OP-TEE design

Contents

1. Introduction

OP-TEE is a so called Trusted Execution Environment, in short a TEE, for ARM based chips supporting TrustZone technology. OP-TEE consists of three components.

- OP-TEE Client, which is the client API running in normal world user space.
- OP-TEE Linux Kernel driver, which is the driver that handles the communication between normal world user space and secure world.
- OP-TEE Trusted OS, which is the Trusted OS running in secure world.

OP-TEE was designed with scalability and portability in mind and as of now it has been ported to quite a few different platforms, both ARMv7-A and ARMv8-A from different vendors. For a full list, please see Platforms Supported.

OP-TEE OS is made of 2 main components: the OP-TEE core and a collection of libraries designed for being used by Trusted Applications. While OP-TEE core executes in the ARM CPU privileged level (also referred to as 'kernel land'), the Trusted Applications execute in the non-privileged level (also referred to as the 'userland'). The static libraries provided by the OP-TEE OS enable Trusted Applications to call secure services executing at a more privileged level.

2. Platform initialization

TBD

3. Secure Monitor Calls - SMC

3.1 SMC handling

TBD

3.2 SMC Interface

The OP-TEE SMC interface is defined in two levels using optee_smc.h and optee_msg.h. The former file defines SMC identifiers and what is passed in the registers for each SMC. The latter file defines the OP-TEE Message protocol which is not restricted to only SMC even if that currently is the only option available.

3.3 Communication using SMC Interface

The main structure used for the SMC communication is defined in struct optee_msg_arg. If we are looking into the source code, we could see that communication mainly is achieved using `optee_msg_arg` and `thread_smc_args`, where `optee_msg_arg` could be seen as the main structure. What will happen is that the OP-TEE Linux Kernel driver will get the parameters either from OP-TEE Client or directly from an internal service in the Linux kernel. The TEE driver will populate the struct `optee_msg_arg` with the parameters plus some additional bookkeeping information. Parameters for the SMC are passed in registers 1 to 7, register 0 holds the SMC id which among other things tells whether it is a standard or a fast call.

4. Thread handling

The OP-TEE core uses a couple of threads to be able to support running jobs in parallel (not fully enabled!). There are handlers for different purposes. In thread.c you will find a function called `thread_init_primary` which assigns `init_handlers` (functions) that should be called when OP-TEE core receives standard or fast calls, FIQ and PSCI calls. There are default handlers for these services, but the platform can decide if they want to implement their own platform specific handlers instead.

Synchronization

OP-TEE has three primitives for synchronization of threads and CPUs: spin-lock, mutex, and condvar.

Spin-lock

A spin-lock is represented as an `unsigned int`. This is the most primitive lock. Interrupts should be disabled before attempting to take a spin-lock and should remain disabled until the lock is released. A spin-lock is initialized with `SPINLOCK_UNLOCK`.

Function	Purpose
`cpu_spin_lock()`	Locks a spin-lock
`cpu_spin_trylock()`	Locks a spin-lock if unlocked and returns `0` else the spin-lock is unchanged and the function returns `!0`
`cpu_spin_unlock()`	Unlocks a spin-lock

Mutex

A mutex is represented by `struct mutex`. A mutex can be locked and unlocked with interrupts enabled or disabled, but only from a normal thread. A mutex cannot be used in an interrupt handler, abort handler or before a thread has been selected for the CPU. A mutex is initialized with either `MUTEX_INITIALIZER` or `mutex_init()`.

Function	Purpose
`mutex_lock()`	Locks a mutex. If the mutex is unlocked this is a fast operation, else the function issues an RPC to wait in normal world.
`mutex_unlock()`	Unlocks a mutex. If there is no waiters this is a fast operation, else the function issues an RPC to wake up a waiter in normal world.
`mutex_trylock()`	Locks a mutex if unlocked and returns `true` else the mutex is unchanged and the function returns `false`.
`mutex_destroy()`	Asserts that the mutex is unlocked and there is no waiters, after this the memory used by the mutex can be freed.

When a mutex is locked it is owned by the thread calling `mutex_lock()` or `mutex_trylock()`, the mutex may only be unlocked by the thread owning the mutex. A thread should not exit to TA user space when holding a mutex.

Condvar

A condvar is represented by `struct condvar`. A condvar is similar to a pthread_condvar_t in the pthreads standard, only less advanced. Condition variables are used to wait for some condition to be fulfilled and are always used together a mutex. Once a condition variable has been used together with a certain mutex, it must only be used with that mutex until destroyed. A condvar is initialized with `CONDVAR_INITIALIZER` or `condvar_init()`.

Function	Purpose

`condvar_wait()`	Atomically unlocks the supplied mutex and waits in normal world via an RPC for the condition variable to be signaled, when the function returns the mutex is locked again.
`condvar_signal()`	Wakes up one waiter of the condition variable (waiting in `condvar_wait()`)
`condvar_broadcast()`	Wake up all waiters of the condition variable.

The caller of `condvar_signal()` or `condvar_broadcast()` should hold the mutex associated with the condition variable to guarantee that a waiter does not miss the signal.

5. MMU

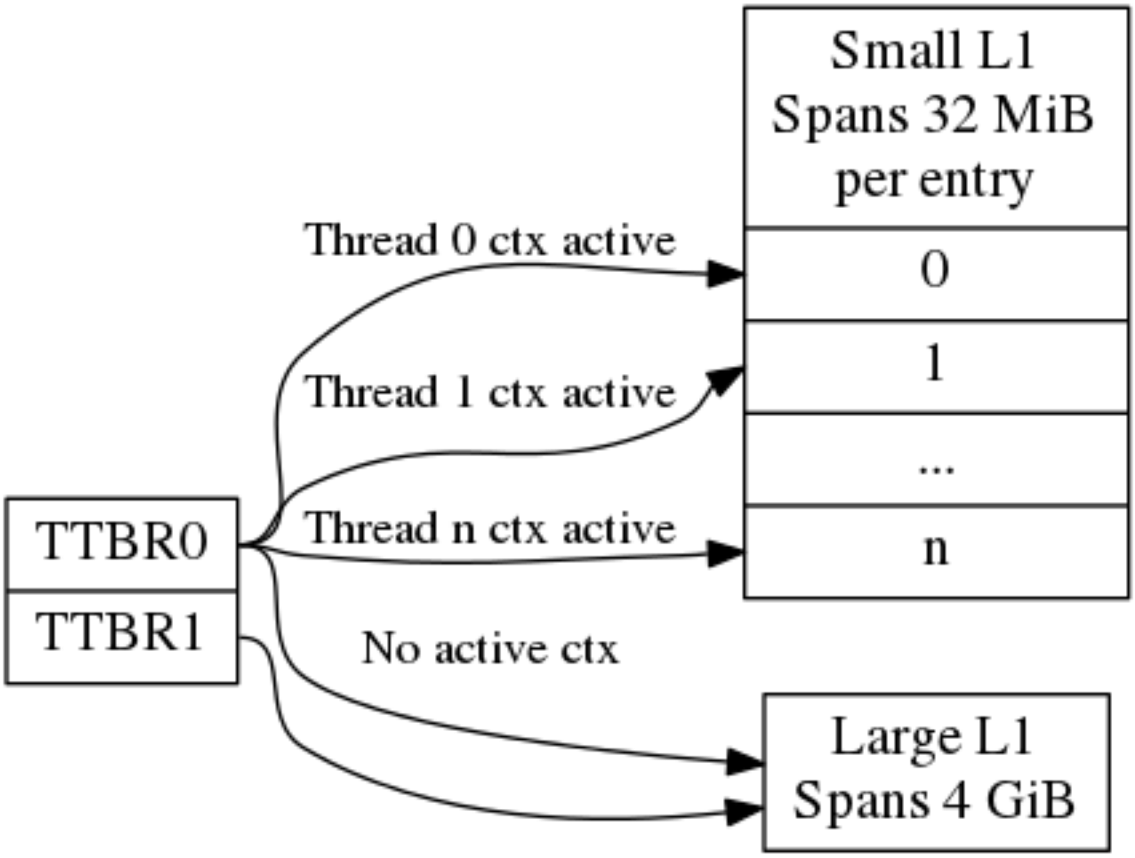
Translation tables

OP-TEE uses several L1 translation tables, one large spanning 4 GiB and two or more small tables spanning 32 MiB. The large translation table handles kernel mode mapping and matches all addresses not covered by the small translation tables. The small translation tables are assigned per thread and covers the mapping of the virtual memory space for one TA context.

Memory space between small and large translation table is configured by TTBRC. TTBR1 always points to the large translation table. TTBR0 points to the a small translation table when user mapping is active and to the large translation table when no user mapping is currently active.

The translation tables has certain alignment constraints, the alignment (of the physical address) has to be the same as the size of the translation table. The translation tables are statically allocated to avoid fragmentation of memory due to the alignment constraints.

Each thread has one small L1 translation table of its own. Each TA context has a compact representation of its L1 translation table. The compact representation is used to initialize the thread specific L1 translation table when the TA context is activated.



Translation tables and switching to user mode

This section only applies with `CFG_WITH_LPAE=n` and `CFG_CORE_UNMAP_CORE_AT_EL0=y`.
When switching to user mode only a minimal kernel mode mapping is kept. This is achieved by selecting a zeroed out big L1 translation in TTBR1 when transitioning to user mode. When returning back to kernel mode the original L1 translation table is restored in TTBR1.

Translation tables and switching to normal world

When switching to normal world either via a foreign interrupt or RPC there is a chance that secure world will resume execution on a different CPU. This means that the new CPU need to be configured with the context of the currently active TA. This is solved by always setting the TA context in the CPU when resuming execution. Here is room for improvements since it is more likely than not that it is the same CPU that resumes execution in secure world.

6. Stacks

Different stacks are used during different stages. The stacks are:

- Secure monitor stack (128 bytes), bound to the CPU. Only available if OP-TEE is compiled with a secure monitor always the case if the target is ARMv7-A but never for ARMv8-A.
- Temp stack (small ~1KB), bound to the CPU. Used when transitioning from one state to another. Interrupts are always disabled when using this stack, aborts are fatal when using the temp stack.
- Abort stack (medium ~2KB), bound to the CPU. Used when trapping a data or pre-fetch abort. Aborts from user space are never fatal the TA is only killed. Aborts from kernel mode are used by the pager to do the demand paging, if pager is disabled all kernel mode aborts are fatal.
- Thread stack (large ~8KB), not bound to the CPU instead used by the current thread/task. Interrupts are usually enabled when using this stack.

Notes for ARMv7/AArch32:

Stack	Comment
Temp	Assigned to `SP_SVC` during entry/exit, always assigned to `SP_IRQ` and `SP_FIQ`
Abort	Always assigned to `SP_ABT`
Thread	Assigned to `SP_SVC` while a thread is active

Notes for AArch64: There are only two stack pointers, `SP_EL1` and `SP_EL0`, available for OP-TEE in AArch64. When an exception is received stack pointer is always `SP_EL1` which is used temporarily while assigning an appropriate stack pointer for `SP_EL0`. **`SP_EL1` is always assigned the value of `thread_core_local[cpu_id]`.** This structure has some spare space for temporary storage of registers and also keeps the relevant stack pointers. In general when we talk about assigning a stack pointer to the CPU below we mean `SP_EL0`.

Boot

During early boot the CPU is configured with the temp stack which is used until OP-TEE exits to normal world the first time.
Notes for AArch64: `SPSEL` is always `0` on entry/exit to have `SP_EL0` acting as stack pointer.

Normal entry

Each time OP-TEE is entered from normal world the temp stack is used as the initial stack. For fast calls this is the only stack used. For normal calls an empty thread slot is selected and the CPU switches to that stack.

Normal exit

Normal exit occurs when a thread has finished its task and the thread is freed. When the main thread function, tee_entry_std(), returns interrupts are disabled and the CPU switches to the temp stack instead. The thread is freed and OP-TEE exits to normal world.

RPC exit

RPC exit occurs when OP-TEE need some service from normal world. RPC can currently only be performed with a thread is in running state. RPC is initiated with a call to thread_rpc() which saves the state in a way that when the thread is restored it will continue at the next instruction as if this function did a normal return. CPU switches to use the temp stack before returning to normal world.

Foreign interrupt exit

Foreign interrupt exit occurs when OP-TEE receives a foreign interrupt. For ARM GICv2 mode, foreign interrupt is sent as IRQ which is always handled in normal world. Foreign interrupt exit is similar to RPC exit but it is `thread_irq_handler()` and `elx_irq()` (respectively for ARMv7-A/Aarch32 and for Aarch64) that saves the thread state instead. The thread is resumed in the same way though. For ARM GICv3 mode, foreign interrupt is sent as FIQ which could be handled by either secure world (EL3 in AArch64) or normal world. This mode is not supported yet.

Notes for ARMv7/AArch32: SP_IRQ is initialized to temp stack instead of a separate stack. Prior to exiting to normal world CPU state is changed to SVC and temp stack is selected.
Notes for AArch64: `SP_EL0` is assigned temp stack and is selected during IRQ processing. The original `SP_EL0` is saved in the thread context to be restored when resuming.

Resume entry

OP-TEE is entered using the temp stack in the same way as for normal entry. The thread to resume is looked up and the state is restored to resume execution. The procedure to resume from an RPC exit or an foreign interrupt exit is exactly the same.

Syscall

Syscalls are executed using the thread stack.
Notes for ARMv7/AArch32: Nothing special `SP_SVC` is already set with thread stack.
Notes for syscall AArch64:
Early in the exception processing the original `SP_EL0` is saved in `struct thread_svc_regs` in case the TA is executed in AArch64.
Current thread stack is assigned to `SP_EL0` which is then selected.
When returning `SP_EL0` is assigned what is in `struct thread_svc_regs`.
This allows `tee_svc_sys_return_helper()` having the syscall exception handler return directly to `thread_unwind_user_mode()`.

7. Shared Memory

Shared Memory is a block of memory that is shared between the non-secure and the secure world. It is used to transfer data between both worlds.

Shared Memory Allocation

The shared memory is allocated by the Linux driver from a pool `struct shm_pool`, the pool contains:

- The physical address of the start of the pool
- The size of the pool

- Whether or not the memory is cached
- List of chunk of memory allocated.

Note that:

- The shared memory pool is physically contiguous.
- The shared memory area is not secure as it is used by both non-secure and secure world.

Shared Memory Configuration

It is the Linux kernel driver for OP-TEE that is responsible for initializing the shared memory pool, given information provided by the OP-TEE core. The Linux driver issues a SMC call `OPTEE_SMC_GET_SHM_CONFIG` to retrieve the information

- Physical address of the start of the pool
- Size of the pool
- Whether or not the memory is cached

The shared memory pool configuration is platform specific. The memory mapping, including the area `MEM_AREA_NSEC_SHM` (shared memory with non-secure world), is retrieved by calling the platform-specific function `bootcfg_get_memory()`. Please refer to this function and the area type `MEM_AREA_NSEC_SHM` to see the configuration for the platform of interest. The Linux driver will then initialize the shared memory pool accordingly.

Shared Memory Chunk Allocation

It is the Linux kernel driver for OP-TEE that is responsible for allocating chunks of shared memory. OP-TEE linux kernel driver relies on linux kernel generic allocation support (`CONFIG_GENERIC_ALLOCATION`) to allocation/release of shared memory physical chunks. OP-TEE linux kernel driver relies on linux kernel dma-buf support (`CONFIG_DMA_SHARED_BUFFER`) to track shared memory buffers references.

Shared Memory Usage

From the Client Application

The client application can ask for shared memory allocation using the GlobalPlatform Client API function `TEEC_AllocateSharedMemory()`. The client application can also provide shared memory through the GlobalPlatform Client API function `TEEC_RegisterSharedMemory()`. In such a case, the provided memory must be physically contiguous so that the OP-TEE core, that does not handle scatter-gather memory, is able to use the provided range of memory addresses. Note that the reference count of a shared memory chunk is incremented when shared memory is registered, and initialized to 1 on allocation.

From the Linux Driver

Occasionally the Linux kernel driver needs to allocate shared memory for the communication with secure world, for example when using buffers of type TEEC_TempMemoryReference.

From the OP-TEE core

In case the OP-TEE core needs information from the TEE supplicant (dynamic TA loading, REE time request,...), shared memory must be allocated. Allocation depends on the use case. The OP-TEE core asks for the following shared memory allocation:

- `optee_msg_arg` structure, used to pass the arguments to the non-secure world, where the allocation will be done by sending a `OPTEE_SMC_RPC_FUNC_ALLOC` message.
- In some cases, a payload might be needed for storing the result from TEE supplicant, for example when loading a Trusted Application. This type of allocation will be done by sending the message `OPTEE_MSG_RPC_CMD_SHM_ALLOC(OPTEE_MSG_RPC_SHM_TYPE_APPL,...)`, which then will return:
    - the physical address of the shared memory
    - a handle to the memory, that later on will be used later on when freeing this memory.

From the TEE Supplicant

The TEE supplicant is also working with shared memory, used to exchange data between normal and secure worlds. The TEE supplicant receives a memory address from the OP-TEE core, used to store the data. This is for example the case when a Trusted Application is loaded. In this case, the TEE supplicant must register the provided shared memory in the same way a client application would do, involving the Linux driver.

8. Pager

OP-TEE currently requires ~256 KiB RAM for OP-TEE kernel memory. This is not a problem if OP-TEE uses TrustZone protected DDR, but for security reasons OP-TEE may need to use TrustZone protected SRAM instead. The amount of available SRAM varies between platforms, from just a few KiB up to over 512 KiB. Platforms with just a few KiB of SRAM cannot be expected to be able to run a complete TEE solution in SRAM. But those with 128 to 256 KiB of SRAM can be expected to have a capable TEE solution in SRAM. The pager provides a solution to this by demand paging parts of OP-TEE using virtual memory.

Secure memory

TrustZone protected SRAM is generally considered more secure than TrustZone protected DRAM as there is usually more attack vectors on DRAM. The attack vectors are hardware dependent and can be different for different platforms.

Backing store

TrustZone protected DRAM or in some cases non-secure DRAM is used as backing store. The data in the backing store is integrity protected with one hash (SHA-256) per page (4KiB). Readonly pages are not encrypted since the OP-TEE binary itself is not encrypted.

Partitioning of memory

The code that handles demand paging must always be available as it would otherwise lead to deadlock. The virtual memory is partitioned as:

```
  Type       Sections
+--------------+-----------------+
|              | text            |
|              | rodata          |
|              | data            |
| unpaged      | bss             |
|              | heap1           |
|              | nozi            |
|              | heap2           |
+--------------+-----------------+
| init / paged | text_init       |
|              | rodata_init     |
```

```
+-------------- +-----------------+
| paged         | text_pageable   |
|               | rodata_pageable |
+---------------+-----------------+
| demand alloc  |                 |
|               |                 |
+---------------+-----------------+
```

Where "`nozi`" stands for "not zero initialized", this section contains entry stacks (thread stack when TEE pager is not enabled) and translation tables (TEE pager cached translation table when the pager is enabled and LPAE MMU is used).

The "`init`" area is available when OP-TEE is initializing and contains everything that is needed to initialize the pager. After the pager has been initialized this area will be used for demand paged instead.

The "`demand alloc`" area is a special area where the pages are allocated and removed from the pager on demand. Those pages are returned when OP-TEE does not need them any longer. The thread stacks currently belongs this area. This means that when a stack is not used the physical pages can be used by the pager for better performance.

The technique to gather code in the different area is based on compiling all functions and data into separate sections. The unpaged text and rodata is then gathered by linking all object files with `--gc-sections` to eliminate sections that are outside the dependency graph of the entry functions for unpaged functions. A script analyzes this ELF file and generates the bits of the final link script. The process is repeated for init text and rodata. What is not "unpaged" or "init" becomes "paged".

Partitioning of the binary

The binary is partitioned into four parts as:

```
+----------+
| Header   |
+----------+
| Init     |
+----------+
| Hashes   |
+----------+
| Pageable |
+----------+
```

Header is defined as:

```
#define OPTEE_MAGIC             0x4554504f
```

```
#define OPTEE_VERSION           1
#define OPTEE_ARCH_ARM32        0
#define OPTEE_ARCH_ARM64        1
```

```
struct optee_header {
        uint32_t magic;
        uint8_t version;
        uint8_t arch;
        uint16_t flags;
        uint32_t init_size;
        uint32_t init_load_addr_hi;
        uint32_t init_load_addr_lo;
        uint32_t init_mem_usage;
        uint32_t paged_size;
};
```

The header is only used by the loader of OP-TEE, not OP-TEE itself. To initialize OP-TEE the loader loads the complete binary into memory and copies what follows the header and the following `init_size` bytes to `(init_load_addr_hi << 32 | init_load_addr_lo)`. `init_mem_usage` is used by the loader to be able to check that there is enough physical memory available for OP-TEE to be able to initialize at all. The loader supplies in `r0/x0` the address of the first byte following what was not copied and jumps to the load address to start OP-TEE.

In addition to overall binary with partitions inside described as above, extra three binaries are generated simultaneously during build process for loaders who support loading separate binaries:

```
+-----------+
| Header    |
+-----------+
```

```
+-----------+
| Init      |
+-----------+
| Hashes    |
+-----------+
```

```
+-----------+
| Pageable  |
+-----------+
```

In this case, loaders load header binary first to get image list and information of each image; and then load each of them into specific load address assigned in structure. These binaries are named with v2 suffix to distinguish from the existing binaries. Header format is updated to help loaders loading binaries efficiently:

```
#define OPTEE_IMAGE_ID_PAGER    0
#define OPTEE_IMAGE_ID_PAGED    1

struct optee_image {
        uint32_t load_addr_hi;
        uint32_t load_addr_lo;
        uint32_t image_id;
        uint32_t size;
};

struct optee_header_v2 {
        uint32_t magic;
        uint8_t version;
        uint8_t arch;
        uint16_t flags;
        uint32_t nb_images;
        struct optee_image optee_image[];
};
```

Magic number and architecture are identical as original. Version is increased to 2. `load_addr_hi` and `load_addr_lo` may be 0xFFFFFFFF for pageable binary since pageable part may get loaded by loader into dynamic available position. `image_id` indicates how loader handles current binary. Loaders who don't support separate loading just ignore all v2 binaries.

Initializing the pager

The pager is initialized as early as possible during boot in order to minimize the "init" area. The global variable `tee_mm_vcore` describes the virtual memory range that is covered by the level 2 translation table supplied to `tee_pager_init()`.

Assign pageable areas

A virtual memory range to be handled by the pager is registered with a call to `tee_pager_add_core_area()`.

```
bool tee_pager_add_area(tee_mm_entry_t *mm, uint32_t flags,
const void *store,
              const void *hashes);
```

which takes a pointer to `tee_mm_entry_t` to tell the range, flags to tell how memory should be mapped (readonly, execute etc), and pointers to backing store and hashes of the pages.

Assign physical pages

Physical SRAM pages are supplied by calling `tee_pager_add_pages()`

```
void tee_pager_add_pages(tee_vaddr_t vaddr, size_t npages,
bool unmap);
```

`tee_pager_add_pages()` takes the physical address stored in the entry mapping the virtual address "vaddr" and "npages" entries after that and uses it to map new pages when needed. The unmap parameter tells whether the pages should be unmapped immediately since they does not contain initialized data or be kept mapped until they need to be recycled. The pages in the "init" area are supplied with `unmap == false` since those page have valid content and are in use.

Invocation

The pager is invoked as part of the abort handler. A pool of physical pages are used to map different virtual addresses. When a new virtual address needs to be mapped a free physical page is mapped at the new address, if a free physical page cannot be found the oldest physical page is selected instead. When the page is mapped new data is copied from backing store and the hash of the page is verified. If it is OK the pager returns from the exception to resume the execution.

Paging of user TA

Paging of user TAs can optionally be enabled with CFG_PAGED_USER_TA=y. Paging of user TAs is analogous to paging of OP-TEE kernel parts but with a few differences:

- Read/write pages are paged in addition to read-only pages
- Page tables are managed dynamically

tee_pager_add_uta_area() is used to setup initial read/write mapping needed when populating the TA. When the TA is fully populated and relocated tee_pager_set_uta_area_attr() changes the mapping of the area to strict permissions used when the TA is running.

9. Memory objects

A memory object, MOBJ, describes a piece of memory. The interface provided is mostly abstract when it comes to using the MOBJ to populate translation tables etc.
There is different kinds of MOBJs describing:

- physically contiguous memory
  - created with mobj_phys_alloc()
- virtual memory
  - one instance with the name mobj_virt available
  - spans the entire virtual address space
- physically contiguous memory allocated from a tee_mm_pool_t *
  - created with mobj_mm_alloc()
- paged memory
  - created with mobj_paged_alloc()
  - only contains the supplied size and makes mobj_is_paged() return true if supplied as argument
- secure copy paged shared memory
  - created with mobj_seccpy_shm_alloc()
  - makes mobj_is_paged() and mobj_is_secure() return true if supplied as argument

10. Cryptographic abstraction layer

Cryptographic operations are implemented inside the TEE core by the LibTomCrypt library. An abstraction layer allows for replacing the default implementation, as explained in crypto.md.

11. libutee

The GlobalPlatform Core Internal API describes services that are provided to Trusted Applications. libutee is a library that implements this API.
libutee is a static library the Trusted Applications shall statically link against. Trusted Applications do execute in non-privileged secure userspace and libutee also aims at being executed in the non-privileged secure userspace.

Some services for this API are fully statically implemented inside the libutee library while some services for the API are implemented inside the OP-TEE core (privileged level) and libutee calls such services through system calls.

12. Trusted Applications

Pseudo TAs and User Mode TAs

There are two ways to implement Trusted Applications (TAs), pseudo TAs and user mode TAs. User mode TAs are full featured Trusted Applications as specified by the GlobalPlatform TEE specifications, these are simply referred to as 'Trusted Applications'. For most cases, user mode TAs are preferred.

Pseudo Trusted Applications

These are implemented directly to the OP-TEE core tree in, eg, `core/arch/arm/pta`, and are built along with and statically built into the OP-TEE core blob.
The pseudo Trusted Applications included in OP-TEE already are OP-TEE secure privileged level services hidden behind a "GlobalPlatform TA Client" API. These pseudo-TAs are used for various purposes such as specific secure services or embedded tests services.
Pseudo TAs do not benefit from the GlobalPlatform Core Internal API support specified by the GlobalPlatform TEE specs. These APIs are provided to TAs as a static library each TA shall link against (the "libutee") and that calls OP-TEE core service through system calls. As OP-TEE core does not link with libutee, Pseudo TAs can only use the OP-TEE core internal APIs and routines.
As pseudo TAs have the same privileged execution level as the OP-TEE core code itself, such situation may not be desirable for complex TAs.
In most cases an unprivileged (user mode) TA is the best choice instead of adding your code directly to the OP-TEE core. However if you decide your application is best handled directly in OP-TEE core like this, you can look at `core/arch/arm/pta/stats.c` as a template and just add your pseudo TA based on that to the `sub.mk` in the same directory.

User Mode Trusted Applications

User Mode Trusted Applications are loaded (mapped into memory) by OP-TEE core in the Secure World when something in the REE wants to talk to that particular application UUID. They run at a lower CPU privilege level than OP-TEE core code. In that respect, they are quite similar to regular applications running in the Rich Execution Environment (REE), except that they execute in Secure World.
Trusted Application benefit from the GlobalPlatform Core Internal API as specified by the GlobalPlatform TEE specifications.
There are several types of user mode TAs, which differ by the way they are stored.

"Normal" or Secure Storage Trusted Applications

These are stored in secure storage. The meta data is stored in a database of all installed TAs and the actual binary is stored encrypted as a separate file in the untrusted REE filesystem.
Before these TAs can be loaded they have to be installed first, this is something that can be done during initial deployment or at a later stage. For test purposes the test program xtest can install a TA into secure storage with the command:
`xtest --install-ta`

"Legacy" or REE FS Trusted Applications

They consist of a cleartext signed ELF file, named from the UUID of the TA and the suffix ".ta".
They are built separately from the OP-TEE core boot-time blob, although when they are built they use the same build system, and are signed with the key from the build of the original OP-TEE core blob.
Because the TAs are signed, they are able to be stored in the untrusted REE filesystem, and `tee-supplicant` will take care of passing them to be checked and loaded by the Secure World OP-TEE core.

Early Trusted Applications

The so-called early TAs are virtually identical to the normal (REE FS) TAs, but insted of being loaded from the Normal World file system, they are linked into a special data section in the TEE core blob. Therefore, they are available even before `tee-supplicant` and the Normal World filesystems have come up. More details in commit early_tas.

Special treatment of Trusted Applications

Syscalls

User mode TAs are not directly bound to function exports in the OP-TEE core blob, both because the TA code is kept at arm's length by executing at a different privileged level, and because TAs direct binding to addresses in the core would require upgrades of all TAs synchronusly with upgrades of the OP-TEE core blob. Instead, the resolution of OP-TEE core exports in the TA is done at runtime.

OP-TEE does this by using syscalls, the same kind of way as the Linux kernel provides a stable API for its userland programs. TAs are written to use syscall wrappers to access functions exported from OP-TEE core, so this all happens automatically when a TA wants to use an API exported from OP-TEE core.

Pseudo TAs and anything else directly built into OP-TEE core do not require going through a syscall interface, since they can just link directly as they are directly part of the core.

Most of the services defined by the GlobalPlatform Core Internal API are implemented through syscall from the TA to the OP-TEE core privileged level: cryptographic services, communications with other TAs, ... Some services were added through OP-TEE development such as ASCII message tracing.

Syscalls are provided already for all public exports from OP-TEE core that a Dynamic TA is expected to use, so you only need to take care about this if you will add new exported from OP-TEE core that TAs will want to use.

Malloc mapping

The OP-TEE core code has its own private memory allocation heap that is mapped into its MMU view only and cannot be seen by Trusted Applications. The core code uses `malloc()` and `free()` style APIs.

Trusted Applications also have their own private memory allocation heaps that are visible to the owning TA, and to OP-TEE core. TAs manage their heaps using `TEE_Malloc()` and `TEE_Free()` style apis.

Heap	Visible to	Inaccessible to
core	core	any TA
TA	core, same TA	any other TA

This enforces "Chinese Walls" between the TA views of Secure World. Since OP-TEE core cannot perform allocations in the TA's private heap, and the TA is not going to be able to access allocations from the OP-TEE core heap, it means only allocations from the TA heap are visible to both the TA and OP-TEE core. When performing syscalls between a TA and OP-TEE core then, the TA side must provide all the memory allocations for buffers, etc used by both sides.

Malloc pool

The OP-TEE core malloc heap is defined by `CFG_CORE_HEAP_SIZE` in `mk/config.mk`.
However for TAs, the individual TA TEE_Malloc() heap size is defined by `TA_DATA_SIZE` in `user_ta_header_defines.h`. Likewise the TA stack size is set in the same file, in `TA_STACK_SIZE`.

File format of a Dynamic Trusted Application

The format a TA is:

```
<Signed header>
<ELF>
```

Where `<ELF>` is the content of a standard ELF file and `<Signed header>` consists of:

Type	Name	Comment
`uint32_t`	magic	Holds the magic number `0x4f545348`
`uint32_t`	img_type	image type, values defined by enum shdr_img_type
`uint32_t`	img_size	image size in bytes
`uint32_t`	algo	algorithm, defined by public key algorithms `TEE_ALG_*` from TEE Internal API specification
`uint16_t`	hash_size	size of the signed hash
`uint16_t`	sig_size	size of the signature
`uint8_t[hash_size]`	hash	Hash of the fields above and the `<ELF>` above
`uint8_t[sig_size]`	signature	Signature of hash