section 4.1.3 gives an overview of the potential types of memory corruption vulnerabilities. The typical pitfalls during coding are detailed in section 4.1.4. In section 4.1.5 an explanation of the basic technical reasons of memory corruption attacks and the corresponding state-of-the-art protection techniques on various attack stages is given. Further, possible practical solutions to implement and integrate the presented protection techniques in terms of the AUTOSAR AP are presented in Section 4.1.6.

4.1.3 Overview

The exploitation of vulnerabilities and its mitigation is a complex topic. Computer security researchers continuously develop new attacks and corresponding defenses. A general model for memory corruption attacks and the corresponding protecting techniques is described in [2]. The model (cf. Figure 4.1) summarizes the general causes of vulnerabilities, the way to exploit them according to the targeted impact, as well as mitigation policies on the individual attack stages for four types of attacks: *Code corruption attack*, *Control-flow hijack attack*, *Data-only attack*, and *Information leak*. On each attack stage they define several policies that must hold to prevent a successful attack.

The first two stages are common for all attack types and describe the root cause of vulnerabilities. In the first stage a memory corruption manipulates a pointer. When this *invalid* pointer is then dereferenced, a corruption is triggered. A pointer is invalid if it is an *out-of-bounds* pointer, i.e. pointing out of the bounds of a previously allocated memory area, or if it becomes a *dangling pointer*, i.e. pointing to a deleted object. Commonly known out-of-bounds vulnerabilities are for example: *buffer over-/underflow*, *format string bug*, and *indexing bugs* like *integer overflow*, *truncation* or *signedness bug*, or *incorrect pointer casting*. Typical dangling pointer vulnerabilities are: *use-after-free* or *double-free*. A collection of C and C++ related issues can be found, for instance, in the *List of Software Weakness Types* of the *Common Weakness Enumeration (CWE)* from *MITRE*[1]. The exploration of memory errors is the first step of an attack. Subsequently a pointer is dereferenced to read, write or free memory.

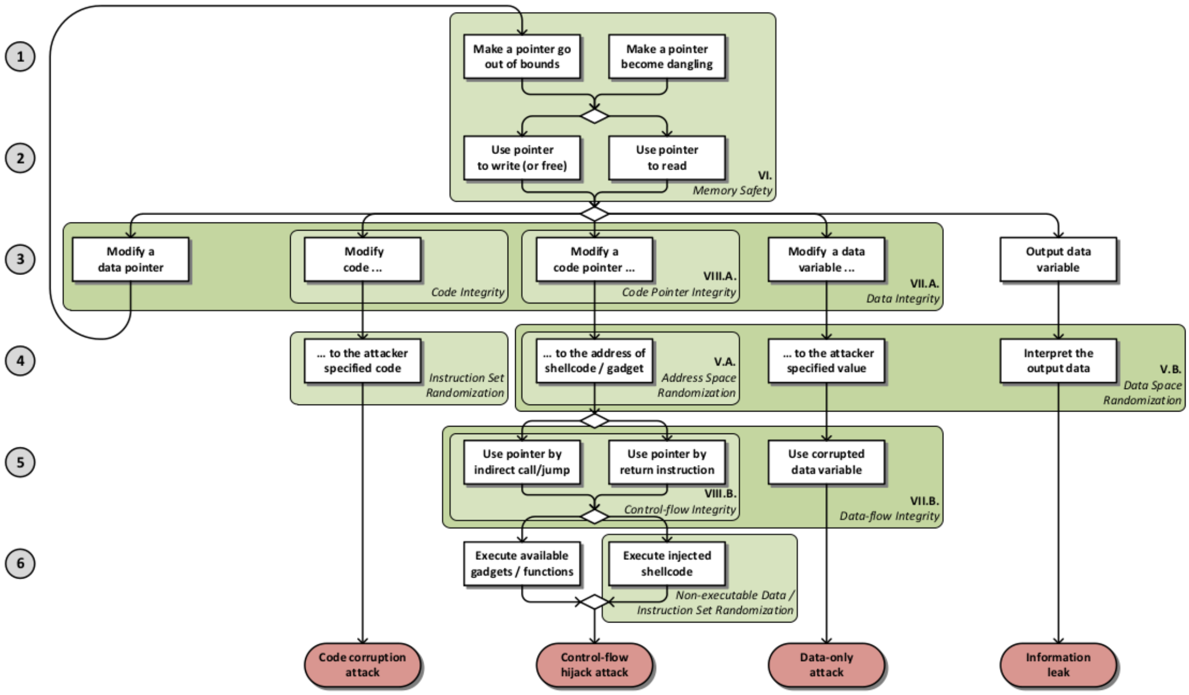

1
2
3
4
5
6
Make a pointer go out of bounds
Make a pointer become dangling
Use pointer to write (or free)
Use pointer to read
VI.
Memory Safety
Modify a data pointer
Modify code ...
Code Integrity
Modify a code pointer ...
VIII.A.
Code Pointer Integrity
Modify a data variable ...
VII.A.
Data Integrity
Output data variable
... to the attacker specified code
Instruction Set Randomization
... to the address of shellcode / gadget
V.A.
Address Space Randomization
... to the attacker specified value
Interpret the output data
V.B.
Data Space Randomization
Use pointer by indirect call/jump
Use pointer by return instruction
VIII.B.
Control-flow Integrity
Use corrupted data variable
VII.B.
Data-flow Integrity
Execute available gadgets / functions
Execute injected shellcode
Non-executable Data / Instruction Set Randomization
Code corruption attack
Control-flow hijack attack
Data-only attack
Information leak

Figure 4.1: Attack model from [2] demonstrating four attack types, policies mitigating the attacks in different attack stages

4.1.4 Secure Coding

A first measure to counter vulnerabilities at their root is to avoid mistakes and errors in the first place. To reach this goal programmers have to take care of many pitfalls during the development process. A simple example is the usage of unsafe functions from the standard C library like `strcpy()`. It copies a null character terminated character string to a buffer until the null character is reached. If the allocated destination buffer is not large enough, the function still copies characters behind the end of the buffer and thus overwrites other data. This is one of many pitfalls commonly known as a *buffer overflow* and can be used by an attacker, for example, to overwrite the stored return pointer if the buffer is allocated on the stack. For the given example a programmer should use safer variants instead. To that end, many standard C library

[1] `http://cwe.mitre.org/data/definitions/659.html`

functions have been supplemented with versions including a bounds check, for `strcpy()` this is `strncpy()`. Therewith the length of the input is limited and the buffer, if it is allocated properly, does not get overflowed. While there are supposedly more safe functions, such as `strncpy()`, they come with their own quirks and flaws. But also more complex, context related issues must be considered.

To avoid memory leaks, dangling pointers, or multiple deallocations of memory, usage of the “resource acquisition is initialization” (RAII) idiom is strongly encouraged. The goal is to make sure every previously allocated resource will be deallocated properly. Applying RAII to C++ means to encapsulate the allocation and corresponding deallocating of a resource into a dedicated class. While the resource will be allocated in the constructor, it’s meant to be deallocated by the destructor of the same object. This ensures proper resource deallocation at the end of the objects lifetime. However, it must be made sure the encapsulating objects lifetime is limited to the time the resource in question is in use. Usually, this is achieved by creating block scope objects placed on the stack. While RAII could also be used for memory allocations on heap, it is not limited to this use case. RAII also helps to prevent deadlocks when dealing with mutexes were the whole logic being protected by the mutex will be executed in context of the object acquiring and releasing a lock. It’s also noteworthy that RAII does not necessarily require an encapsulating class, but could also be implemented by means of compiler extensions were a stack object, e.g., a local variable or structure, could be associated with a corresponding clean up function. Such extensions are available for LLVM and other compilers like GCC supporting GNU syntax. This makes it possible to apply RAII to plain C.

In practice programmers should have coding guidelines at hand like the *MISRA* for safety-related systems. Unfortunately the C++ Core Guidelines do not cover a rule set for security related issues [3]. But there are third party guidelines which deals with these issues, like the *SEI CERT C++ Coding Standard*[2].

Since these guides are very comprehensive only few programmers will follow them in practice due to time reasons. However, there are some tools that can support the check against some rules in a static code analysis, e.g. *Flawfinder*[3], *RATS*[4], or *CodeSonar*[5]. In any case the application of tools does not guarantee vulnerability-free code as runtime conditions (or execution contexts) are out-of-scope of such tools. Similarly, identified vulnerabilities may not be fixed sufficiently with respect to runtime behavior.

4.1.5 Attacks and Countermeasures

For a second line of defense it is assumed that vulnerabilities are present and that some will always be inserted by developers. Therefore a requirement for enhanced

[2] `https://www.securecoding.cert.org/confluence/pages/viewpage.action?pageId=637`

[3] `https://www.dwheeler.com/flawfinder/`

[4] `https://security.web.cern.ch/security/recommendations/en/codetools/rats.shtml`

[5] `https://www.grammatech.com/products/codesonar`

countermeasures is independence from written code. The goal is to mitigate exploitation of vulnerabilities.

4.1.5.1 Code Corruption Attack

A *Code Corruption Attack* intends to manipulate the executable instructions in the text segment in the virtual memory space and to breach the *Code Integrity* policy (cf. Figure 4.1).

The countermeasure is to set the memory pages containing code to read-only or W $\oplus$ X (write xor execute), respectively. It has to be implemented on both system levels, i.e. the processor as well as the operating system. The MMU of the CPU has to provide fine-grained memory permission layout (e.g. NX-bit [4, p.248]) or the operating system should emulate this. Further, the operating system level has to support the underlying permission layout, e.g. like W $\oplus$ X [5] or Data Execution Prevention (DEP) . But care has to be taken if self-modifying code and Just-In-Time (JIT) compilation is used, as the generated code must first be written to writeable pages, which are then set to be executable.

4.1.5.2 Control-flow Hijack Attack

A *Control-flow Hijack Attack* starts with the exploitation of a memory corruption to modify a code pointer so that it points to an attacker defined address and the *Code Pointer Integrity* policy is harmed (cf. Figure 4.1). This pointer is then used by a indirect control flow transfer in the original code. Therewith the control-flow is diverted from the original and so its *Control-flow Integrity* is violated. The last step is the execution of the exploit payload. The literature distinguishes between two approaches: *code-injection attacks* and *code-reuse attacks*. While code-injection attacks [6] are based on injecting arbitrary and custom instructions (a.k.a. *shellcode*) into the memory as exploit payload, code-reuse attacks, such as *Return Oriented Programming* (ROP) [7], *Jump Oriented Programming* (JOP) [8], and *return-to-libc* [9], utilize existing code in the process memory to construct so called *gadgets*, which enable the targeted malicious functionality.

All in all, a control-flow hijack attack will be successful if the integrity of a code pointer and of the control-flow are broken. Further, the value of the target address of the malicious functionality must be known and in the case of code-injection, the memory pages holding the injected code must be executable.

The goal of *Code Pointer Integrity* (CPI) is satisfied if all dereferences that either dereference or access sensitive pointers, such as direct and references to code pointers, are not modified (cf. [10]). There are a few recent feasible approaches which detect the alteration of code pointers and references to code pointers at this early stage. The *Code Pointer Integrity* [10] mechanism provides full memory safety but just for direct and references to code pointers. According to the authors, this approach protects against all control-flow hijack attacks. CPI is a combination of static code analysis to identify all sensitive pointers, rewrite the program to protect identified pointers in a safe memory region, called *safe-stack*, and instruction level isolation that controls the access to the safe region. These mechanisms require both compiler and runtime support and comes with an overhead of ca. 8% on runtime. An additional requirement is Code Integrity. *Code Pointer Separation* (CPS) [10] is a relaxation of CPI.

Among others, CPS limits the set of protected pointers to code pointers (no indirections) to lower the overhead to ca. 2%. It still has strong detection guarantees.

A further approach to detect modification on code pointers is *Pointer Authentication* [11]. This approach uses cryptographic functions to authenticate and verify pointers before dereferencing. Pointers are replaced by a generated signature and cannot be dereferenced directly. This requires compiler and instruction set support. To reduce overhead, hardware acceleration for the cryptographic primitives is required.

With *Stack Smashing Protection* (SSP) stack-based buffer overflows, which overwrite the saved return address, can be detected. Therefore, a pseudo-random value, also known as *Stack Canary* or *Stack Cookie*, is inserted on the stack before the saved base pointer and the saved return address as part of the function prologue. When the function returns and the function epilogue is performed, the value is compared to a protected copy. If the value is overwritten by a buffer overflow targeting the return address, the program aborts, because the values do not match anymore.

As mentioned before, code-injection attacks require executable memory pages for the injected instructions. With principle of *W* $\oplus$ *X*, also called *Data Execution Prevention* (DEP), a memory page is either flagged as writable or executable, but not both. This prevents that instructions overwrite data memory such as stack or heap and execute it afterwards. The approach requires a fine-grained page permissions support either by the MMU of the CPU and the so called *NX-bit* (No-execute bit) or emulated in Software as described in Section 4.1.5.1. Moreover, the employed operating system must support it.

Code-reuse attacks are not affected by the W $\oplus$ X mechanism since existing memory regions marked as executable are utilized and no additional code must be injected into the memory. To mitigate such kind of attacks currently deployed countermeasures are implemented on previous attack stages. On the fourth attack stage it is stated that the target address of the malicious functionality must be known. In general, the attacker knows or can just estimate an address in the virtual address space since it is static for a binary after compilation. A countermeasure in practice is the obfuscation of the address space layout by *Address Space Layout Randomization* (ASLR) [12]. Therefore, the locations of various memory segments get randomized which makes it harder to predict the correct target addresses. ASLR requires high entropy to prevent brute-force de-randomization attacks and depends on the prevention of unintended Information Leaks (Section 4.1.5.4) that are used by dynamically constructed exploit payloads. To guarantee high entropy ASLR should be implemented on 64-bit architectures (or above). Additionally, every memory area must be randomized, including stack, heap, main code segment, and libraries.

In addition to ASLR the policy Control-flow Integrity intends to detect a diversion of the original control-flow. Established techniques are: *Shadow Stack* and *Control-flow in-*

tegrity (Abadi) (CFI) [13]. The idea of shadow stack is to push the saved return address to a separate shadow stack so that it is compared upon a function return. In addition, CFI also protects indirect calls and jumps as well. The original CFI creates a static control-flow graph by determining valid targets statically and give them a unique identity (ID). Afterwards, calls and returns are instrumented to compare the target address to the ID before jumping there. It is required to protect valid targets from overwritten by W $\oplus$ X.

4.1.5.3 Data-only Attack

A memory corruption can also be exploited to modify security critical data that is not related to control-flow data. For instance, exploiting a buffer overflow to alter a conditional construct can lead to unintended program behavior. Therewith the policy *Data Integrity* is violated. Techniques such as *Data Space Randomization* and *Write Integrity Testing* (WIT) makes it harder to perform such kinds of attacks but they are not established in practice yet.

4.1.5.4 Information Leak

Memory corruption attacks are also used to leak memory contents. Therewith probabilistic countermeasures like ASLR can be circumvented by the knowledge of randomly generated data. As for the data-only attack *Data Space Randomization* might help to mitigate information leakage.

4.1.6 Existing Solutions

In this section current state-of-the-art solutions of implemented countermeasures mentioned in the sections before are presented. For each approach the system level (compiler, operating system, or hardware) at which an approach is enforced is stated and which technical and security requirements are expected.

4.1.6.1 Write xor Execute, Data Execution Prevention (DEP)

System Level: Hardware, Operating System

The idea of this approach is to flag memory pages either writable or executable, but not both at the same time. Therewith code-injected attacks are mitigated. At the lowest system level a mechanism for fine-grained memory page permissions is required. Further the operating system must support the hardware mechanism or even emulate a memory page permission mechanism.

Architecture	Instruction Set	Enforcement
x86	AMD64 [14, p. 56]	No-eXecution bit (NX-bit), Page Table

	Intel64	eXecute Disable (XD-bit), Page Table
ARM	ARMv6	execute never bit (XN-bit), Page Table
	ARMv8-A	PEN privileged execute never, PAN privileged access never
SPARC	Oracle SPARC Architecture 2011	Translation Storage Buffer (optional)
PowerPC	IBM PowerISA [15] [16, p. 33]	Segment Lookaside Buffer (SLB)

Table 4.1: Examples of Hardware Support for Execution Prevention

Family	Name	Implementation
Linux	Linux kernel	Linux kernel mainline $\geq$ 2.6.8 [17]
	PaX	Patch for the Linux kernel, uses hardware support or emulates memory page permission [18]
	Exec Shield	Patch for the Linux kernel, part of Fedora Core 1 through 6[6] and Red Hat Enterprise Linux $\geq$ 3[7,8], uses hardware support or emulates memory page
	grsecurity	Patch for the Linux kernel, uses hardware support or emulates memory page permission[9,10]
	Android	Android $\geq$ 2.3[11]
Unix	OpenBSD	OpenBSD $\geq$ 3.3[12]
	NetBSD	NetBSD $\geq$ 2.0[13]
	FreeBSD	FreeBSD $\geq$ 5.3

Table 4.2: Examples of Operating System Support for Execution Prevention

4.1.6.2 Stack Smashing Protection (SSP)

System Level: Compiler

Stack Smashing Protection (SSP) mechanisms place pseudo-random values (*Stack Canaries* or *Stack Cookie*) on the stack before the saved base pointer and the saved return address as part of the function prologue and compare the value again before a function returns. SSP is enforced at compile-time. Due to performance reasons, the

[6] https://archives.fedoraproject.org/pub/archive/fedora/linux/core/1/x86_64/os/RELEASE-NOTES.html

[7] http://people.redhat.com/mingo/exec-shield/

[8] https://www.redhat.com/f/pdf/rhel/WHP0006US_Execshield.pdf

[9] https://en.wikibooks.org/wiki/Grsecurity/Appendix/Grsecurity_and_PaX_Configuration_Options#Enforce_non-executable_kernel_pages

[10] https://en.wikibooks.org/wiki/Grsecurity/Appendix/Grsecurity_and_PaX_Configuration_Options#Paging_based_non-executable_pages

[11] https://source.android.com/security/#memory-management-security-enhancements

[12] http://www.openbsd.org/33.html

[13] http://www.netbsd.org/docs/kernel/non-exec.html

compiler has to decide which function has to be protected. If the compiler implementation makes the wrong decision and the concerned function is vulnerable, SSP fails. Further, information leaks enable an attacker to read the pseudo-random value and integrate it to her exploit so that the buffer is overwritten with the correct value.

Compiler	Option	Description
GNU Compiler Collection (GCC)[14]	`-fstack-protector`	Emit extra code to check for buffer overflows, such as stack smashing attacks. This is done by adding a guard variable to functions with vulnerable objects. This includes functions that call alloca, and functions with buffers larger than 8 bytes. The guards are initialized when a function is entered and then checked when the function exits. If a guard check fails, an error message is printed and the program exits.
	`-fstack-protector-all`	Like -fstack-protector except that all functions are protected.
	`-fstack-protector-strong`	Like -fstack-protector but includes additional functions to be protected – those that have local array definitions, or have references to local frame addresses.
	`-fstack-protector-explicit`	Like -fstack-protector but only protects those functions which have the stack_protect attribute.
Clang[15]	`-fstack-protector-all`	Force the usage of stack protectors for all functions.
	`-fstack-protector-strong`	Use a strong heuristic to apply stack protectors to functions.
	`-fstack-protector`	Enable stack protectors for functions potentially vulnerable to stack smashing.
Intel C++ Compiler[16]	`-fstack-security-check`	This option determines whether the compiler generates code that detects some buffer overruns that overwrite the return address. This is a common technique for exploiting code that does not enforce buffer size restrictions.
Keil ARM C/C++ Compiler[17]	`-protect_stack`	Use `-protect_stack` to enable the stack protection feature. Use `-no_protect_stack` to explicitly disable this feature. If both options are specified, the last option specified takes effect.
	`-protect_stack_all`	The `-protect_stack_all` option adds this protection to all functions regardless of their vulnerability.

Table 4.3: Examples of Stack Smashing Protection Compiler Support

[14] https://gcc.gnu.org/onlinedocs/gcc-7.2.0/gcc/Instrumentation-Options.html#Instrumentation-Options

[15] https://clang.llvm.org/docs/ClangCommandLineReference.html#cmdoption-clang-fstack-protector

[16] https://software.intel.com/en-us/node/523162

[17] http://www.keil.com/support/man/docs/armcc/armcc_chr1359124940593.htm

4.1.6.3 Address Space Layout Randomization (ASLR)

System Level: Compiler, Operating System

Address Space Layout Randomization (ASLR) obfuscates the address space layout of a process. Therewith the locations of various memory segments get randomized which makes it harder to predict the correct target address which is needed to perform a code-reuse attack. ASLR requires high entropy to prevent brute-force de-randomization attacks and depends on the prevention of unintended Information Leak (Section 4.1.5.4) that are used by dynamically constructed exploit payloads. To guarantee high entropy ASLR should be implemented on 64-bit architectures (or above). Additionally, ASLR requires position-independent executables (PIE) which allows to use a random base address for the main executable binary.

ASLR is enforced by the operating system primarily but requires position-independent executables for binaries and position independent code for shared libraries generated by the complier.

Family	Name	Implementation
Linux	Linux kernel	Linux kernel mainline $\geq$ 3.14[18]. ASLR for user-space programs and Kernel Address Space Layout Randomization (KASLR)[19] for the kernel itself.
	PaX	Patch for the Linux kernel[20]
	Exec Shield	Patch for the Linux kernel[21]
	grsecurity	Patch for Linux kernel[22]
	Android	Android $\geq$ 4.1[23]
BSD	OpenBSD	OpenBSD $\geq$ 4.4[24]
	NetBSD	NetBSD $\geq$ 5.0[25]
	FreeBSD	FreeBSD as patch[26]

Table 4.4: Examples of ASLR Operating System Support

Compiler	Option	Description

[18] https://lwn.net/Articles/569635/

[19] http://selinuxproject.org/~jmorris/lss2013_slides/cook_kaslr.pdf

[20] https://pax.grsecurity.net/docs/aslr.txt

[21] http://www.redhat.com/f/pdf/rhel/WHP0006US_Execshield.pdf

[22] https://en.wikibooks.org/wiki/Grsecurity/Appendix/Grsecurity_and_PaX_Configuration_Options#Restrict_mprotect.28.29

[23] https://source.android.com/security/enhancements/enhancements41

[24] https://www.openbsd.org/plus44.html

[25] https://netbsd.org/releases/formal-5/NetBSD-5.0.html

[26] https://hardenedbsd.org/content/freebsd-and-hardenedbsd-feature-comparisons

GNU Compiler Collection (GCC)[27,28]	`-fpie, -fPIE`	These options are similar to `-fpic` and `-fPIC`, but generated position independent code can be only linked into executables. Usually these options are used when `-pie` GCC option is used during linking. This is especially difficult to plumb into packaging in a safe way, since it requires the executable be built with `-fPIE` for any `.o` files that are linked at the end with `-pie`. There is some amount of performance loss, but only due to the `-fPIE`, which is already true for all the linked libraries (via their `-fPIC`).
	-fPIC	If supported for the target machine, emit position-independent code, suitable for dynamic linking and avoiding any limit on the size of the global offset table. This option makes a difference on AArch64, m68k, PowerPC and SPARC. Position-independent code requires special support, and therefore works only on certain machines.
Clang[29]	`-fpie, -fPIE`	See GCC.
	`-fPIC`	See GCC.
Intel C++ Compiler[30,31]	`-pie`	Determines whether the compiler generates position-independent code that will be linked into an executable.
	`-fpic`	Determines whether the compiler generates position-independent code.
Keil ARM C/C++ Compiler[32]	`-bare_metal_pie`	(Bare-metal PIE support is deprecated. There is support for `-fropi` and `-frwpi` in armclang. You can use these options to create bare-metal position independent executables.) A bare-metal Position Independent Executable (PIE) is an executable that does not need to be executed at a specific address but can be executed at any suitably aligned address.
	`-fropi, -fno-ropi`	Enables or disables the generation of Read-Only Position-Independent (ROPI) code.
	`-frwpi, -fno-rwpi`	Enables or disables the generation of Read/Write Position-Independent (RWPI) code.

[27] `https://gcc.gnu.org/onlinedocs/gcc-7.2.0/gcc/Code-Gen-Options.html#Code-Gen-Options`

[28] `https://wiki.debian.org/Hardening#gcc_-pie_-fPIE`

[29] `https://clang.llvm.org/docs/ControlFlowIntegrity.html`

[30] `https://software.intel.com/en-us/node/523278`

[31] `https://software.intel.com/en-us/node/523158`

[32] `http://www.keil.com/support/man/docs/armclang_dev/armclang_dev_chr1405439371691.htm`

Table 4.5: Examples of ASLR Compiler Support

4.1.6.4 Control-flow Integrity (CFI)

System Level: Compiler

Control-flow Integrity (CFI) is a current research topic. However, Clang includes an implementation of a number of Control-flow Integrity (CFI) schemes, which are designed to abort the program upon detecting certain forms of undefined behavior that can potentially allow attackers to subvert the program's control flow. These schemes have been optimized for performance, allowing developers to enable them in release builds. The CFI implementation in Clang has a performance overhead of ca. 1% and a binary size overhead of ca. 15% (only forward-edges)[33].

Compiler	Option	Description
GNU Compiler Collection (GCC)[34]	`-fvtable-verify =[std|preinit|none]`	This option is only available when compiling C++ code. It turns on (or off, if using `-fvtable-verify=none`) the security feature that verifies at run time, for every virtual call, that the vtable pointer through which the call is made is valid for the type of the object, and has not been corrupted or overwritten. If an invalid vtable pointer is detected at run time, an error is reported and execution of the program is immediately halted. This option causes run-time data structures to be built at program startup, which are used for verifying the vtable pointers. The options `std` and `preinit` control the timing of when these data structures are built. In both cases the data structures are built before execution reaches main. Using `-fvtable-verify=std` causes the data structures to be built after shared libraries have been loaded and initialized. `-fvtable-verify=preinit` causes them to be built before shared libraries have been loaded and initialized. If this option appears multiple times in the command line with different values specified, `none` takes highest priority over both `std` and `preinit`; `preinit` takes priority over `std`.
Clang[35]	`-fsanitize=cfi-cast-strict`	Enables strict cast checks.
	`-fsanitize=cfi-derived-cast`	Base-to-derived cast to the wrong dynamic type.

[33] `https://clang.llvm.org/docs/ControlFlowIntegrity.html`

[34] `https://gcc.gnu.org/onlinedocs/gcc-7.2.0/gcc/Code-Gen-Options.html#Code-Gen-Options`

[35] `https://clang.llvm.org/docs/ControlFlowIntegrity.html`

	`-fsanitize=cfi-unrelated-cast`	Cast from void* or another unrelated type to the wrong dynamic type.
	`-fsanitize=cfi-nvcall`	Non-virtual call via an object whose vptr is of the wrong dynamic type.
	`-fsanitize=cfi-vcall`	Virtual call via an object whose vptr is of the wrong dynamic type.
	`-fsanitize=cfi-icall`	Indirect call of a function with wrong dynamic type.
	`-fsanitize=cfi`	Enable all the schemes.

Table 4.6: Examples of CFI Compiler Support

4.1.6.5 Code Pointer Integrity (CPI), Code Pointer Separation (CPS)

System Level: Compiler

Code-Pointer Integrity (CPI) is a property of C/C++ programs that guarantees absence of control-flow hijack attacks by requiring integrity of all direct and indirect pointers to code. Code-Pointer Separation (CPS) is a simplified version of CPI that provides strong protection against such attacks in practice. SafeStack is a component of CPI/CPS, which can be used independently and protects against stack-based control-flow hijacks.

CPI/CPS/SafeStack can be automatically enforced for C/C++ programs through compile-time instrumentation with low performance overheads of 8.5% / 1.9% / 0.05% correspondingly. The SafeStack enforcement mechanism is now part of the Clang compiler, while CPI and CPS are available as research prototypes. For the current status please see [19].

Compiler	Option	Description
Clang[36],[37]	`-fsanitize=safe-stack`	SafeStack is an instrumentation pass that protects programs against attacks based on stack buffer overflows, without introducing any measurable performance overhead. It works by separating the program stack into two distinct regions: the safe stack and the unsafe stack. The safe stack stores return addresses, register spills, and local variables that are always accessed in a safe way, while the unsafe stack stores everything else. This separation ensures that buffer overflows on the unsafe stack cannot be used to overwrite anything on the safe stack.

Table 4.7: Examples of CPI and CPS Compiler Support

[36] `http://dslab.epfl.ch/proj/cpi/`

[37] `https://clang.llvm.org/docs/SafeStack.html`

4.1.6.6 Pointer Authentication

System Level: Hardware, Compiler

Pointer Authentication uses cryptographic functions to authenticate and verify pointers before dereferencing [11]. Pointers are replaced by a generated signature and cannot be dereferenced directly. This requires compiler and instruction set support. ARM recently introduces the Pointer Authentication extensions in ARMv8.3-A specification[38]. The GCC introduces basic support for pointer authentication in version 7[39] for the *AArch64* target (ARMv8.3-A architecture). The overhead is negligible because of hardware acceleration for the cryptographic primitives[40].

Compiler	Option	Description
GNU Compiler Collection (GCC)[41]	-msign-return-address= scope	Select the function scope on which return address signing will be applied. Permissible values are `none`, which disables return address signing, `non-leaf`, which enables pointer signing for functions which are not leaf functions, and `all`, which enables pointer signing for all functions. The default value is `none`.

Table 4.8: Examples of Pointer Authentication Compiler Support

4.1.7 Isolation

Isolating software components within a system is a common protection measure to protect other components from erroneous ones, either through unintentional programming errors, or intentional harm caused by an attacker taking over a corruptible component. While the protective measures detailed in section 4.1.2 are a preventive measure, intended to impede an attacker from taking over a software component by exploiting programming errors, isolation intends to limit the influence an attacker might have to other software components *after* taking over a software component. As such, isolation is only an effective measure, if the architecture of the system is appropriately designed, dividing and isolating different functional aspects of the system accordingly. Note that this guide does not cover this architectural aspect of isolation, but the technical aspect, i.e. *how* isolation can be implemented.

The following sections describe two approaches to isolation: the isolation of multiple software components between each other, and the isolation of software components and the operating system itself. These two approaches are orthogonal – i.e. horizontal

[38] `https://community.arm.com/processors/b/blog/posts/armv8-a-architecture-2016-additions`

[39] `https://gcc.gnu.org/gcc-7/changes.html`

[40] `https://lwn.net/Articles/719270/`

[41] `https://gcc.gnu.org/onlinedocs/gcc-7.1.0/gcc/AArch64-Options.html#AArch64-Options`

isolation between applications and vertical isolation between applications and the OS – and can be combined accordingly.

4.1.8 Horizontal Isolation

4.1.8.1 Virtual Memory

The oldest and most prevalent isolation mechanism is the concept of virtual memory, i.e. presenting each running software component of a system with its own virtual address space, which is mapped to the available physical memory by the operating system. The origins date back to the 1950s, with the original intention of hiding the fragmentation of physical memory, but offers the possibility of isolating software components. As each component operates in a virtual address space, it cannot access the memory of other components (unless explicitly allowed by the operating system). This feature requires hardware support, e.g. by a Memory Management Unit (MMU), but this support is nearly ubiquitous in most computer systems except very small microcontrollers.

An extension of this concept is that of *virtual machines* (or *virtualization*), whereby multiple virtual machines (VM) are emulated by a *hypervisor*. Each VM may run a complete operating system, depending on the degree of virtualization even in an unmodified state. The hypervisor controls the access of each VM to the physical hardware components, or even emulate certain components such as network interfaces. Similar to virtual memory, the virtualization requires dedicated hardware support to achieve an appropriate level of performance and security.

Note that both approaches have limitations. The isolation provided by virtual memory or virtualization is only as strong as the operating system or hypervisor itself, as a malicious application might take control over the OS or hypervisor through a programming error (the measures described in section 4.1.10 intend to minimize this attack surface). Similarly, a malicious application might use its access to other hardware components to circumvent the isolation, as some hardware components may have unrestricted access to the systems memory. “IOMMUs”, a technique which presents hardware components with a virtual address space, can be used to counter this. Lastly, an attacker might use the volatile properties of physical memory itself to circumvent the isolation. For example, in [20] the “rowhammer” attack is described, which is capable of flipping bits in memory locations usually inaccessible to an application. The attack uses prolonged reads to a memory location performed in quick succession, which in the case of “DRAM” memory will cause neighbouring memory cells to change state. This effect has been shown to be capable of raising the privileges of an application in Linux and Android (cf. [21]) systems. System designers must consider using one or more mitigations to such attacks, for example, by using memory with error correction, or software mitigations as shown in [22].

4.1.9 OS-Level Virtualization

A more lightweight form of virtualization, often called operating-system-level virtualization or *containerization*, is available in modern OS. Prominent examples are “LXC”[42], which is built on top of the Linux Kernel Namespacing functionality, or the “Jail”[43] functionality provided by the FreeBSD operating system. These tools only virtualize certain resources of an operating system, for example, file system, the process tree, or the network stack. This way, the operating system creates a *container* with a tightly controlled access to system resources or other containers. In contrast to full virtualization, these containers cannot execute a different operating system, albeit a completely separate user-space instance can be run side-by-side.

OS Family	Solution	Description
UNIX	chroot	This is a system call available in many UNIX alike systems, which can be used to set up a an execution environment with a different root filesystem. As such, it only isolates the filesystem of the host from the container. If the container contains privileged processes, they can easily affect the system
Linux	Namespaces, LXC, Docker, systemd-nspawn	Many solutions building upon the Linux Namespacing functionality exist, many allowing the setup of isolated containers. Resources of other containers or the host are not visible to the processes running inside these containers, unless assigned. This way, even privileged processes inside a container are not capable of affecting the rest of the system.
FreeBSD	Jails	A solution similar to chroot, except for improved security. For example, these containers (or called “jails” in this context) offer an isolated network, as well as restricting the capabilities of privileged processes inside (e.g. privileged processes cannot affect the rest of the system).

Table 4.9: Operating System Virtualization / Container Implementations

4.1.10 Vertical Isolation

Isolating the operating system from applications, often called *sandboxing* is an another important aspect of a protected runtime environment. The basic idea is to limit the capabilities of a process, i.e. restricting what a process can do[44]. The classic way to

[42] https://linuxcontainers.org/

[43] https://www.freebsd.org/doc/handbook/jails.html

[44] Not to be confused with “what a process does”, as the behaviour of a process is changed by an attack.

do this is by dropping privileges as soon as they are not needed anymore, i.e. *privilege revocation*. For example, the `ping` command requires root privileges on UNIX systems to create a raw network socket, but will drop its privileges to a regular user after creating it. Ideally, a software component should drop (or never be given) any privileges it does not require, or drop them as soon as they are no longer required. As with the example of `ping`, any software component must then be structured with a setup phase, in which all advanced privileges are used and subsequently dropped. The following shows a few examples of operating system functionalities, which allow an application to drop capabilities or privileges.

OS Family	**Solution**	**Description**
Linux	Seccomp Mode 1 (Strict) [23]	Processes on the Linux operating system can limit their set of allowed system calls in a very easy manner. The allowed subset is extremely strict, limiting the process to `read`, `write`, `exit` and `sigreturn`. Once activated, this Seccomp mode cannot be deactivated again.
Linux	Seccomp Mode 2 (Filter) [23]	A more recent version of the Seccomp mode, the seccomp filter mode, allows a much more fine-grained control. The concept is to allow a process to attach a small filter program, which will check each system call. This filter program must be a “Berkley Packet Filter” (BPF), a very restricted form of byte-code, which will be executed by the kernel before each system call. This filter can than examine each system call, for example, check which system call is made or what the parameters are set. The filter then returns a decision as to what the kernel should do. The system call can be allowed or blocked and if the call is blocked, several choices can be made as to how it is blocked. The filter may decide to immediately kill the process, to simply let the system call return an error, send a signal to the offending process or to notify a tracer attached to the program (such as a debugger). A notable property of these filters is, that they are inherited by the spawned child processes, which enables a setup of a filter before a potentially dangerous process is started.
FreeBSD	Securelevel [24, chapter 13]	This functionality limits the possibilities of all processes running on a system in incremental levels, which cannot be lowered once entered (until a reboot of the system).

OpenBSD	Pledge [25]	This functionality can be used to limit the system calls a process can execute. Certain system calls can be prohibited completely, others can be restricted in their functionality. For example, the `open` system call can be limited to only open a small set of system files, or the `mprotect` cannot set memory to be executable. Once the limitations are in place, the process cannot lift them again.

Table 4.10: Sandboxing Mechanisms in Operating Systems

4.2 Isolated Runtime Environment

There are multiple technologies that isolate computing environments from one another in order to increase security. Trusted Execution Environments (TEEs) [26], Secure Elements (SEs) [27] and integrated SEs are well-known examples.

Whilst different technologies have different capabilities and trade-offs, all ensure that sensitive data is stored, processed, and protected in an isolated and trusted environment; offering protection against attacks generated in the rest of the device and even from other actors inside the execution environment.

4.2.1 Hardware Trust Anchors

Hardware trust anchors have the main functions to protect sensitive data from manipulation and to support computation intensive crypto functions.

Examples of standardized Hardware Trust Anchors include:

1. Hardware Security Modules (HSM)
2. Secure Hardware Extensions (SHE)
3. Trusted Platform Modules (TPM)

4.2.1.1 Hardware Security Module

The current industry standard for the most robust cybersecurity solutions in the automotive industry is a Hardware Security Module (HSM). HSMs in automotive are often based on the EVITA (E-safety Vehicle Intrusion protected Applications) standard. EVITA defines different levels of security - Light, medium and full to address different security requirements. Typically, it includes

- **Secure boot** - Ensures the ECU firmware is authenticated and not tampered in the boot process

- **Cryptographic technologies** - Hardware accelerators for symmetric and asymmetric cryptography, random number generation, and other cryptographic primitives.
- **Secure storage** - Protected RAM and flash area for program code and data
  - to store Secure firmware and sensitive data, such as cryptographic keys and certificates.
  - **Firmware Integrity:** The dedicated memory ensures that security-related firmware can be updated securely and that the integrity of the firmware is maintained, preventing unauthorized modifications.
- **Secure communication support** - Protects data between ECUs, or between ECU and external interfaces.

HSMs can be implemented as either separate controllers or integrated within ECUs, depending on the specific needs and constraints of the automotive system. Each approach has its own set of benefits and trade-offs, and the choice will depend on the particular security, performance, cost, and space requirements of the vehicle's electronic architecture.

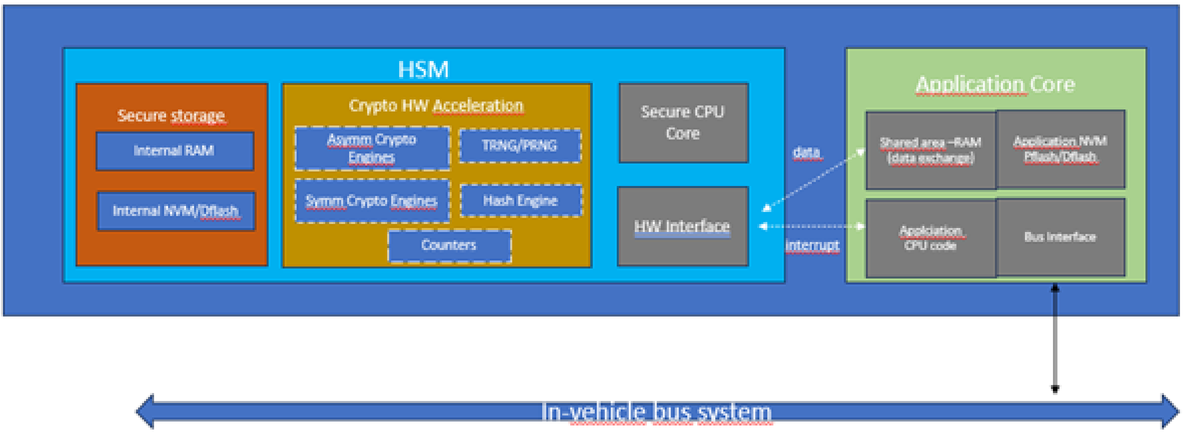


Figure 4.2: General structure of an Automotive HSM

4.2.1.2 Secure Hardware Extensions (SHE)

SHE is a security standard designed for automotive microcontrollers, developed by the Hersteller Initiative Software (HIS), a consortium of major German car manufacturers.

SHE consists of 3 building blocks

- A storage area to keep the sensitive information
- Implementation of a block cipher
- Control logic connecting to the CPU

SHE can be implemented in several ways: a finite state machine or small dedicated CPU core.

While both SHE and HSM provide hardware-based security for automotive systems, SHE focuses on essential security functions suitable for basic requirements, whereas HSM offers a comprehensive set of advanced security features for high-security applications. The choice between SHE and HSM depends on the specific security needs, complexity, and cost considerations of the automotive system.

4.2.1.3 Trusted Platform Modules

TPMs are specialized hardware components that focus on foundational security features like secure boot and platform integrity verification, suitable for securing the overall vehicle platform.

4.2.2 Trusted Execution Environments

Modern CPUs provide a collection of isolation technologies. Different forms of Memory Protection or Memory Management units can isolate one region of memory from another. Different processor modes can ensure that code executing at lower privilege cannot access resources associated with higher privilege. In some CPU architectures, a combination of these two techniques is used to provide effective isolation against software attacks.

Many CPU vendors offer a hardware-based Trusted Execution Environment or TEE for their MCU's and MPU's for their Root of Trust. A hardware-based TEE provides a source of integrity (e.g. trusted boot) and confidentiality (secure storage and crypto operations). Where higher levels of assurance and attack resistance are required, the TEE can be used with an optional trusted subsystem that can protect from physical attacks.

4.2.2.1 TEE Architecture

A Trusted Execution Environment is the name given to an execution environment formed by a combination of CPU-based isolation, plus a software operating system. TEEs can in theory be created by any isolation technology. This gives a solution which can be highly performant (as it leverages the high-power primary CPU) and secure against software attacks. This blend of features meets the requirements of many automotive applications.

Trusted Execution Environments provide a secure environment for application code. Whilst a major use case is to protect cryptographic functions and thus provide similar aims to an HSM, they have far broader applicability. TEEs are often used to provide capabilities such as secure logging and audit or to protect access to peripherals, for example when enforcing Digital Media Rights protection for high-definition streaming video.

TEEs are provided with an API set, and optionally an associated protection profile.

TEEs provide isolation from the regular execution environment (REE) running one or more operating systems, possibly under control of a hypervisor.

Figure 3 illustrates the top-level logical separation between REE and TEE on the same platform.

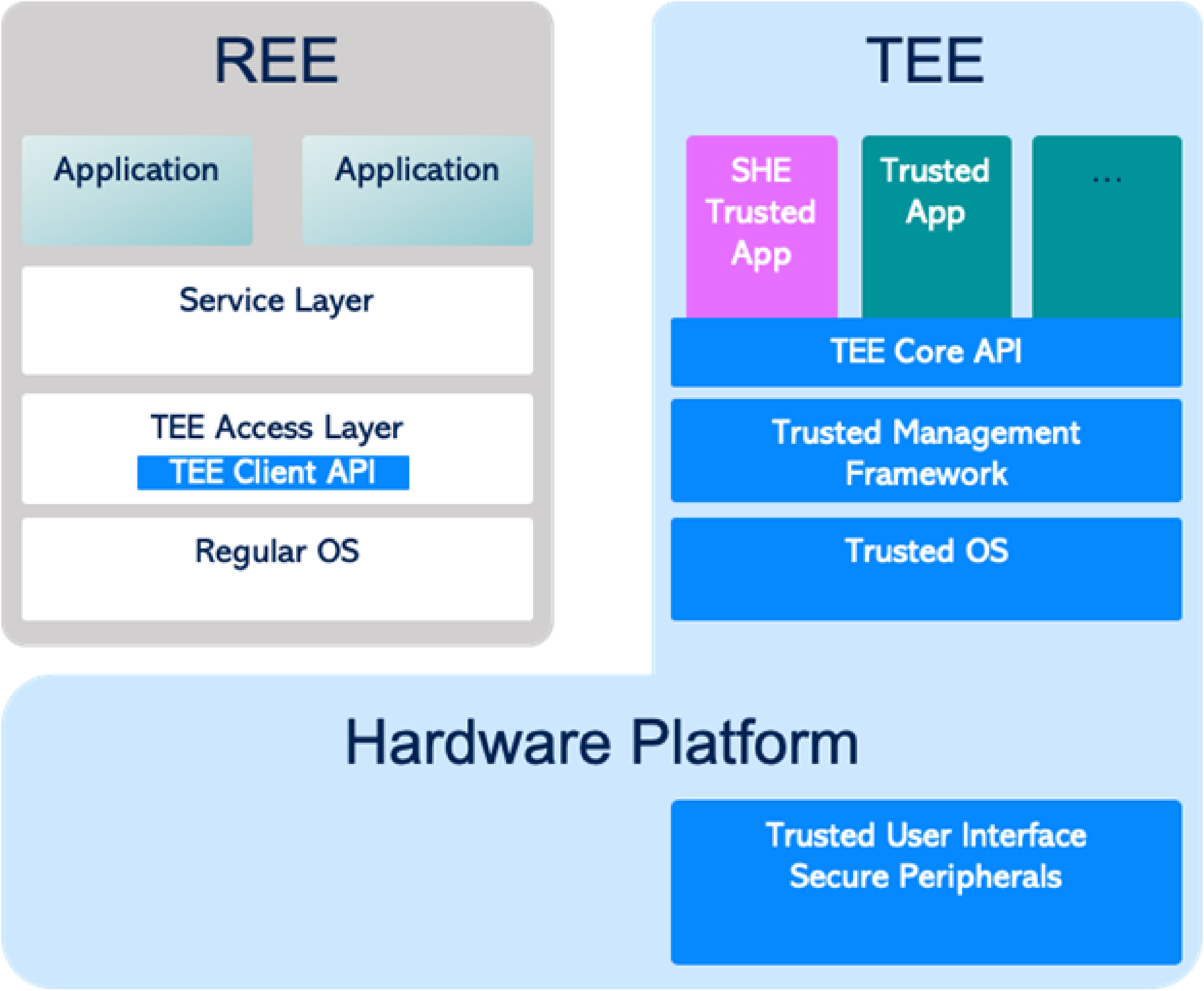


Figure 4.3: Trusted Execution Environment Architecture

TEEs provide additional assurances such as isolation between multiple applications within the TEE, secure boot, the provision of state-of-the-art cryptographic toolbox [28], and access control over hardware peripherals.

TEEs support different chipset architectures and different uses of Hypervisors. Figure 4 shows more details about a flexible TEE-based architecture.

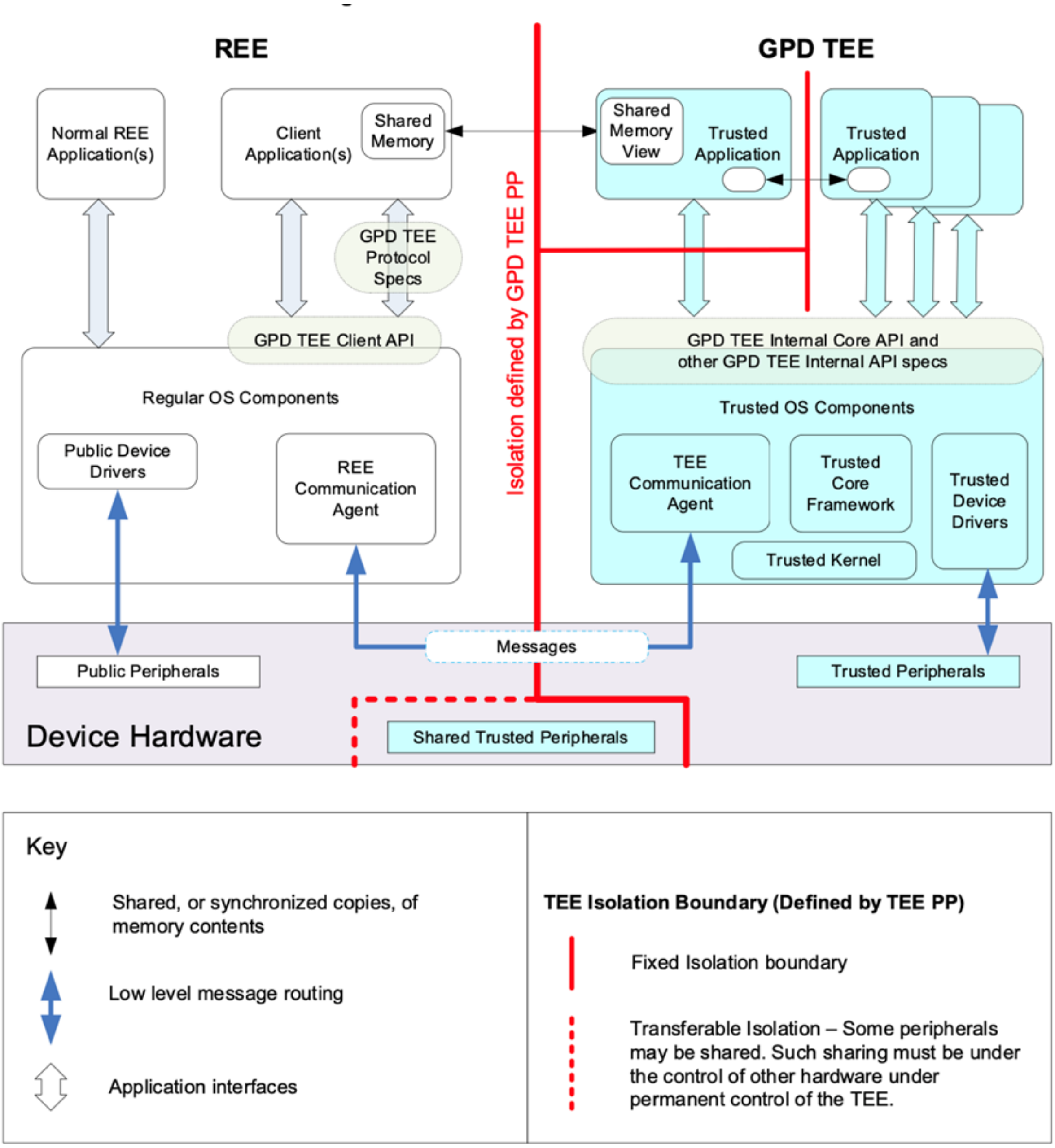


Figure 4.4: TEE Software Architecture

The goal of the TEE Software Architecture is to enable Trusted Applications (TAs) to provide isolated and trustworthy capabilities, which can then be used through Client Applications (CAs).

4.2.2.2 TEE Summary

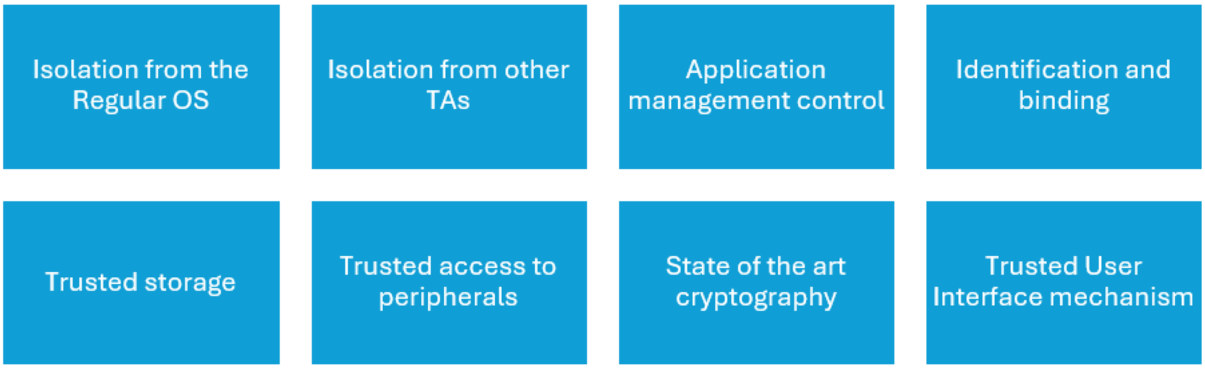

Isolation from the Regular OS
Isolation from other TAs
Application management control
Identification and binding
Trusted storage
Trusted access to peripherals
State of the art cryptography
Trusted User Interface mechanism

Figure 4.5: TEE Summary

The TEE typically runs on an application-class processor, and therefore offers high processing speeds and a large amount of accessible memory. TEEs often have privileged access to hardware peripherals, enabling them to be used to mediate access to a protected peripheral, for example to provide a Trusted User Interface (privileged access to display) or to provide secure connectivity (privileged access to keys stored in a Secure Element, HSM, or SHE).

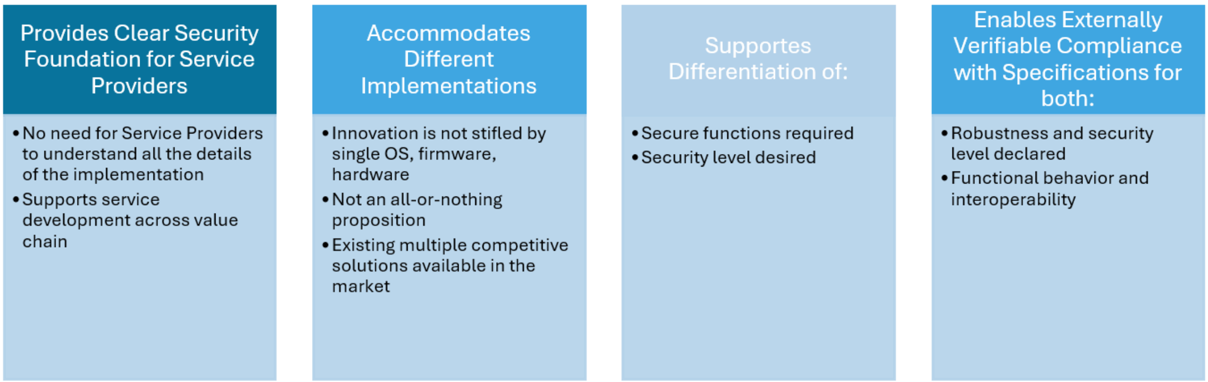
These features are part of the mandatory requirements specified in the TEE protection profile, which ensure interoperability and agreed security robustness level. Secure remote update is possible for different deployment models including one-to-one and one-to-many, as needed.

4.3 Global Platform Standards

4.3.1 Introduction

Global Platform is a technical standards organization dedicated to security technologies. Its members are focused on enabling the efficient launch and management of innovative, secure-by-design digital services and devices which deliver end-to-end security, privacy, simplicity, interoperability, and convenience to users.

GlobalPlatform specifications accommodate different kinds of hardware, operating systems, and firmware. They support innovation and portability, as well as fostering creative solutions available in the market. To this end, an application written for one SE or TEE can be easily ported to another. Common APIs and approaches across vendors mean that engineers learn transferable skills.



Provides Clear Security Foundation for Service Providers	Accommodates Different Implementations	Supportes Differentiation of:	Enables Externally Verifiable Compliance with Specifications for both:
• No need for Service Providers to understand all the details of the implementation • Supports service development across value chain	• Innovation is not stifled by single OS, firmware, hardware • Not an all-or-nothing proposition • Existing multiple competitive solutions available in the market	• Secure functions required • Security level desired	• Robustness and security level declared • Functional behavior and interoperability

Figure 4.6: GlobalPlatform Technologies: Providing Flexibility While Supporting Innovation and Portability

GlobalPlatform has defined protocols for OS update and Trusted Application updates for both Trusted Execution Environments [29] and Secure Elements [30] (ref SAM). Given current expectations regarding post-quantum algorithms, even the simplest system using cryptography is likely to need updates during its lifetime. If OTA updates are not supported, the only alternative is an expensive recall.

With standardized APIs and standardized protection profile, GlobalPlatform TEE offers the best of class functional and security interoperable solution for various hardware design.

4.3.2 TEE Protection Profile

At the highest level, a TEE that meets the Global Platform TEE Protection Profile ([TEE PP]) is an environment where the following are true:

- Authenticity: All code executing inside the TEE has been authenticated.
- Integrity: Unless explicitly shared with entities outside the TEE, the ongoing integrity of all TEE assets is assured through isolation, cryptography, or other mechanisms.
- Data Confidentiality: Unless explicitly shared with entities outside the TEE, the ongoing confidentiality of the contents of all TEE data assets - including keys - is assured through isolation or other mechanisms such as cryptography.
- TA Code Confidentiality: TEE capabilities, such as isolation or cryptography, can be used to provide confidentiality of the TA code asset.
- Security: The TEE resists known remote and software attacks, and a set of external hardware attacks.
- Debug and Trace: Both code and other assets are protected from unauthorized debug tracing and control operations being performed through the device's debug and test features.

The full published protection profile can be found here:
`https://globalplatform.org/specs-library/tee-protection-profile-v1-3/`
and
`https://globalplatform.org/specs-library/use_of_tee_pp_and_pp-modules/`.

Global Platform TEEs are certified by 3rd party labs using this profile.

4.4 Secure Communication

4.4.1 Introduction

AUTOSAR specifies multiple secure communication protocols usable across the several OSI layers. The subsequent chapters provide an overview of these protocols detailing their advantages and disadvantages as well as possible use cases.

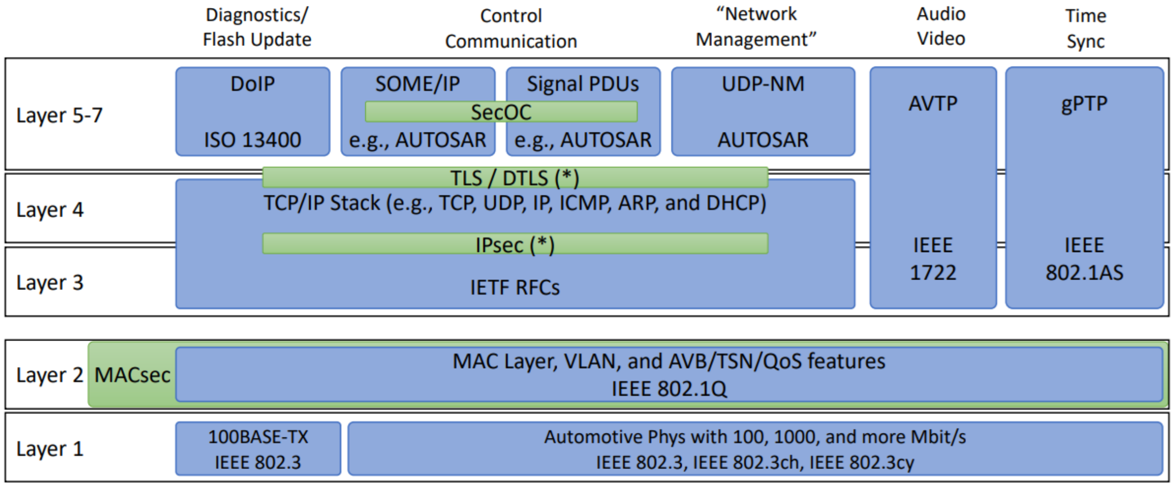


Figure 4.7: Secure communication protocols

4.4.2 Post Quantum Cryptography

Post-quantum security refers to cryptographic algorithms and protocols designed to resist attacks by quantum computers. With the next breakthrough in quantum computing, cryptographic schemes used today might no longer be considered secure. Quantum computers have the potential to solve certain mathematical problems exponentially faster than classical computers, threatening the security of widely used cryptographic algorithms. Shor's algorithm, for example, could factor large numbers efficiently, breaking widely-used asymmetric cryptography like RSA and ECC once quantum computers provide a sufficient number of qubits operating stable enough in superposition to apply Shor's algorithm to asymmetric cryptographic material using today's common key lengths. Microsoft Research has calculated that around 2500 qubits will be needed to compute elliptic curve discrete logarithms to crack a standard 256-bit key. Around 4000 qubits are needed for 2048-bit RSA. [31] [32]

Symmetric cryptography like AES is less severely impacted as no quantum algorithm is currently known to be able to break it. The best attacks lead to a reduction of effective key lengths. Using double key sizes is an obvious solution to achieve the same level of protection achieved before.

Note: All asymmetric cryptographic algorithms required or recommended by the AUTOSAR standard can be compromised once quantum computers will be advanced enough to apply Shor's algorithm on the used keys!

4.4.3 Protection

4.4.3.1 SecOC

The `SecOC` protocol provides a mechanism to verify the authenticity and freshness of PDU based communication between ECUs within the vehicle architecture. The authenticity and integrity of the PDU is ensured, but not the confidentiality. The `SecOC` module calculates and adds a message authentication code (MAC [45]) to the protocol data unit. For replay protection, a freshness value has to be included in the cryptographic calculation. The PDU is transmitted together with the MAC and freshness value (optional) in one frame.

[45] Not to be confused with the Layer 2 functionality in Ethernet.

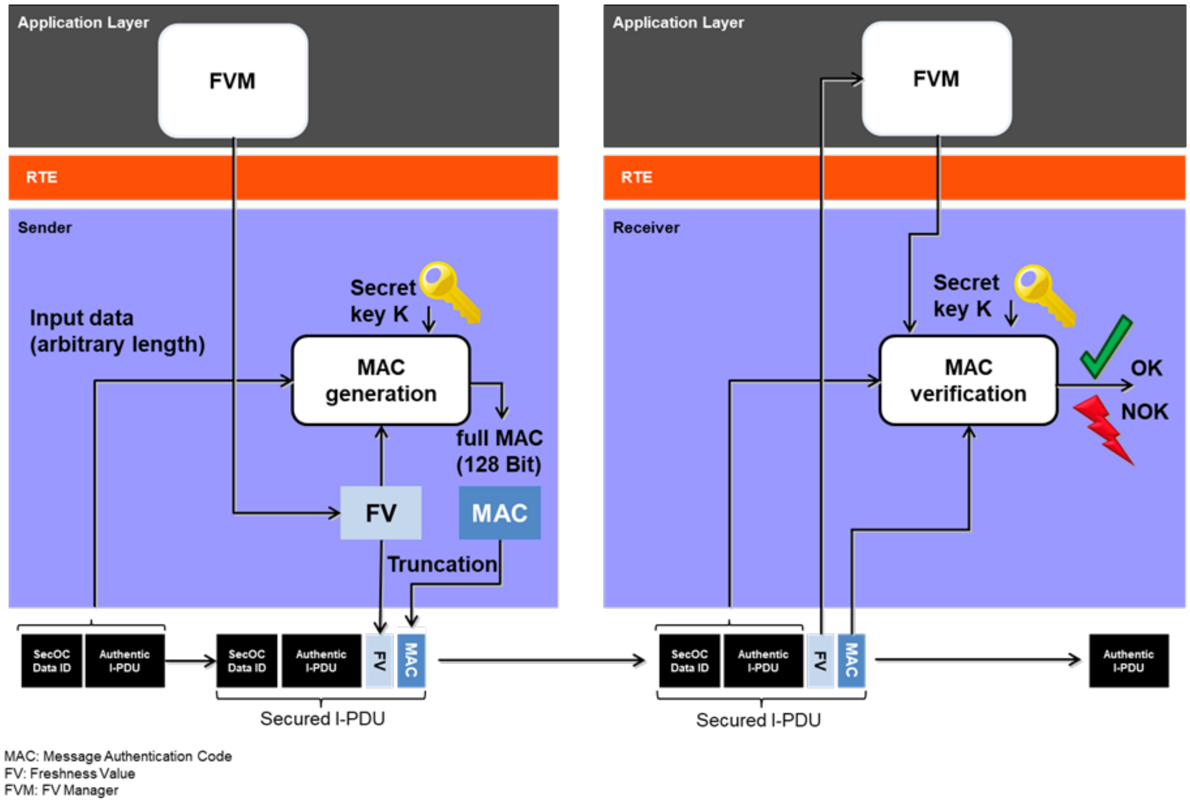


Figure 4.8: Message Authentication and Freshness Verification

Depending on the authentication algorithm used to generate the Authenticator, it may be possible to truncate the resulting Authenticator (e.g. in case of a MAC) generated by the authentication algorithm. Truncation may be desired when the message payload is limited in length and does not have sufficient space to include the full Authenticator, like in case of classical CAN.

The approach requires both the sending ECU and the receiving ECU to implement a SecOC module. The SecOC module integrates on the level of the AUTOSAR PduR. Figure 4.3 and 4.4 show the integration of the SecOC module as part of the AUTOSAR communication stack in classic and adaptive respectively.

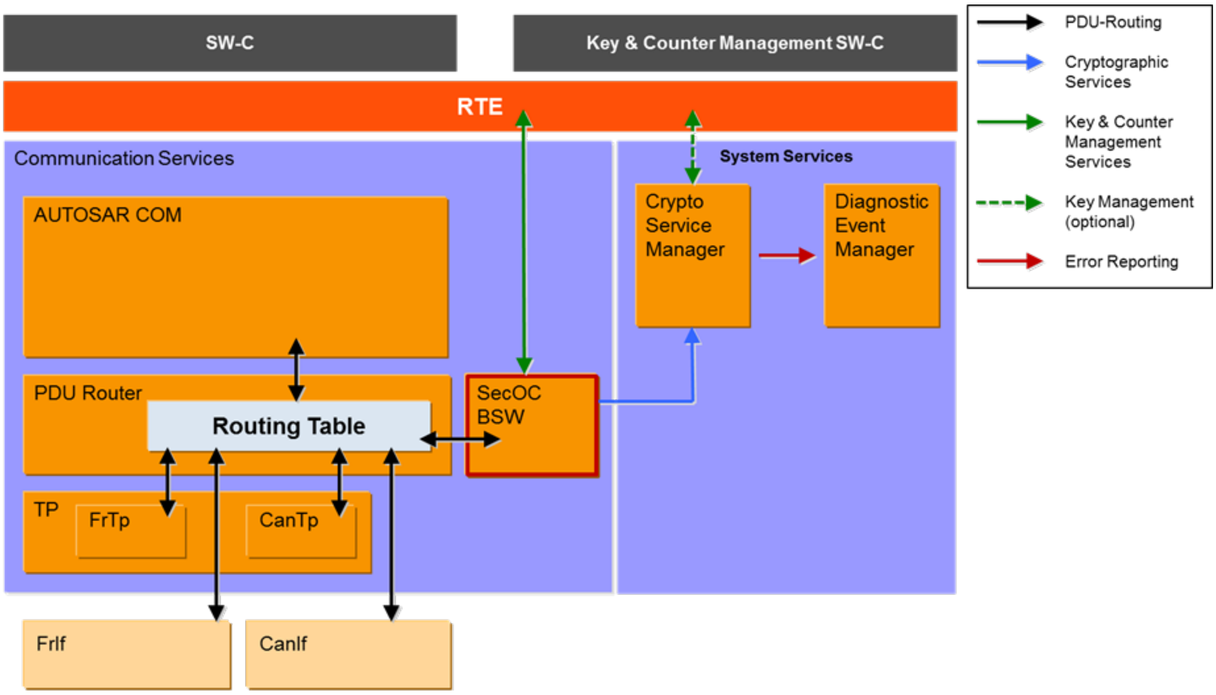


Figure 4.9: SecOC Integration in Classic BSW

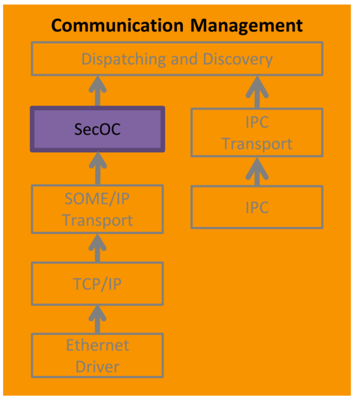


Figure 4.10: SecOC embedded in the Adaptive Communication Management

4.4.3.1.1 Constraints

Below are few of the constraints, based on the current AUTOSAR specification:

- AUTOSAR specifies mainly symmetric authentication approaches with message authentication codes (MACs) for SecOC. However, is is possible to use asymmetric authentication approaches as well.
- In case of SOME/IP protocol, the SOME/IP message id can not be protected by SecOC, because it is stripped before SecOC is invoked.
- SOME/IP-SD can not be protected.

4.4.3.1.2 Pros/Cons

Advantages of using SecOC:

- Broadcastable
- SecOC operates above the transport layer, which is why it is mainly independent from the underlying network protocols.
- SecOC is optimized for low-bandwidth bus systems (e.g. CAN). SecOC supports MAC and FV truncation. (NIST recommends truncation of MAC below 64 bits only with careful analysis.) There is also support to send the cryptographic I-PDU, with Authentication information as a separate message.

Disadvantages of using SecOC:

- SecOC does not offer encryption support by design.
- SecOC is only applicable for in-vehicle communication. SecOC has not been specified to work with MOST and LIN communication networks. With MOST not being specifically supported, the applicability to multimedia and telematic car domains may be limited.
- The SecOC module can only be used to secure the whole SomeIpTp message and cannot be used to secure individual segments of a SomeIpTp message.
- An OEM specific Freshness Value Manager is required.
- Gatewaying-on-the-fly is not supported by SecOC.

4.4.3.1.3 Key Management

1. No session keys
2. High granularity possible (different keys per PDU). Some examples:
   - One global key: ECUs can be swapped easily. If keys are leaked, attackers can attack all systems.
   - One key per vehicle: Keys need to be loaded on an ECU, if components are swapped.
   - One key per message: Ideal but has requires huge storage capacity for the keys.
3. In classic AUTOSAR, the cryptographic materials are handled by KeyM and stored via the Cryptostack interfaces. In adaptive AUTOSAR, the functional cluster Cryptography(FC Crypto) provides crypto APIs for cryptographic material storage and handling.

4.4.3.1.4 Use-cases

Use case	Description
In-Vehicle communication	Authenticated in-vehicle communication with replay and spoofing protection
Low bandwidth support	Support for low-bandwidth bus systems, like CAN
Real-time communication	Support for Real-time communication on AUTOSAR bus systems like CAN or Ethernet

Table 4.11: SecOC use cases

4.4.3.2 (D)TLS

Transport Layer Security (TLS) is a protocol that ensures secure communication over a network by providing encryption, authentication, and integrity for data transmission.

TLS is specified by several RFCs:

- **RFC-5246**: The Transport Layer Security (TLS) Protocol Version 1.2 [33]
- **RFC-8446**: The Transport Layer Security (TLS) Protocol Version 1.3 [34]
- **RFC-6066**: Transport Layer Security (TLS) Extensions [35]
- **RFC-6347**: Datagram Transport Layer Security Version 1.2 [36]

Note: In case both, TLS version 1.2 and TLS version 1.3 are supported for a connection, TLS version 1.3 shall be preferred.

The key capabilities of TLS include:

- **Encryption:** TLS encrypts data to protect it from unauthorized access during transmission, ensuring confidentiality.
- **Authentication:** TLS enables parties to verify each other's identities, preventing impersonation and ensuring that communication is with the intended recipient.
- **Integrity:** TLS ensures that data remains intact and unaltered during transmission, detecting tampering attempts.
- **Flexibility:** TLS supports various cryptographic algorithms, cipher suites, and protocols, allowing for configuration based on security requirements and compatibility.

4.4.3.2.1 Constraints

- Since TLS is not broadcastable, it cannot protect the SOME/IP SD protocol.
- TLS is limited to the crypto algorithms specified for a certain TLS version.

4.4.3.2.2 Pros/Cons

Advantages of using (D)TLS:

- Good interoperability with bus systems from other verticals like PCs or IoT devices.
- Based on proven in use certificate based cryptography.
- Provides encryption for the transported data. However, encryption can be disabled using TLS with NULL cipher suites resulting in authentication of the transported data only.
- Provides end-to-end protection.
- For faster startup time, pre-shared keys could be used.

Disadvantages of using (D)TLS:

- Only protects a single socket connection.
- Cannot protect the lower OSI layers up to L4.
- Supports only IP protocol capable bus systems, like Ethernet or CAN XL.
- The current TLS standards available don't provide post quantum ready asymmetric cryptography yet.
- Does not support broadcast or multicast

4.4.3.2.3 Key managmenent

TLS sessions involve possible mutual authentication, in which one or both parties present their own certificate for validation by the other peer. This requires the ability to sign and validate signatures with both symmetric (pre-shared keys) and asymmetric (PKI-based) credentials. For certificate-based authentication, the contacted party needs to be able to link the peer certificate to a known Certification Authority (CA) to establish trust, which involves chaining certificate validation all the way back to a trusted Root CA.

The main advantage of certificate-based authentication is the ability for peers to authenticate each other without pre-provisioning individual peer credentials, but only Root Authority certificates that usually remain valid for decades. Key establishment, encryption, and integrity algorithms are picked and configured during the initial handshake, where both peers negotiate a common supported set of functions referred to as a cipher suite. This requires the ability for both sides to run a key agreement algorithm such as Diffie-Hellman or ECDH, symmetric ciphers in various modes for line encryption, and hash functions for integrity protection. Care should be taken to ensure that both parties can agree on a common set, and that the minimal possible cipher suite satisfies security requirements set for the secure link.

The following list summarizes the key exchange process.

1. **ClientHello**: ClientHello: TLS client initiates the connection by sending a ClientHello message, which includes, supported TLS versions, supported cipher suites and optional compression methods.
2. **ServerHello**: The server responds with a ServerHello message, selecting a TLS version, a cipher suite and optionally a compression method.
3. **Certificate (if applicable)**: The server sends its digital certificate, containing the server's public key and server CA's signature.
4. **ServerKeyExchange (if applicable)**: In some key exchange methods, such as Diffie-Hellman or ECDSA, the server may send additional key exchange parameters.
5. **CertificateRequest (optional)**: The server may request the client's certificate for mutual authentication.
6. **ClientKeyExchange**: The client generates a pre-master secret and sends it to the server encrypted with the server's public key (from the certificate). This pre-master secret is used to derive the session keys. Alternatively, the client sends its chosen PSK identity to the server.
7. **CertificateVerify (if applicable)**: If the server requested the client's certificate, the client sends a digital signature of the handshake messages to prove possession of the private key corresponding to the client certificate.
8. **ChangeCipherSpec**: Both parties send a ChangeCipherSpec message to indicate that subsequent messages will be encrypted with the negotiated parameters.
9. **Finished**: Both parties send a Finished message to verify the integrity of the handshake and confirm that they can derive the same encryption keys.

4.4.3.2.4 Use-cases

The following table outlines use cases suitable for (D)TLS secured sockets.

Use case	Description
Protect DoIP	TLS is the designated security layer for DoIP diagnostic sessions.
V2G	V2G communication uses TLS for security, for example in smart charging.
Protect SOME/IP services	In contrast to SecOC, TLS can protect all payload of an AUTOSAR PDU including the AUTOSAR PDU header used which overlaps with the SOME/IP message header.
Protect SOVD	TLS is the designated security protocol for SOVD.
Protect Cloud connections	TLS protects common cloud communication protocols like MQTT.

Table 4.12: (D)TLS use cases

4.4.3.3 IPsec

IPsec is a network layer protocol suite that secures network connections by encrypting and/or authenticating IP packets. It constitutes a part of IP protocol suite.

IPsec uses the following protocols:

- **Internet Key Exchange** - Framework for authentication and key exchange.
- **Authentication Header** - (IP protocol 51) for integrity.
- **Encapsulating Security Payload** - (IP protocol 50) for integrity and confidentiality.

IPsec works in two basic modes of operation:

- **Transport mode** - Only the payload of the IP packet is encrypted or authenticated.
- **Tunnel mode** - Entire packet is encrypted or authenticated to a new IP packet with a new IP header. However, the tunnel mode is currently not supported by AUTOSAR, see [37, Section 5.13]

IPsec is an open network standard, maintained by IETF since 1995 and commonly used in network equipment as well as server and desktop operating systems.

- IPsec shall be supported according to **RFC-4301** [38].
- AH shall be supported according to **RFC-4302** [39].
- ESP shall be supported according to **RFC-4303** [40].
- IKEv2 shall be supported according to **RFC-4301** [41].

4.4.3.3.1 Constraints

Below are few of the constraints, based on the current AUTOSAR specification:

- The following ports shall be not protected by IPsec:
  - 500/UDP: IKEv2 packets. [42]
  - 4500/UDP: IKEv2 packets. [42]
  - 6801/TCP: Diagnostics - [37]
- If preshared keys are used: [42]
  - Pre-shared keys (PSK) shall not be used for directly setting up IPsec security associations (SAs).
  - Counter mode encryption algorithms shall not be used in combination with pre-shared keys when setting up SAs directly.

4.4.3.3.2 Pros/Cons

Advantages of using IPsec:

- Supports encryption.
- Supports interoperability with communication protocols of other verticals, like IOT.
- Hides the network topology
- For faster startup time, pre-shared keys could be used for authentication.

Disadvantages of using IPsec:

- Supports only IP protocol capable bus systems, like Ethernet or CAN-XL.
- Not broadcastable.
- If certificates are used for authentication, it requires long start up time for asymmetric algorithms.
- If certificates are used for authentication, it requires Public Key Infrastructure(PKI) to be supported.

4.4.3.3.3 Key Management

Key management is performed by Internet Key Exchange (IKEv2). IKEv2 defines negotiation and authentication processes for IPsec security associations. The Authentications can be done by pre-shared keys or Certificates. A Security Association (SA) is the formation of shared security elements between two network nodes in order to support secure communication. It may include attributes such as: Cryptographic algorithm and mode, traffic encryption key, and parameters for the network data to be passed over the connection. They are usually stored in Security Associations Database.

The following drawing explains the meaning of the IKE module, security associations (SA) and security policies (SP) databases for securing IPsec network communication.

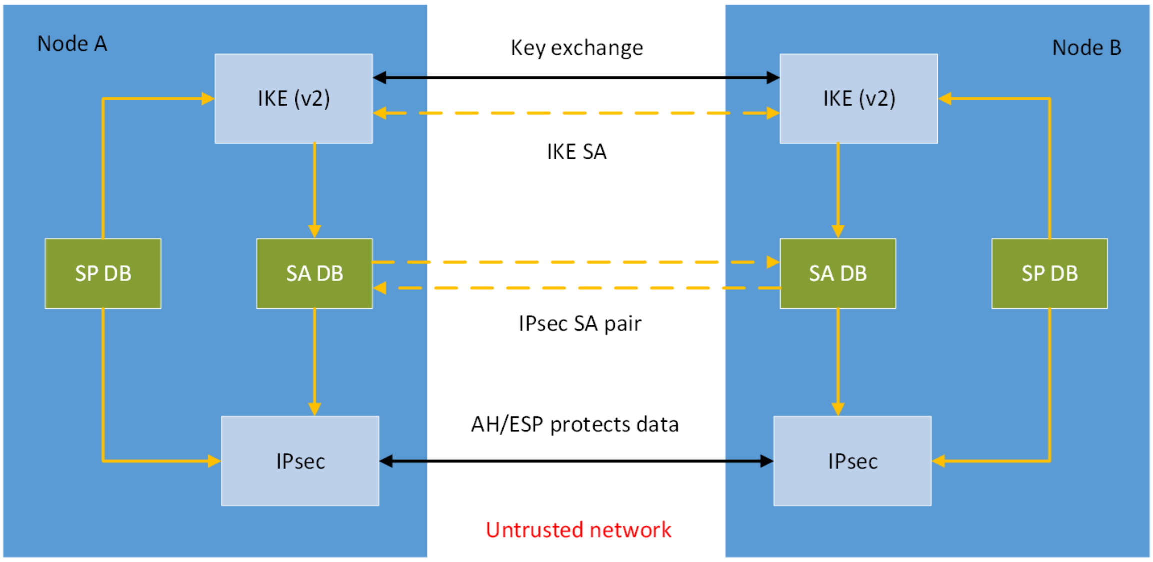


Figure 4.11: SA creation with IKE for network traffic protection

4.4.3.3.4 Use-cases

Use case	Description
In vehicle communication	End-point protection via encryption/authentication with spoofing protection
Protect non PDU protocols	Protect non AUTOSAR PDUs based protocols like video streaming.

Table 4.13: IPsec use cases

4.4.3.4 MACsec

MACsec [46] is an IEEE 802.1AE standard that provides data integrity, authenticity, and "optionally" confidentiality for Ethernet communication. It operates at the Layer 2 (Data Link Layer) of the OSI model, providing point-to-point security for Ethernet communication. It works by encrypting and authenticating Ethernet frames, ensuring only authorized devices can access and modify data on the network.

4.4.3.4.1 Constraints

The AUTOSAR Classic platform dedicates section 4.1 within the Specification of MACsec Key Agreement to a comprehensive exploration of the constraints that need to be considered when implementing MACsec. [43, Section 4.1]

[46] Here MAC refers to the Layer 2 Media Access Control of Ethernet

4.4.3.4.2 Pros/Cons

Advantages of using `MACsec`:

- Provides L2 data Integrity, Authenticity and optionally Confidentiality.
- Supports both software and hardware solutions.
- High Performance and low latency for the HW-based solution.
- Lower CPU Load: in HW-based solution functionality is offloaded to dedicated hardware, typically integrated within the Physical Layer (PHY).

Disadvantages of using `MACsec`:

- No End-to-End Protection: `MACsec` only encrypts individual Ethernet frames, not complete end-to-end communication paths. If a compromised device sits between two secure segments, it can still intercept and manipulate data.
- HW-based solution: Hardware offloading requires dedicated `MACsec` chips.

4.4.3.4.3 Key Management

MKA protocol leverages the IEEE 802.1AE Secure Channels (SC) suite to establish a shared secret key between ECUs for secure communication. Following is a breakdown of the steps involved:

1. Pre-configuration for:
    - Pre-Shared Key (CAK): A unique, cryptographically strong random key is pre-configured and securely stored on each ECU involved in the communication.
2. MKPDU Transmission (Challenge):
    - The MKA module initiates the handshake by transmitting a `MACsec` Key Agreement Protocol Data Unit (MKPDU) containing Key Name "CKN" and integrity MAC "ICV"
3. MKPDU Processing (Response):
    - The receiving ECU receives the challenge MKPDU.
    - The MKA module within the receiving ECU extracts the challenge and verifies the received ICV.
4. MKPDU Verification:
    - Both ECUs involved in the handshake perform verification - each ECU calculates the expected MAC for the received MKPDU.
    - The calculated MAC is then compared to the MAC included within the received MKPDU.

- If the calculated and received MACs match on both sides, it signifies successful authentication. This confirms the identities of both ECUs.

5. Session Agreement Key (SAK) Derivation:
   - The SAK is generated by one MKA participant (Key Server)
6. Secure SAK Distribution:
   - The SAK is confidential and needs to be protected. It's encrypted with a separate Key Encryption Key (KEK) before being securely transferred between devices.
7. SAK Installation and MACsec Activation:
   - Devices decrypt with KEK the received SAK and install it. With established session keys, secure MACsec communication can begin.

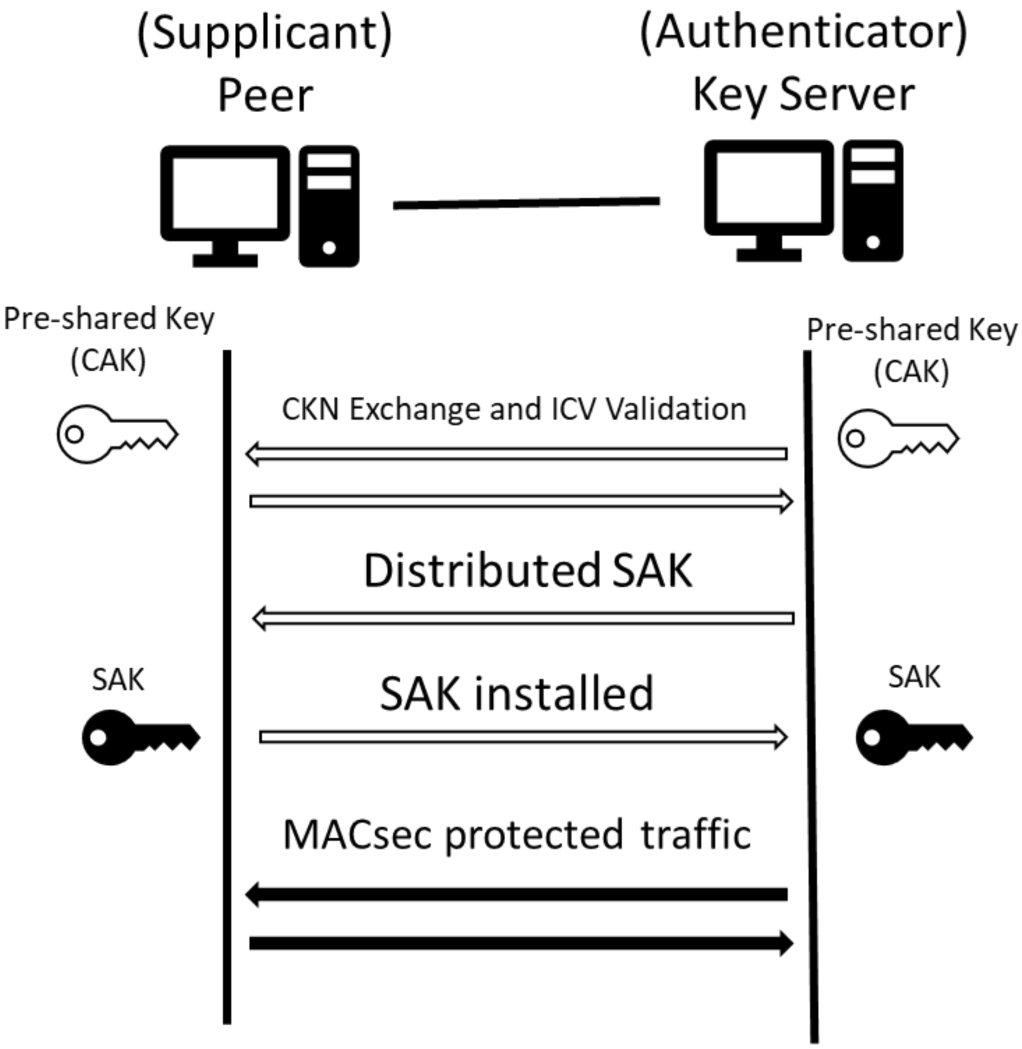


Figure 4.12: MACsec Key Agreement Sequence

4.4.3.4.4 Use-cases

Use case	Description
Secure data transmission	Ethernet Point-to-point encrypted and authenticated communication.
Real-time communication	Ethernet Real-time and High-Performance Communication in HW-based solution.

Table 4.14: MACsec use cases