Rockchip Linux Secure Boot Developer Guide

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Rockchip Electronics Co., Ltd.

No.18 Building, A District, No.89, software Boulevard Fuzhou, Fujian,PRC

Website: www.rock-chips.com

Customer service Tel: +86-4007-700-590

Customer service Fax: +86-591-83951833

Customer service e-Mail: fae@rock-chips.com

Preface

Overview

This document mainly introduces the steps and notices of Secure Boot under RK Linux platform, which is convenient for customers to do secondary development base on it. Secure Boot function is designed to ensure devices with correct and valid firmware, and unsigned or invalid firmware will not boot.

Product Version

Chipset	Kernel verify	Secure Partition
RK3308/RK3328/RK3326/PX30/RK3358	AVB	OTP
RK3399	AVB	EFUSE
RK3588/RK356X	FIT	OTP

Intended Audience

This document (this guide) is mainly intended for:

Technical support engineers

Software development engineers

Revision History

Version	Author	Date	修改说明
V1.0.0	WZZ	2018-10-31	Initial version
V1.0.1	WZZ	2018-12-17	Fix vbmeta to security
V2.0.0	WZZ	2019-06-03	Sign_Tool is compatible with AVB boot.img， Update device-mapper related introduction
V2.0.1	Ruby Zhang	2020-08-10	Update the company name and document format
V3.0.0	WZZ	2022-04-30	Add RK3588 FIT supported Fixed AVB key storage description Add more reference documents Update AVB description Update tool links
V3.0.1	WZZ	2022-09-27	Add RK356X FIT supported statement
V4.0.0	WZZ	2024-01-11	Adapt to the latest make rules of Linux SDK. Couple the compilation methods of AVB and FIT with SDK make rules. Change DM-V/E to system-verity/encryption and modify the compilation methods. Remove Windows UI signing tool Provide KeyBox code.

Contents

Rockchip Linux Secure Boot Developer Guide

1. Secure Boot Introduction
    - 1.1 Linux Secure Boot Process
    - 1.2 Secure Storage
2. Secure Boot
    - 2.1 FIT
        - 2.1.1 Keys Generation
        - 2.1.2 Configuration
        - 2.1.3 U-Boot Compilation and Firmware Signing
        - 2.1.4 Enable Log
    - 2.2 AVB
        - 2.2.1 Keys Generation
        - 2.2.2 Configuration
            - 2.2.2.1 Trust
            - 2.2.2.2 U-boot
            - 2.2.2.3 Parameter
        - 2.2.3 Firmware Signature
        - 2.2.4 AVB Keys Burning Process
        - 2.2.5 Enable Log
        - 2.2.6 Quick Script
        - 2.2.7 Simplified Modification of AVB Functionality
3. System Security
    - 3.1 DM Introduction
        - 3.1.1 Configuration
    - 3.2 System Processing
        - 3.2.1 System-Verity
        - 3.2.2 System-Encryption
            - 3.2.2.1 Key Storage
    - 3.3 Ramdisk Configuration
        - 3.3.1 Ramdisk Initial Script Configuration
        - 3.3.2 Ramdisk Compilation Configuration
        - 3.3.3 Ramdisk Packaging
4. KeyBox
    - 4.1 Independent Compilation
    - 4.2 tee_user_app Compilation
    - 4.3 Enable OPTEE in Kernel
    - 4.4 KeyBox Modification Recommendations
5. Secure Information Burning
    - 5.1 Key Hash
        - 5.1.1 OTP
        - 5.1.2 eFuse
    - 5.2 Custom Security Information
6. Security Demo
    - 6.1 SDK Configuration
    - 6.2 Detailed Configuration
        - 6.2.1 Key Generation
        - 6.2.2 U-Boot Modification
        - 6.2.3 Kernel Modification
        - 6.2.4 Buildroot Modification
        - 6.2.5 Ramdisk Modification
    - 6.3 Verification Method
    - 6.4 Debugging Method
7. References

1. Secure Boot Introduction

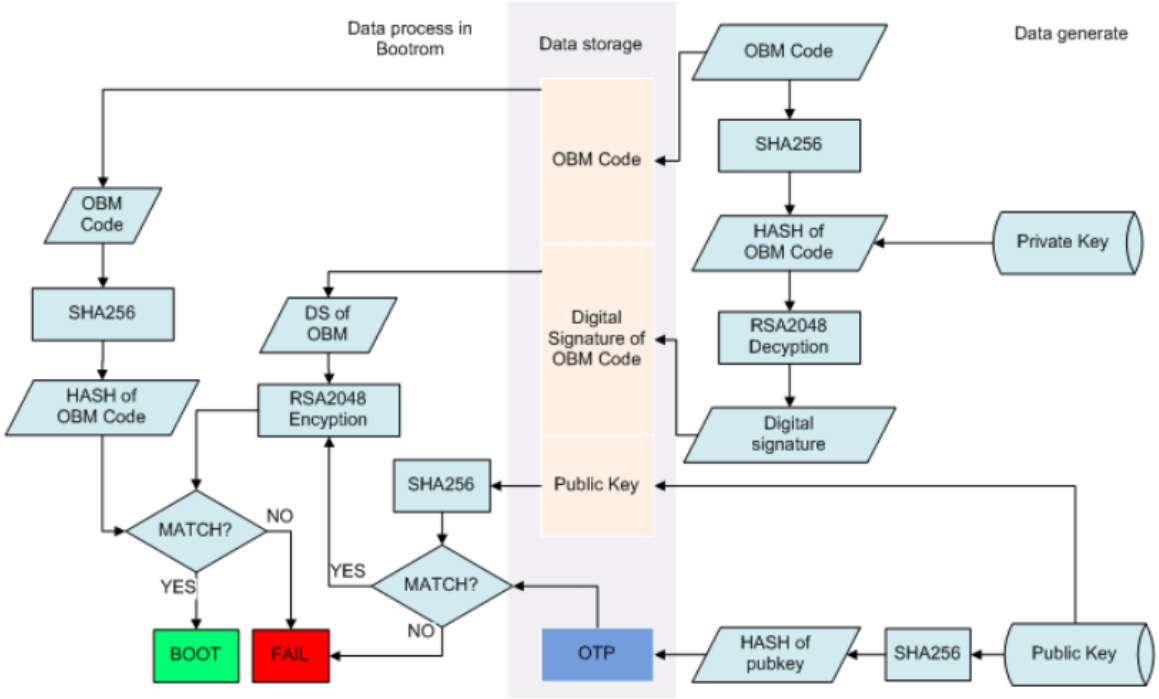
Secure Boot is a set of verification processes designed to ensure the integrity and legitimacy of the firmware running on a device. Its primary purpose is to act as a protective measure against malicious software injection by unauthorized third-party users. Upon enabling Secure Boot, if the protected partition is tampered with, the device will generate an error or even halt its operation.

Secure Boot mainly protects the pre-boot partition of the system. For the system and user partitions, this document provides partition encryption and verification schemes.

	System-Verity	**System-Encryption**
On Disk	Clear text at rest	Encrypted text at rest
System Key	Clear text public key stored in Boot.img firmware	Encrypted key stored in RPMB partition
Anti-Copy	No	Yes
Anti-Tamper	Yes	Yes

Before proceeding, refer to Product Version to know the classification of chip platforms. Different platforms have varying chip resources and adopt different security strategies. Read relevant sections according to the classification. This document is based on the general SDK and aims to assist customers in building a firmware security solution from scratch. Additionally, it provides some scripts to help customers manage and streamline the process of building a secure firmware.

1.1 Linux Secure Boot Process



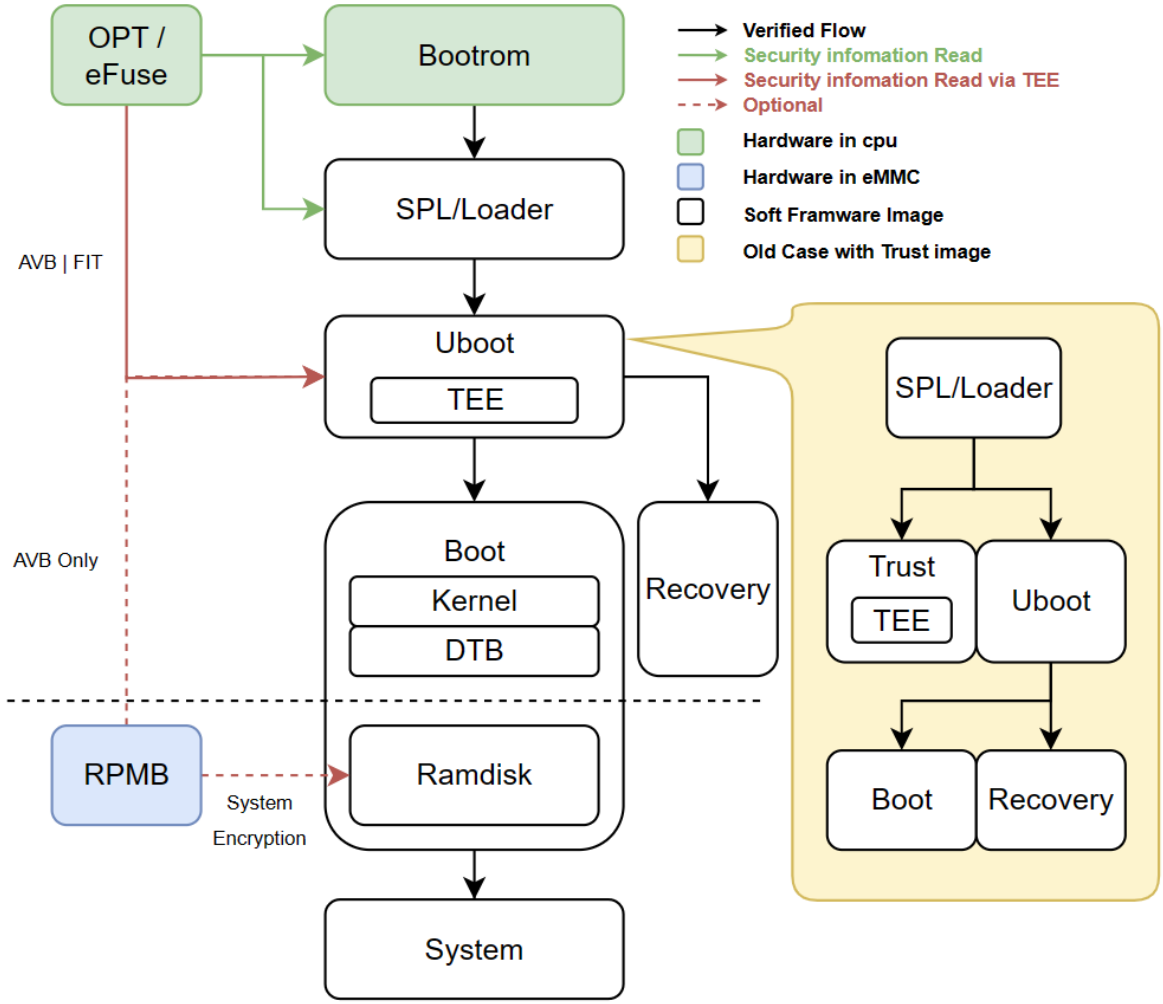
The above flowchart illustrates the process of Bootrom verifying the loader, and the verification process for other firmware is similar.

In summary, a signed firmware package consists of Firmware (OBM Code) + Digital Signature + Public Key. Both the Digital Signature and Public Key are added by the signing tool.

In terms of storage, the signed firmware is placed on eMMC or Flash, while the Public Key Hash is stored in OTP (eFuse) of the chip.

During startup, the firmware's public key is verified using the hash in OTP, and then the digital signature is verified using the public key. This process ensures the binding of the chip with the signed code.

Please refer to "Rockchip-Secure-Boot-Application-Note-V1.9.pdf" for details.



Note: The Trust firmware is at the same level as the Uboot firmware, both verified by SPL or Loader, following the same verification process as Uboot. On new chip platforms, the Trust firmware has been integrated into the Uboot firmware.

Based on the above rules, each firmware utilizes the same set of keys for signing, It only requires writing a Public Key Hash to OTP/eFuse. Then, each firmware verifies the subsequent firmware in a cascading manner using the Public Key Hash, forming a trusted chain to ensure that the firmware in the chain is both intact and legitimate.

The primary code for Secure Boot is provided by U-boot, ensuring the security of the firmware behind U-boot. **The verification or encryption of the System is handled by Ramdisk (please refer to the System Security section)**.

1.2 Secure Storage

To enhance the security of the trusted chain, the trusted root of the chain needs to be stored in a hardware module and establish a strong binding state with the hardware.

In addition to the trusted root storage, the Linux platform provides several security storage areas for customers to store custom information:

Storage Area	Description
OTP / eFuse	Located in the SOC, both are irreversible burn mechanisms. OTP can be burned by Miniloader / SPL, eFuse can only be burned by PC tools. Different SOCs use different media, and currently, on the Linux platform: eFuse: RK3399 / RK3288 OTP: RK3308 / RK3326 / PX30 / RK3328 The size of OTP/eFuse space varies for each chip, but it is generally not very large, usually enough for one or two keys.
RPMB	A physical partition located in eMMC, not visible on the file system, requires SOC authentication access (only be accessed by TEE), The partition's content is stored encrypted, cannot be mounted, generally considered a secure area.
Security Partition	A logical partition on the storage medium, added as a temporary partition to compensate for the lack of RPMB on Flash. The partition's content is stored encrypted, cannot be mounted, but may be forcibly erased. Accessible only by TEE. (Forced erasure, TEE access errors, Secure Boot cannot start normally).

Note: Since OTP (eFuse) is mainly used internally by Rockchip, customer security information should prioritize other areas such as RPMB/Security. If there are specific requirements, please apply for the corresponding information through the business channel.

2. Secure Boot

In the Linux system, there are two Secure Boot schemes: the FIT scheme and the AVB scheme. The effects of both schemes are the same, but they cannot be used interchangeably. Please refer to the Product Version section to determine which scheme to adopt for each chip specifically.

2.1 FIT

FIT (Flattened Image Tree) is a booting solution supported by U-Boot for a new type of firmware, it supports the packaging and verification of multiple images. FIT utilizes an `its` (Image Source File) to describe image information, and ultimately generates a `itb` (Flattened Image Tree Blob) using the `mkimage` tool. The its file follows the syntax rules of DTS (Device Tree Source), providing great flexibility and direct compatibility with the `libfdt` library and related tools. It also comes with a new set of security verification methods.

For more detailed information about FIT, refer to Chapter Twelve of the `Rockchip_Developer_Guide_UBoot_Nextdev`.

2.1.1 Keys Generation

Execute the following three commands within the U-Boot project to generate an RSA key pair for signing. Typically, this process only needs to be done once. Subsequently, use this key pair for signing and verifying firmware. Please handle and store them securely.

```
# 1. The directory where the key is placed: keys
mkdir -p keys

# 2. Use Rockchip's "rk_sign_tool" tool to generate RSA2048 private keys,
privateKey.pem and publicKey.pem, rename and store them as keys/dev.key and
keys/dev.pubkey respectively. The command is:
../rkbin/tools/rk_sign_tool kk --bits 2048 --out .
ln -s privateKey.pem keys/dev.key
ln -s publicKey.pem keys/dev.pubkey

# 3.Use -x509 and the private key to generate a self-signed certificate:
keys/dev.crt (the effect is essentially the same as the public key)
openssl req -batch -new -x509 -key keys/dev.key -out keys/dev.crt
```

> If the error message is that there is no .rnd file in the user directory:
>
> Can't load /home4/cjh//.rnd into RNG
> 140522933268928:error:2406F079:random number generator:RAND_load_file:Cannot open file:../crypto/rand/randfile.c:88:Filename=/home4/cjh//.rnd
>
> Please create manually first: touch ~/.rnd

Use `ls keys/` to view the results:

```
dev.crt dev.key dev.pubkey
```

> Note: The above names of "keys", "dev.key", "dev.crt" and "dev.pubkey" are fixed and should not be altered. Because these names have been statically defined in its file, packaging will fail if they are changed.

2.1.2 Configuration

Opens the following configuration of U-Boot's defconfig:

```
# Required
CONFIG_FIT_SIGNATURE=y
CONFIG_SPL_FIT_SIGNATURE=y

# Optional
CONFIG_FIT_ROLLBACK_PROTECT=y       # boot.img Rollback protect
CONFIG_SPL_FIT_ROLLBACK_PROTECT=y   # uboot.img Rollback protect
```

> It is recommended to select configurations by "make menuconfig" and then update the original defconfig file with "make savedefconfig." In this way, you can avoid incorrect dependencies caused by imposing defconfig configuration, which in turn leads to compilation failure.

2.1.3 U-Boot Compilation and Firmware Signing

During U-Boot compilation, boot.img, recovery.img, loader.bin, and uboot.img are signed simultaneously. Therefore, before compilation, it is necessary to determine the locations of boot.img and recovery.img to be signed.

(1) Basic Commands (Non-rollback):

```
./make.sh rv1126 --spl-new --boot_img boot.img --recovery_img recovery.img
```

Compilation result:

```
#......
# After compilation is completed, generate signed uboot.img, boot.img and
recovery.img.
start to sign rv1126_spl_loader_v1.00.100.bin
# ......
sign loader ok.
# ......
Image(signed, version=0):  uboot.img (FIT with uboot, trust...) is ready
Image(signed, version=0):  recovery.img (FIT with kernel, fdt, resource...) is
ready
Image(signed, version=0):  boot.img (FIT with kernel, fdt, resource...) is ready
Image(signed):  rv1126_spl_loader_v1.05.106.bin (with spl, ddr, usbplug) is ready
pack uboot.img okay! Input: /home4/cjh/rkbin/RKTRUST/RV1126TOS.ini

Platform RV1126 is build OK, with new .config(make rv1126-secure_defconfig)
```

(2)Extended command 1:

If anti-rollback is enabled, the rollback parameter must be added to (1) above. For example:

```
// Specify the minimum version numbers of uboot.img, boot.img and recovery.img as
10, 12 and 12 respectively.
./make.sh rv1126 --spl-new --boot_img boot.img --recovery_img recovery.img --
rollback-index-uboot 10 --rollback-index-boot 12 --rollback-index-recovery 12
```

Compilation result:

```
...

// After the compilation is completed, the signed uboot.img, boot.img and
recovery.img are generated, and include the anti-rollback version number.
start to sign rv1126_spl_loader_v1.00.100.bin
......
sign loader ok.
......
Image(signed, version=0, rollback-index=10):  uboot.img (FIT with uboot, trust)
is ready
Image(signed, version=0, rollback-index=12):  recovery.img (FIT with kernel, fdt,
resource...) is ready
Image(signed, version=0, rollback-index=12):  boot.img (FIT with kernel, fdt,
resource...) is ready
Image(signed):  rv1126_spl_loader_v1.00.100.bin (with spl, ddr, usbplug) is ready
```

(3)Extended command 2:

If you want to burn the public key hash to OTP/eFUSE, you must add the parameter `--burn-key-hash` to the above (1) or (2). For example:

```
# Specify the minimum version numbers of uboot.img, boot.img and recovery.img as
10, 12 and 12 respectively.
# Require burning the public key hash into OTP/eFUSE in the SPL stage.
./make.sh rv1126 --spl-new --boot_img boot.img --recovery_img recovery.img --
rollback-index-uboot 10 --rollback-index-boot 12 --rollback-index-recovery 12 --
burn-key-hash
```

> After turning on rollback, the updated version number must not be lower than the previous version (can be same), otherwise the system will not allow startup

Compilation result:

```
#......
# Enable burn-key-hash
### spl/u-boot-spl.dtb: burn-key-hash=1

# After compilation is completed, generate signed uboot.img, boot.img and
recovery.img, and include the anti-rollback version number.
start to sign rv1126_spl_loader_v1.00.100.bin
# ......
sign loader ok.
# ......
Image(signed, version=0, rollback-index=10):  uboot.img (FIT with uboot, trust)
is ready
Image(signed, version=0, rollback-index=12):  recovery.img (FIT with kernel, fdt,
resource...) is ready
Image(signed, version=0, rollback-index=12):  boot.img (FIT with kernel, fdt,
resource...) is ready
Image(signed):  rv1126_spl_loader_v1.00.100.bin (with spl, ddr, usbplug) is ready
```

> When powering on the device, you should see the SPL print: "RSA: Write key hash successfully."

Note: Whether the public key hash is burned will only affect whether Maskrom verifies loader, and once burned, it cannot be revoked. The verification process for loader, U-Boot, and subsequent stages remains consistent. Therefore, during the debugging phase, it is advisable not to use "burn-key-hash".

(4) Extended Command 3: FIT Firmware Signing Extended Command 3

For the convenience of updating boot and recovery, U-Boot also supports signing boot or recovery firmware separately. It requires a complete compilation of the U-Boot firmware with signing at least once before.

```
./make.sh rv1126 --spl-new
# Before compilation, ensure that U-Boot has been compiled at least once with
signing enabled.

./scripts/fit.sh --boot_img boot.img            # Sign boot.img separately
./scripts/fit.sh --recovery_img recovery.img    # Sign recovery.img separately
```

> Please make sure U-boot contains the `scripts: fit.sh: repack boot / recovery individually` patch (Change-Id: Ib9c0396625971469e13e8092d233e2aea5714486)

(5) Notes:

- `--boot_img`: Optional. Specifies the boot.img to be signed.
- `--recovery_img`: Optional. Specifies the recovery.img to be signed.
- `--rollback-index-uboot`, `--rollback-index-boot`, `--rollback-index-recovery`: Optional. Specifies the anti-rollback version numbers.
- `--spl-new`: If this parameter is not included in the compilation command, it will use the spl file from rkbin to generate the loader by default. Otherwise, it will use the spl file compiled at the moment to package the loader.

Because the u-boot-spl.dtb needs to contain the RSA public key (provided by users), the SDK released by Rockchip will not submit spl files that support secure boot to the rkbin repository. Therefore, users need to specify the `--spl-new` parameter when compiling. However, users can also submit their own spl version to the rkbin project, and after that, they do not need to specify this parameter during firmware compilation. They can use this stable version of the spl file every time.
After compilation, three firmware files will be generated: loader, uboot.img, boot.img. As long as the RSA Key remains unchanged, it is allowed to individually update any of these firmware files.

2.1.4 Enable Log

The firmware configuration is normal. Burn the Key Hash into the OTP according to "Key Hash". You will see the following log.

```
...
Trying to boot from MMC1
//SPL completes signature verification
sha256,rsa2048:dev+
// Anti-rollback detection: The current uboot.img firmware version number is 10,
and the minimum version number of this device is 9
rollback index: 10 >= 9, OK
// SPL completes hash verification of each sub-mirror
### Checking optee ... sha256+ OK
### Checking uboot ... sha256+ OK
### Checking fdt ... sha256+ OK

Jumping to U-Boot via OP-TEE
I/TC:
E/TC:0 0 plat_rockchip_pmu_init:2003 0
E/TC:0 0 plat_rockchip_pmu_init:2006 cpu off
```

```
E/TC:0 0 plat_rockchip_pmusram_prepare:1945 pmu sram prepare 0x14b10000 0x8400880
0x1c
E/TC:0 0 plat_rockchip_pmu_init:2020 pmu sram prepare
E/TC:0 0 plat_rockchip_pmu_init:2056 remap
I/TC: OP-TEE version: 3.6.0-233-g35ecf936 #1 Tue Mar 31 08:46:13 UTC 2020 arm
I/TC: Next entry point address: 0x00400000
I/TC: Initialized
......
### Loading kernel from FIT Image at 3d8122c0 ...
   Using 'conf' configuration
   // Uboot completes signature verification
   Verifying Hash Integrity ... sha256,rsa2048:dev+ OK
   // Anti-rollback detection: The current boot.img firmware version number is
22, and the minimum version number of this device is 21
   Verifying Rollback-index ... 22 >= 21, OK
   Trying 'kernel' kernel subimage
......
   Verifying Hash Integrity ... sha256+ OK  // hash verification of kernel is
completed
### Loading ramdisk from FIT Image at 3d8122c0 ...
   Using 'conf' configuration
   Trying 'ramdisk' ramdisk subimage
......
   Verifying Hash Integrity ... sha256+ OK  // hash verification of ramdisk is
completed
   Loading ramdisk from 0x3dd3d4c0 to 0x0a200000
### Loading fdt from FIT Image at 3d8122c0 ...
   Using 'conf' configuration
   Trying 'fdt' fdt subimage
......
   Verifying Hash Integrity ... sha256+ OK // hash verification of Fdt is
completed
   Loading fdt from 0x3d812ec0 to 0x08300000
   Booting using the fdt blob at 0x8300000
   Loading Kernel Image from 0x3d8234c0 to 0x02008000 ... OK
   Using Device Tree in place at 08300000, end 0831359d
Adding bank: 0x00000000 - 0x08400000 (size: 0x08400000)
Adding bank: 0x0848a000 - 0x40000000 (size: 0x37b76000)
Total: 236.327 ms

Starting kernel ...
```

Replacing any non-signed firmware will result in the system being unable to start properly.

2.2 AVB

AVB (Android Verified Boot) is primarily used in the Android system and establishes a complete trusted chain around U-Boot firmware, starting from a hardware-protected trusted root and extending all the way to the bootloader and partitions before and after U-Boot (such as boot or recovery partitions).

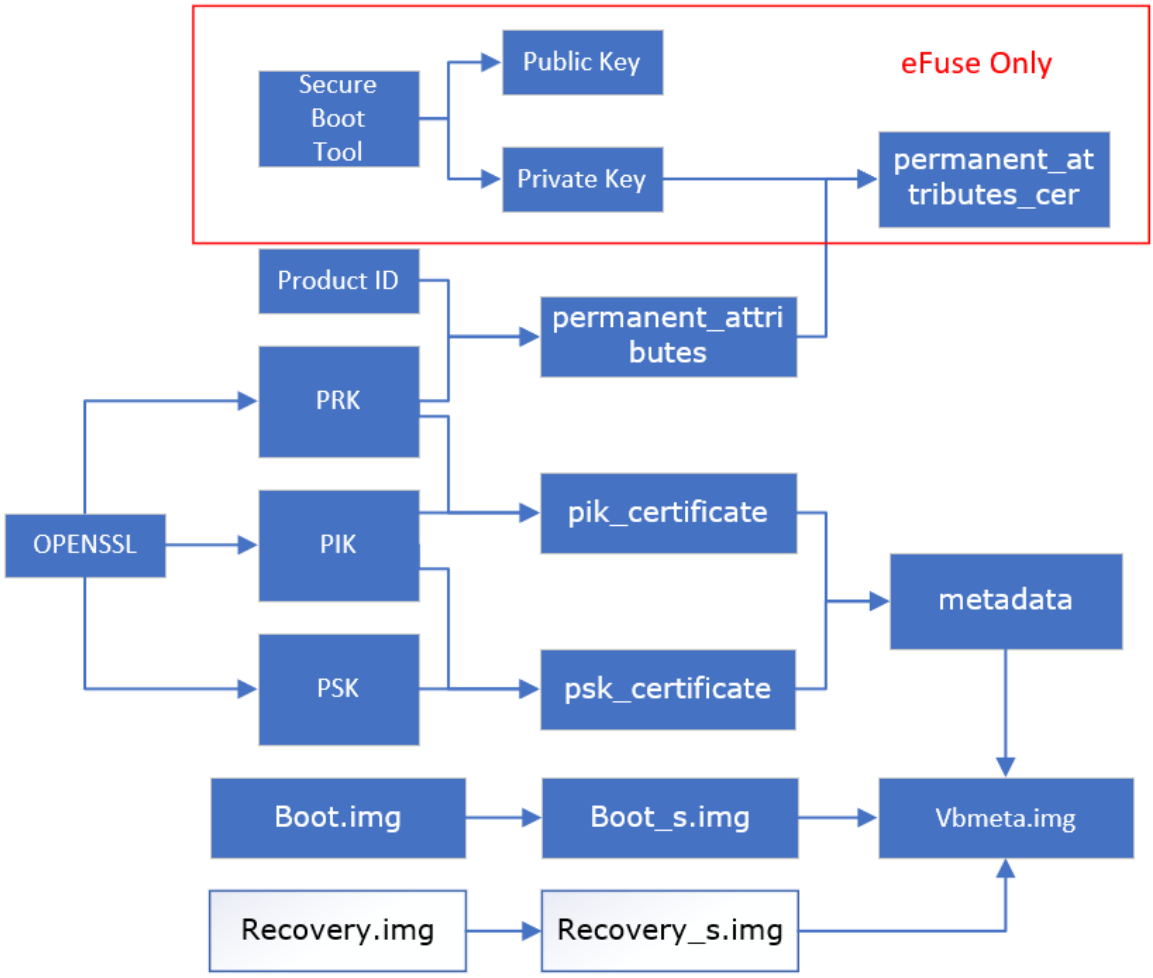
On Linux systems, due to the absence of Android system components, AVB is cropped to perform verification only for the boot and recovery partitions. The verification from Loader to U-Boot is handled by RK's proprietary solution.

2.2.1 Keys Generation

Verification from Loader to U-Boot is completed by RK's proprietary solution, which requires generating a set of RSA key pairs, the same sa the FIT solution, please refer to FIT Keys Generation.

In addition to this, AVB includes the following four keys:

- Product RootKey (PRK): The Root Key of AVB, verified by Base Secure Boot's Key in eFuse devices. In OTP devices, it is directly read from PRK-Hash information pre-stored in OTP.
- Product Intermediate Key (PIK): An intermediate key with intermediary roles.
- Product Signing Key (PSK): Used for signing firmware.
- Product Unlock Key (PUK): Used for unlocking the device.



AVB derives a series of files based on these four keys, as shown in the image above. For details, refer to Google AVB open source documentation:https://android.googlesource.com/platform/external/avb/+/master/README.md.

In comparison to the original AVB, on Linux, we have mainly focused on extracting the core firmware verification functionality of AVB. To adapt it to the Rockchip platform on eFuse devices, we have additionally generated `permanent_attributes_cer.bin`. This allows us to save space in eFuse by directly verifying `permanent_attributes.bin` information using the loader's public key, without the need to store it in eFuse.

A set of test certificates and keys is already available under `tools/linux/Linux_SecurityAVB/avb_keys`. You can use these during the debugging phase for convenience. However, for the final product, please replace them with your own private keys. You can generate them following the steps below.

```
cd tools/linux/Linux_SecurityAVB/
touch avb_keys/temp.bin

# Input 16 bytes product id, like "0123456789ABCDE"
# Or use random id,
# head -c 16 /dev/urandom | od -An -t x | tr -d ' \n' > avb_keys/product_id.bin
echo -n $PRODUCT_ID > avb_keys/product_id.bin

# Generate test keys.
openssl genpkey -algorithm RSA -pkeyopt rsa_keygen_bits:4096 -outform PEM -out
avb_keys/testkey_prk.pem
openssl genpkey -algorithm RSA -pkeyopt rsa_keygen_bits:4096 -outform PEM -out
avb_keys/testkey_psk.pem
openssl genpkey -algorithm RSA -pkeyopt rsa_keygen_bits:4096 -outform PEM -out
avb_keys/testkey_pik.pem
openssl genpkey -algorithm RSA -pkeyopt rsa_keygen_bits:4096 -outform PEM -out
avb_keys/testkey_puk.pem

# Generate certificate.bin and metadata.
python scripts/avbtool make_atx_certificate --output=avb_keys/pik_certificate.bin
--subject=avb_keys/temp.bin --subject_key=avb_keys/testkey_pik.pem --
subject_is_intermediate_authority --subject_key_version 42 --
authority_key=avb_keys/testkey_prk.pem
python scripts/avbtool make_atx_certificate --output=avb_keys/psk_certificate.bin
--subject=avb_keys/product_id.bin --subject_key=avb_keys/testkey_psk.pem --
subject_key_version 42 --authority_key=avb_keys/testkey_pik.pem
python scripts/avbtool make_atx_certificate --output=avb_keys/puk_certificate.bin
--subject=avb_keys/product_id.bin --subject_key=avb_keys/testkey_puk.pem --
usage=com.google.android.things.vboot.unlock --subject_key_version 42 --
authority_key=avb_keys/testkey_pik.pem
python scripts/avbtool make_atx_metadata --output=avb_keys/metadata.bin --
intermediate_key_certificate=avb_keys/pik_certificate.bin --
product_key_certificate=avb_keys/psk_certificate.bin

# Generate permanent_attributes.bin
python scripts/avbtool make_atx_permanent_attributes --
output=avb_keys/permanent_attributes.bin --product_id=avb_keys/product_id.bin --
root_authority_key=avb_keys/testkey_prk.pem

# If eFuse device used, generate permanent_attributes.bin.
openssl dgst -sha256 -out avb_keys/permanent_attributes_cer.bin -sign dev.key
avb_keys/permanent_attributes.bin
```

Therefore, AVB solution Keys includes the following two parts, located in two directories:

```
PC:~/SDK$ tree u-boot/keys/
.
├── dev.key
└── dev.pubkey

PC:~/SDK$ tree tools/linux/Linux_SecurityAVB/avb_keys
.
├── metadata.bin
├── permanent_attributes.bin
├── pik_certificate.bin
├── product_id.bin
├── psk_certificate.bin
```

```
├── puk_certificate.bin
├── testkey_pik.pem
├── testkey_prk.pem
├── testkey_psk.pem
└── testkey_puk.pem
# testkey_*.pem is the key of AVB, and the other bin files are key certificates
derived from the AVB key according to specific uses.
```

2.2.2 Configuration

2.2.2.1 Trust

Enter rkbin/RKTRUST, take RK3308 as an example, find RK3308TRUST.ini, and change:

```
[BL32_OPTION]
SEC=0
```

To:

```
[BL32_OPTION]
SEC=1
```

`BL32_OPTION` is enabled by default in the trust with TOS format, such as `RK3288TOS.ini`

2.2.2.2 U-boot

U-boot requires the following features:

```
# OPTEE support
CONFIG_OPTEE_CLIENT=y
CONFIG_OPTEE_V1=y           #RK312x/RK322x/RK3288/RK3228H/RK3368/RK3399 and V2
are mutually exclusive
CONFIG_OPTEE_V2=y           #RK3308/RK3326 and V1 are mutually exclusive

# CRYPTO support
CONFIG_DM_CRYPTO=y          # IT is required for eFuse device
CONFIG_ROCKCHIP_CRYPTO_V1=y # For eFuse devices,For example, RK3399/RK3288,
select according to chip
CONFIG_ROCKCHIP_CRYPTO_V2=y # eFuse device, For example, RK1808, select according
to chip
# AVB support
CONFIG_AVB_LIBAVB=y
CONFIG_AVB_LIBAVB_AB=y
CONFIG_AVB_LIBAVB_ATX=y
CONFIG_AVB_LIBAVB_USER=y
CONFIG_RK_AVB_LIBAVB_USER=y
CONFIG_AVB_VBMETA_PUBLIC_KEY_VALIDATE=y
CONFIG_ANDROID_AVB=y
CONFIG_OPTEE_ALWAYS_USE_SECURITY_PARTITION=y # For a non-eMMC device, to enable
it, a security partition must exist.
CONFIG_ROCKCHIP_PRELOADER_PUB_KEY=y          # Only available for eFuse devices
CONFIG_RK_AVB_LIBAVB_ENABLE_ATH_UNLOCK=y
```

```
#fastboot support
CONFIG_FASTBOOT=y
CONFIG_FASTBOOT_BUF_ADDR=0x2000000            # Can be modified if necessary
CONFIG_FASTBOOT_BUF_SIZE=0x08000000           # Can be modified if necessary
CONFIG_FASTBOOT_FLASH=y
CONFIG_FASTBOOT_FLASH_MMC_DEV=0
```

> On some platforms, fastboot is not enabled by default in U-boot configuration. During a normal boot, you can view the current memory status by holding `Ctrl-M`. To manually configure `CONFIG_FASTBOOT_BUF_*`, ensure that the starting address and size do not conflict with the current memory configuration.

Use `./make.sh xxxx` to generate `uboot.img`, `trust.img`, and `loader.bin`.

2.2.2.3 Parameter

The `vbmeta` is a mandatory item in the partition table, and the `security` partition can be optionally added depending on the hardware:

- The `vbmeta` partition stores the signature information for target partitions and has a size of 1M.
- The `security` partition is generally used as an alternative to RPMB. If the device does not have RPMB on non-eMMC devices, this partition needs to be added with a size of 4M. If `CONFIG_OPTEE_ALWAYS_USE_SECURITY_PARTITION` is enabled, the use of the security partition is enforced.

Therefore, a typical partition table allocation can be as follows:

```
# AVB parameter:
0x00002000@0x00004000(uboot),0x00002000@0x00006000(trust),0x00002000@0x00008000(
misc),0x00010000@0x0000a000(boot),0x00010000@0x0001a000(recovery),0x00010000@0x0
002a000(backup),0x00020000@0x0003a000(oem),0x00300000@0x0005a000(system),0x00000
800@0x0035a000(vbmeta),0x00002000@0x0035a800(security),-
@0x0035c800(userdata:grow)
uuid:system=614e0000-0000-4b53-8000-1d28000054a9
```

When downloading, the partition name on the download tool must be modified simultaneously. After modification, parameter.txt must be reloaded.

2.2.3 Firmware Signature

The `rk_sign_tool` is used to sign Loader, Uboot, and Trust

```
export RK_SIGN_TOOL=${SDK_DIR}/rkbin/tools/rk_sign_tool
export KEYS=${SDK_DIR}/u-boot/keys    # Keys generates chapters. The key is
stored under uboot/keys by default,.
${RK_SIGN_TOOL} cc --chip $CHIP
${RK_SIGN_TOOL} lk --key $KEYS/dev.key --pubkey $KEYS/dev.pubkey

${RK_SIGN_TOOL} sl --loader < path to loader.bin >
${RK_SIGN_TOOL} si --img < path to trust.img or uboot.img >
```

> The default signature does not burn the OTP Public Key Hash, which facilitates debugging.

> To burn OTP Public Key Hash, you need to add `sign_flag=0x20` in `${SDK_DIR}/rkbin/tools/setting.ini`

`The avbtool` is used to sign Boot and Recovery:

```
# Sign boot.img
IMAG=boot.img # path to boot.img
SIZE=`ls ${IMAGE} -l | awk '{printf $5}'`
SIZE=$[(SIZE / 4096 + 18) * 4096] # Align 4K
python scripts/avbtool add_hash_footer --image ${IMAGE} --partition_size ${SIZE}
--partition_name boot --key avb_keys/testkey_psk.pem --algorithm SHA512_RSA4096
# Generate the boot.img with signed information

python scripts/avbtool make_vbmeta_image --public_key_metadata
avb_keys/metadata.bin --include_descriptors_from_image ${IMAGE} --algorithm
SHA256_RSA4096 --rollback_index 0 --key avb_keys/testkey_psk.pem  --output
out/vbmeta.img
# Generated the out/vbmeta.img corresponding to boot.img

# Sign recovery.img
IMAG=recovery.img # path to recovery.img
SIZE=$(get_from_parameter) # Get the size of the recovery partition from
parameter. Partition size must be 4K aligned.
python scripts/avbtool add_hash_footer --image ${IMAGE} --partition_size ${SIZE}
--partition_name boot --key avb_keys/testkey_psk.pem --algorithm SHA512_RSA4096 -
-public_key_metadata avb_keys/metadata.bin
# Generate recovery.img with signed information. Recovery does not need to be
bound to vbmeta and comes with metadata information.
```

2.2.4 AVB Keys Burning Process

AVB firmware allows the device to operate in Lock and Unlock two states:

- Lock: The device undergoes strict firmware verification, and if firmware verification fails, the boot process will be stopped. This mode is suitable for production.
- Unlock: The device operates in a flexible firmware verification mode, where it will issue an error warning upon firmware verification failure but will not stop the boot process. This mode is suitable for debugging purposes.

These two locking states of AVB can be modified in "fastboot" mode. Therefore, after burning the AVB firmware, the device needs to be restarted, entered into fastboot mode, and combined with PC fastboot commands to burn the AVB Keys into the device and lock it to achieve security protection.

Depending on the U-boot version, some versions may directly enter fastboot mode when AVB is first started, while others may boot directly into the system. If the device boots directly into the system, you can use the `reboot fastboot` command to force the device into fastboot mode.

In fastboot mode, use the following commands to burn AVB Keys and lock the device.

```
cd ${SDK_DIR}/tools/linux/Linux_SecurityAVB

# download permanent_attributes.bin
./scripts/fastboot stage avb_keys/permanent_attributes.bin
./scripts/fastboot oem fuse at-perm-attr

# If eFuse device:
./scripts/fastboot stage avb_keys/permanent_attributes_cer.bin
./scripts/fastboot oem fuse at-rsa-perm-attr

# Lock device
./scripts/fastboot oem at-lock-vboot
```

After the lock is successful and then restarted, you can see the following log:

```
ANDROID: reboot reason: "(none)"
read_is_device_unlocked() ops returned that device is LOCKED
```

If you need to unlock the device, use the following command:

```
./scripts/fastboot oem at-get-vboot-unlock-challenge
./scripts/fastboot get_staged raw_unlock_challenge.bin
python ./scripts/avb-challenge-verify.py raw_unlock_challenge.bin
avb_keys/product_id.bin # Generate unlock_challenge.bin
python ./scripts/avbtool make_atx_unlock_credential --
output=unlock_credential.bin --
intermediate_key_certificate=avb_keys/pik_certificate.bin --
unlock_key_certificate=avb_keys/puk_certificate.bin --
challenge=unlock_challenge.bin --unlock_key=$KEYS/testkey_puk.pem
./scripts/fastboot stage unlock_credential.bin
./scripts/cmd_fastboot oem at-unlock-vboot
```

2.2.5 Enable Log

After completely burning the AVB firmware and locking the device, you can see the following output:

```
DDR Version V1.31 20210118
...
Boot1 Release Time: Mar 29 2021 14:15:15, version: 1.27
...
StorageInit ok = 10694
SecureMode = 1                          # OTP / eFuse have been burned
Secure read PBA: 0x4
# Head flags=0x20b3                     # | Only when burning the signature
loader with Sign_flag = 0x20 for the first time
# SecureCheckHeader 0, 0, 0             # | The OTP burning Log will be
printed, and then power on the computer again, but there will be no such Log.
# SecureWriteOTP                        # |
# enable secure flag!                   # |
# otp write key success! !!             # |
atags_set_pub_key: ret:(0)              # public key verification is valid
SecureInit ret = 0, SecureMode = 1      # Start by SecureMode
...
```

```
U-Boot 2017.09-gfae486e407-210107 #zain (Aug 18 2021 - 17:34:57 +0800)
...
Hit key to stop autoboot('CTRL+C'):  0
ANDROID: reboot reason: "(none)"
Vboot=1, AVB images, AVB erify
read_is_device_unlocked() ops returned that device is LOCKED # The device is in
Lock state
Fdt Ramdisk skip relocation
Booting IMAGE kernel at 0x00680000 with fdt at 0x1f00000...  # Kernel loads
normally and no errors are reported.
...
```

2.2.6 Quick Script

To simplify the above AVB operation steps, management scripts are provided in `tools/linux/Linux_SecurityAVB/`, and `avb_user_avb_user_tool.sh` provides the following shortcut functions:

```
# Generate AVB Keys
./avb_user_tool.sh -n <Product ID> #The size of Product ID is 16 bytes.

# Sign boot and recovery, final image in `out`.
./avb_user_tool.sh -s -b < /path/to/boot.img > -r < /path/to/recovery.img > #
Remove -r option if no recovery.img
# Loader / Uboot / Trust still use `rk_sign_tool`.

# Lock and Unlock device
# Save root password for fastboot operation.
./avb_user_tool.sh --su_pswd < /user/password >
# Mark eFuse tool, and generate permanent_attributes_cer.bin. OTP device skip
this step.
./avb_user_tool.sh -f < /path/to/privatekey.pem >
# download AVB Keys
./avb_user_tool.sh -d
# Lock device
./avb_user_tool.sh -l # reboot device after finishing lock.

# Unlock device
./avb_user_tool.sh -u # reboot device after finishing unlock.
```

2.2.7 Simplified Modification of AVB Functionality

The conventional use of AVB requires a separate AVB key download step outside the normal firmware download process, complicating the flashing process and increasing production costs. This is because the normal AVB key download uses AVB's public key, which is only used for verification purposes. Therefore, as long as the public key is not tampered with, it can be kept the clear text in the firmware. Based on this principle, this section provides a solution to package the AVB public key into the U-boot code. U-boot will be verified by the loader as usual, ensuring that the public key is legitimate and valid. Compared to the standard AVB solution, the AVB key download step via `fastboot` can be omitted.

This solution differs from the standard AVB process and is considered a non-standard modification. As a result, the code must be manually applied and cannot be merged into the mainline.

```
diff --git a/common/android_bootloader.c b/common/android_bootloader.c
index 5525fe620e8..7d59257633f 100644
--- a/common/android_bootloader.c
+++ b/common/android_bootloader.c
@@ -801,6 +801,7 @@ static AvbSlotVerifyResult android_slot_verify(char
*boot_partname,
        if (ops->read_is_device_unlocked(ops, (bool *)&unlocked) !=
AVB_IO_RESULT_OK)
                printf("Error determining whether device is unlocked.\n");

+       unlocked = 0; /* Lock State Fixed */
        printf("read_is_device_unlocked() ops returned that device is %s\n",
               (unlocked & LOCK_MASK)? "UNLOCKED" : "LOCKED");

diff --git a/lib/avb/libavb_user/avb_ops_user.c
b/lib/avb/libavb_user/avb_ops_user.c
index 18c0c1fb237..bb96a4bade2 100644
--- a/lib/avb/libavb_user/avb_ops_user.c
+++ b/lib/avb/libavb_user/avb_ops_user.c
@@ -42,6 +42,7 @@
 #include <android_avb/avb_vbmeta_image.h>
 #include <android_avb/avb_atx_validate.h>
 #include <boot_rkimg.h>
+#include <android_avb/avb_root_pub.h>

 static void byte_to_block(int64_t *offset,
                           size_t *num_bytes,
@@ -192,21 +193,17 @@ validate_vbmeta_public_key(AvbOps *ops,
                           size_t public_key_metadata_length,
                           bool *out_is_trusted)
 {
-/* remain AVB_VBMETA_PUBLIC_KEY_VALIDATE to compatible legacy code */
-#if defined(CONFIG_AVB_VBMETA_PUBLIC_KEY_VALIDATE) || \
-    defined(AVB_VBMETA_PUBLIC_KEY_VALIDATE)
-       if (out_is_trusted) {
-               avb_atx_validate_vbmeta_public_key(ops,
-                                                  public_key_data,
-                                                  public_key_length,
-                                                  public_key_metadata,
-                                                  public_key_metadata_length,
-                                                  out_is_trusted);
+       if (!public_key_length || !out_is_trusted || !public_key_data) {
+               printf("%s: Invalid parameters\n", __func__);
+               return AVB_IO_RESULT_ERROR_IO;
        }
-#else
-       if (out_is_trusted)
+
+       *out_is_trusted = false;
+       if (public_key_length != avb_root_pub_bin_len)
+               return AVB_IO_RESULT_ERROR_IO;
+       if (memcmp(public_key_data, avb_root_pub_bin, public_key_length) == 0)
                *out_is_trusted = true;
-#endif
+
        return AVB_IO_RESULT_OK;
 }
```

```
@@ -558,21 +555,17 @@ AvbIOResult validate_public_key_for_partition(AvbOps *ops,
                                               bool *out_is_trusted,
                                               uint32_t
*out_rollback_index_location)
 {
-/* remain AVB_VBMETA_PUBLIC_KEY_VALIDATE to compatible legacy code */
-#if defined(CONFIG_AVB_VBMETA_PUBLIC_KEY_VALIDATE) || \
-    defined(AVB_VBMETA_PUBLIC_KEY_VALIDATE)
-       if (out_is_trusted) {
-               avb_atx_validate_vbmeta_public_key(ops,
-                                                  public_key_data,
-                                                  public_key_length,
-                                                  public_key_metadata,
-                                                  public_key_metadata_length,
-                                                  out_is_trusted);
+       if (!public_key_length || !out_is_trusted || !public_key_data) {
+               printf("%s: Invalid parameters\n", __func__);
+               return AVB_IO_RESULT_ERROR_IO;
        }
-#else
-       if (out_is_trusted)
+
+       *out_is_trusted = false;
+       if (public_key_length != avb_root_pub_bin_len)
+               return AVB_IO_RESULT_ERROR_IO;
+       if (memcmp(public_key_data, avb_root_pub_bin, public_key_length) == 0)
                *out_is_trusted = true;
-#endif
+
        *out_rollback_index_location = 0;
        return AVB_IO_RESULT_OK;
 }
```

Generate a public key file and put it into U-boot, waiting for compilation.

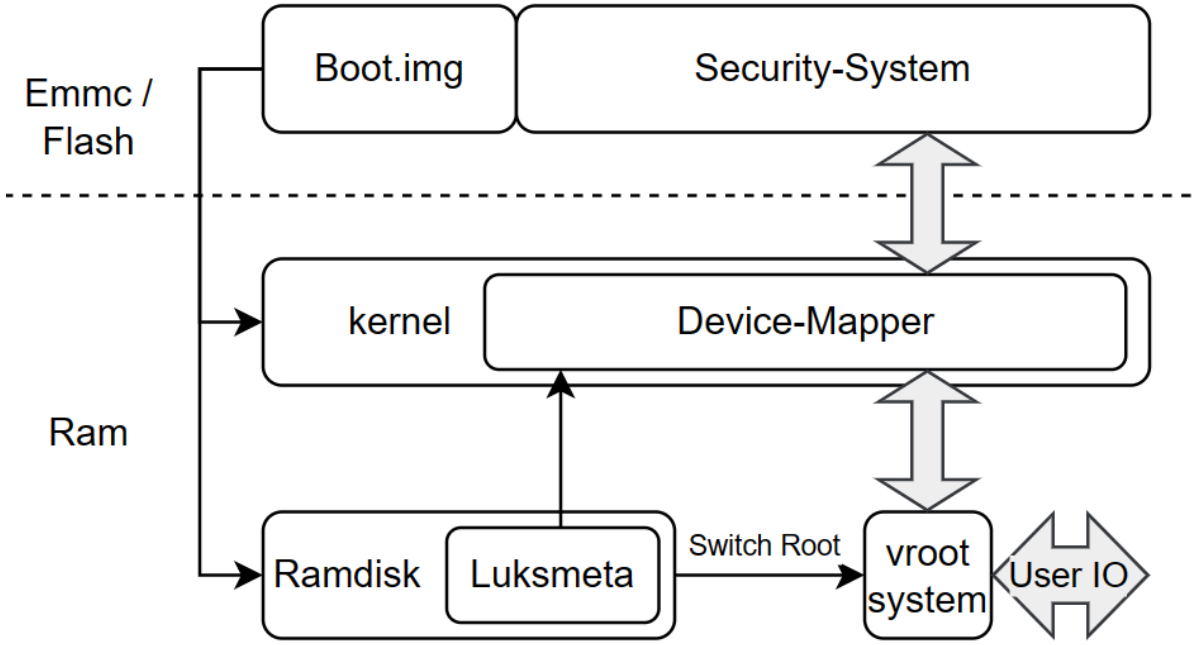
```
./scripts/avbtool extract_public_key --key avb_keys/testkey_psk.pem --output
avb_root_pub.bin

echo "#ifndef __AVB_ROOT_PUB_H_" > avb_root_pub.h
echo "#define __AVB_ROOT_PUB_H_" >> avb_root_pub.h
echo "" >> avb_root_pub.h
xxd -i avb_root_pub.bin >> avb_root_pub.h
echo "" >> avb_root_pub.h
echo "#endif /* __AVB_ROOT_PUB_H_ */" >> avb_root_pub.h

cp avb_root_pub.h $UBoot/include/android_avb/.
```

Following AVB U-boot Configuration, and compile the signed U-boot.

3. System Security



The above diagram roughly illustrates how boot.img verifies or decrypts the system:

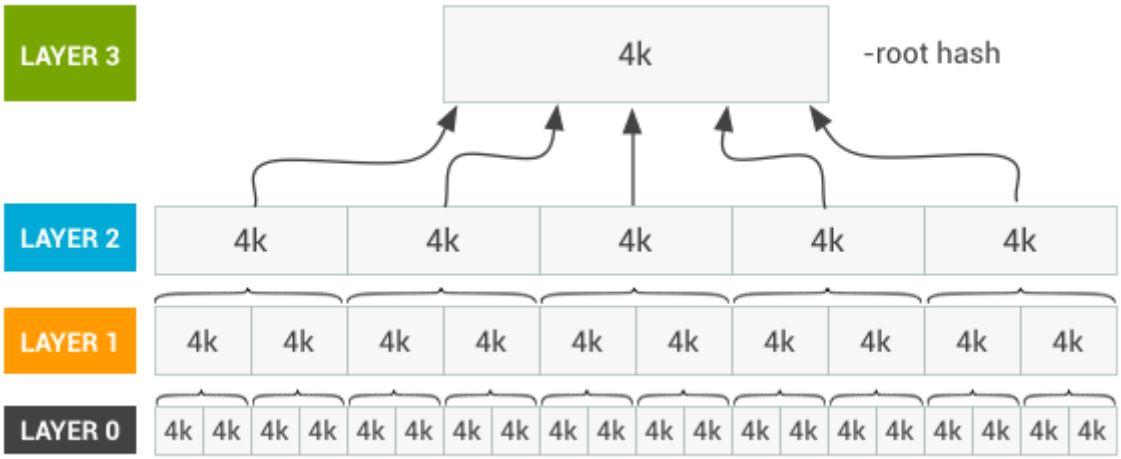
1. Boot.img must be protected under Secure Boot to ensure the security foundation of this mechanism.
2. Ramdisk uses the Luksmeta toolset, calls the Kernel's Device-Mapper feature to virtualize the Security-System as a vroot system node, and then switches to the final system using the `switch_root` command.
3. Reads and writes to the root filesystem by the final system or users are reflected in the Security-System partition via Device-Mapper.
4. Once any tampering with the content of the system partition is detected, the system will return IO errors, and the tampered parts will not function properly.

3.1 DM Introduction

System partitions are generally much larger in volume. Calculating a hash for the entire partition during boot would consume a lot of time. Therefore, the verification of the system partition needs to be done in the Kernel by enabling the Device-Mapper feature, which can significantly reduce boot time.

Combining Device-Mapper technology with Crypt can achieve rapid verification or encryption/decryption of large firmware. Let's take rapid verification as an example to introduce.

The Device-Mapper-Verity mechanism divides the verification firmware into 4K chunks, calculates a hash for each 4K data chunk, iterates through multiple layers, and generates a corresponding Hash-Map and Root-Hash.



Root-Hash first verifies the Hash-Map to ensure its accuracy, and then a virtual partition is created through Device-Mapper-Verity and mounted . When using the partition, Kernel performs hash verification separately for the 4K partition where the access I/O occurs and compares it with the Hash-Map. When an error is detected during verification, it returns an I/O error, similar to symptoms of filesystem corruption.

Similarly, encryption and decryption is to change the Hash algorithm into a symmetric encryption algorithm.

The advantages of Device-Mapper include fast verification, and the larger the firmware, the more noticeable the effect. The disadvantages is that storage read speed may be slightly affected.

For more details, you can refer to the Kernel documentation under `Documentation/device-mapper/` or https://source.android.google.cn/security/verifiedboot/dm-verity.

3.1.1 Configuration

The Device-Mapper feature requires the Kernel to enable the following configuration:

```
CONFIG_BLK_DEV_DM=y
CONFIG_DM_CRYPT=y
CONFIG_BLK_DEV_CRYPTOLOOP=y
CONFIG_DM_VERITY=y
```

> At this point, the boot.img generated by the Kernel compilation does not have the capability to actively verify or decrypt the system. As shown in the diagram in System Security, it is necessary to package the Ramdisk and Kernel together to have the ability for active verification or decryption, as introduction in the Ramdisk Configuration section.

3.2 System Processing

Choose one of the following operations as needed.

3.2.1 System-Verity

System verification is accomplished by the third-party tool `veritysetup`. `veritysetup` is a command-line tool used in Linux systems to set up and manage dm-verity (Device-Mapper-Verity). dm-verity is a module in the Kernel, based on Device-Mapper, and is used to provide block-level data integrity protection. It is typically used to prevent unauthorized modifications to the filesystem or system files.

`veritysetup` generates Hash-Map and Root-Hash based on the target system image. The Hash-Map can be directly appended to the end of the system image using a tool, while the Root-Hash is packaged into the Ramdisk of `boot.img`. During startup, Ramdisk is responsible for using the Root-Hash to virtualize the target image as a `vroot` block device through dm-verity. After mounting, it switches to the target system using the `switch_root` command.

On a PC, processing is done on the system image by attaching to the Hash-Map at the end of the system image and saving the Root-Hash

```
target_image=$(realpath $path_to_system_img)              #Enter the system image,
and the verification information is directly attached to the input image.

sectors=$(ls -l "$target_image" | awk '{printf $5}')      # Get image size
hash_offset=$[(sectors / 1024 / 1024 + 2) * 1024 * 1024] # The system is aligned
at 1M, calculates the offset of Hash-Map placement, and the 2M space behind the
system image
result=$(veritysetup --hash-offset=$hash_offset format "$target_image"
"$target_image")
# Save data for subsequent operations
echo "root_hash=$(echo ${result##*:})" > security.info
echo "hash_offset=$hash_offset" >> security.info
```

> The Root-Hash is stored in `security.info` and will be used in the Ramdisk Initial Script Configuration.
>
> Note: Images created by this method contain an additional segment of Hash-Map data compared to the original image. They can still be treated as regular systems and can be directly mounted and used without going through `veritysetup` processing.

3.2.2 System-Encryption

System-Encryption is achieved by the third-party tool `dmsetup`. `dmsetup` is a command-line tool used in Linux systems to manage Device Mapper devices. It allows users to create and manage virtual block devices, which can perform various operations such as merging, splitting, remapping, and encryption.

On a PC, `dmsetup` is used to create an encryption container using Device Mapper, where the system to be encrypted is placed inside the container to complete the encryption process.

```
target_image=$(realpath $path_to_system_img)     # Enter system image
security_system=${path_to_output_system}         # Output encryption system
key=$(cat ${path_to_key_file})                   # To read the encryption key, the
key length must match the following algorithm
cipher=${cipher_name}                            # Symmetric encryption algorithm
name, such as aes-cbc-plain

sectors=$(ls -l "$target_image" | awk '{printf $5}')
sectors=$[(sectors + (21 * 1024 * 1024) - 1) / 512] # remain 20M for partition
info / unit: 512 bytes

#Create an encrypted container
loopdevice=$(losetup -f)
```

```
mappername=encfs-$(shuf -i 1-10000000000000000000 -n 1)
dd if=/dev/null of="$security_system" seek=$sectors bs=512
sudo losetup $loopdevice "$security_system"
sudo dmsetup create $mappername --table "0 $sectors crypt $cipher $key 0
$loopdevice 0 1 allow_discards"

#Put the system into an encrypted container
sudo dd if="$target_image" of=/dev/mapper/$mappername conv=fsync

sync && sudo dmsetup remove $mappername
sudo losetup -d $loopdevice

# Save data for subsequent operations
echo "cipher=$cipher" > security.info
echo "key=$key" >> security.info
```

The packaged encrypted system is encrypted text and cannot be directly decoded for use. Similar to system verification, when using the encrypted system, the Ramdisk is involved. It provides the encryption algorithm and key to Ramdisk, the system partition is virtualized into the `/dev/mapper/vroot` node using the `dmsetup` tool and then mounted for use.

For Ramdisk configuration, refer to the Ramdisk Initial Script Configuration section. In contrast to System-Verity, the encryption keys for System-Encryption cannot be directly stored in the Ramdisk firmware.

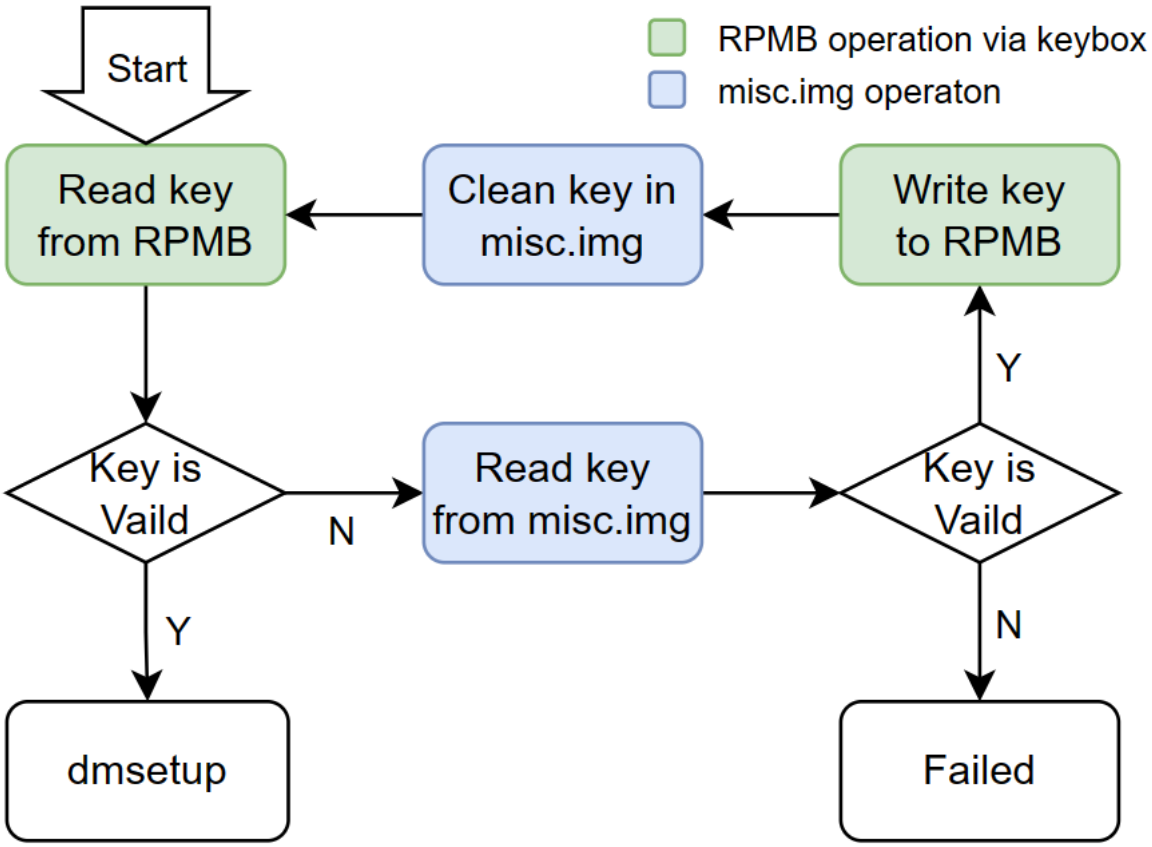
3.2.2.1 Key Storage

In contrast to System-Verity, the encryption keys for System-Encryption cannot be directly stored in the Ramdisk firmware. The SDK stores the key in `misc.img` by default, the Ramdisk reads the keys from `misc.img`， and then transfers them to secure storage (RPMB or the Security partition), simultaneously clearing `misc.img`.

On a PC, you can package the keys into `misc.img` by the following command:

```
# The key is stored at an offset of 10K in the misc image by default.
MISC=misc.img                                                    # Original misc file
key="af16857cf77982040e6dbeee739d00619847b0e16a25c8a9589b4ce93aced6b1"
dd if="$MISC" of=security-misc.img bs=1k count=10
echo -en "\x40\x00" >> security-misc.img                         # Declare that the key
length bit is 64 bytes (0x40)
echo -n "$key" >> security-misc.img                             # write key
skip=$[10 * 1024 + 64 + 2]
dd if="$MISC" of=security-misc.img seek=$skip skip=$skip bs=1
# Generate security-misc.img of the key
```

In the Ramdisk, the key handling process is depicted in the diagram:



In the diagram, operations for reading and writing keys from RPMB are all performed through the KeyBox software. Additionally, certain runtime restrictions have been implemented to prevent KeyBox from being extracted from the Ramdisk for unauthorized use. For example, it must run within a program with PID=1 and must be executed in the Ramdisk. For more details on KeyBox, you can refer to the KeyBox section.

3.3 Ramdisk Configuration

In the Linux SDK, the Ramdisk is a small system generated by Buildroot, packaged together with the Kernel into the boot.img. In the system security solution, the Ramdisk is primarily responsible for decrypting or verifying the system. After completing system decryption or verification, it uses `switch_root` to switch to the target system and then self-destructs. Different configurations are required depending on the purpose of use.

3.3.1 Ramdisk Initial Script Configuration

In the Ramdisk, all tasks are carried out in the `/init` `(buildroot/output/rockchip_${chip}_ramboot/target/init)` script. The `init` script decrypts or verifies the system based on the packaging type of the system and uniformly generates `vroot` device. The general process is showed in the diagram below, which accommodates A/B systems, system verification, and system encryption.

> [1] Under the encrypted system, the system space will be expanded according to the actual size of the system partition.

The `init` script is modified and generated by `buildroot/board/rockchip/common/security-ramdisk-overlay/init.in`. Before operating, please generate the corresponding `security.info` according to the requirements of System-Verity or System-Encryption. The following operations will be used:

```
cp buildroot/board/rockchip/common/security-ramdisk-overlay/init.in \
```

```
   buildroot/board/rockchip/common/security-ramdisk-overlay/init
init_file=buildroot/board/rockchip/common/security-ramdisk-overlay/init
optee_storage=RPMB #Depending on the actual hardware conditions, optee_storage is
filled with RPMB or SECURITY (security partition)
source security.info

# Choose between system-Encryption or System-Verity:
# - System-Verity
sed -i "s/ENC_EN=/ENC_EN=false/" $init_file
sed -i "s/OFFSET=/OFFSET=$hash_offset/" $init_file
sed -i "s/HASH=/HASH=$root_hash/" $init_file
sed -i "s/# exec busybox switch_root/exec busybox switch_root/" "$init_file"

# - System-Encryption
sed -i "s/ENC_EN=/ENC_EN=true/" $init_file
sed -i "s/CIPHER=/CIPHER=$cipher/" $init_file
sed -i "s/SECURITY_STORAGE=RPMB/SECURITY_STORAGE=$optee_storage/" $init_file
sed -i "s/# exec busybox switch_root/exec busybox switch_root/" "$init_file"
```

3.3.2 Ramdisk Compilation Configuration

The default Ramdisk configuration is generally `rockchip_<chip_name>_ramboot_defconfig`. The configuration is set for the purpose of system verification (System-Verity). If the customer has system encryption (System-Encryption) requirements, add the following additional configuration:

```
BR2_PACKAGE_TEE_USER_APP=y # Refer to the KeyBox chapter configuration. Some SDKs
can be included "tee_aarch64_v2.config" directly.
BR2_PACKAGE_TEE_USER_APP_COMPILE_CMD="6432"
BR2_PACKAGE_TEE_USER_APP_TEE_VERSION="v2"
BR2_PACKAGE_TEE_USER_APP_EXTRA_TOOLCHAIN="$(PATH_TO_CROSS_COMPILE)"

BR2_PACKAGE_RECOVERY=y
BR2_PACKAGE_RECOVERY_UPDATEENGINEBIN=y # The encryption key is stored in misc,
and the Recovery option is to add the misc parsing program.
```

> The default configuration will include `BR2_ROOTFS_OVERLAY+="board/rockchip/common/security-ramdisk-overlay/"`, which will put the `init` script of Ramdisk Initial Script Configuration into Ramdisk .
>
> `BR2_PACKAGE_TEE_USER_APP` related configuration meaning, please refer to the KeyBox chapter, please configure flexibly according to actual needs.

The essence of Ramdisk is also a complete middle layer system, so its compilation is the same as regular Buildroot compilation:

```
cd buildroot
./build/envsetup.sh rockchip_${chip}_ramboot_defconfig   # chip: Fill in
according to actual situation
make # Firmware is generated in
output/rockchip_${chip}_ramboot/images/rootfs.cpio.gz
```

Customers can also prepare their own Ramdisk and customize it according to the following requirements:

1. The Ramdisk must include the `Luksmeta` toolset, ensuring at least that `veritysetup` is available for system verification and `dmsetup` is available for system encryption.
2. In the case of a system encryption, TEE programs need to be ported to handle encryption key read/write operations. `UpdateEngine` programs also need to be ported to read the keys from misc, or this part can be separated into an independent program, or keys can be passed in from another source.
3. The `init` startup script of the Ramdisk needs to be modified based on Ramdisk Initial Script Configuration to meet the requirements of mounting the new system.

3.3.3 Ramdisk Packaging

The generated Ramdisk system needs to be packaged together with the Kernel firmware into `boot.img`. The packaging method varies depending on the usage solution:

```
# Package it with kernel into boot.img, choose one of FIT / AVB solutions
cd ${RK_SDK_DIR} # SDK root directory
# FIT solution
./device/rockchip/common/scripts/mk-fitimage.sh boot.img \
    device/rockchip/${chip}/boot4recovery.its \
    kernel/arch/arm64/boot/Image \
    kernel/arch/arm64/boot/dts/rockchip/${RK_KERNEL_DTB} \
    kernel/resource.img \
    buildroot/output/rockchip_${chip}_ramboot/images/rootfs.cpio.gz

#AVB solution
./kernel/scripts/mkbootimg \
    --kernel kernel/arch/arm64/boot/Image \
    --ramdisk buildroot/output/rockchip_${chip}_ramboot/images/rootfs.cpio.gz \
    --second kernel/arch/arm64/boot/dts/rockchip/${RK_KERNEL_DTB} \
    -o boot.img
```

Sign the `boot.img` generated above, please refer to FIT Firmware Signature Extension Command 3 or AVB Firmware Signature

4. KeyBox

When using partition or system encryption, a location for storing keys is required. Typically, keys are stored in RPMB or the Security partition through OPTEE. Since this code is designed to interact directly with the manufacturer's private key, it is generally expected that manufacturers will design this part themselves. However, considering that some customers may not be familiar with OPTEE, the SDK includes an example code called KeyBox, which is used in System-Encryption for demonstration purposes. (**It is recommended for customers to refactor the code**.)

The OPTEE-related code can be found in `<SDK>/external/security/` and includes two repositories: `bin` and `rk_tee_user`.

- `bin` contains precompiled parts of non-public code and headers, forming the foundational library for OPTEE.
- `rk_tee_user` is a project for compiling customers' own CA/TA, and it includes some demo test projects.

For information on how to use OPTEE, please refer to the **Rockchip_Developer_Guide_TEE_SDK_CN.pdf** document, which provides detailed instructions. Here, we will focus on how to compile the KeyBox program.

4.1 Independent Compilation

KeyBox code is located in `<SDK>/buildroot/package/rockchip/tee-user-app`

```
# tree buildroot/package/rockchip/tee-user-app/
buildroot/package/rockchip/tee-user-app/
├── Config.in
├── extra_app
│   ├── host
│   │   ├── main.c
│   │   └── Makefile
│   └── ta
│       ├── include
│       │   ├── ta_keybox.h
│       │   └── user_ta_header_defines.h
│       ├── keybox.c
│       ├── Makefile
│       └── sub.mk
└── tee-user-app.mk
```

When compiling, you should put `host` and `ta` under `extra_app` into `rk_tee_user` respectively, for example:

```
# tree rk_tee_user/v2/host/extra_app/ rk_tee_user/v2/ta/extra_app/
rk_tee_user/v2/host/extra_app/
├── main.c
└── Makefile
rk_tee_user/v2/ta/extra_app/
├── include
│   ├── ta_keybox.h
│   └── user_ta_header_defines.h
├── keybox.c
├── Makefile
└── sub.mk
```

Compilation of `rk_tee_user` generates CA (`keybox_app`) and TA programs at the same time. These two programs run in different environments.

- CA runs in the user space of the system, and the compilation chain is consistent with the system compilation chain.
- TA runs in the TrustZone environment, and the compilation chain needs to be consistent with BL32 (TEE). Without special declaration, the default is the 32-bit compilation chain.

Therefore, `rk_tee_user` compilation may require two different compilation chain configurations.

Take the system as a 64-bit system and the TA as a 32-bit system as an example:

```
cd rk_tee_user/v2 # v1 is the same, but the compilation directory is different.
./build.sh 6432
ARM32_TOOLCHAIN=${ARM32_CROSS_COMPILER_PATH} \
AARCH64_TOOLCHAIN=${AARCH64_CROSS_COMPILER_PATH} \
./build.sh 6432                     # Compile 64-bit CA, 32-bit TA
# Generate program:
# out/ta/extra_app/8c6cf810-685d-4654-ae71-8031beee467e.ta
# out/extra_app/keybox_app
```

4.2 tee_user_app Compilation

The KeyBox program is in Buildroot and compiled using the `tee_user_app` package. Taking a 64-bit system with 32-bit TA compilation as an example, configure the following content to achieve compilation.

```
BR2_PACKAGE_TEE_USER_APP=y
BR2_PACKAGE_TEE_USER_APP_COMPILE_CMD="6432"
BR2_PACKAGE_TEE_USER_APP_TEE_VERSION="v2"
BR2_PACKAGE_TEE_USER_APP_EXTRA_TOOLCHAIN="$(PATH_TO_CROSS_COMPILE)"
```

The generated KeyBox program and TA are automatically integrated into the system.

4.3 Enable OPTEE in Kernel

KeyBox is developed based on the OPTEE function. When used, OPTEE support is added to the Kernel.

```
CONFIG_TEE=y
CONFIG_OPTEE=y
```

At the same time, configure the optee node in dts

```
        optee: optee {
                compatible = "linaro,optee-tz";
                method = "smc";
                status = "okay";
        }
```

4.4 KeyBox Modification Recommendations

The KeyBox section lists a common operation for key storage, and this is an open-source solution to all customers. To enhance the security of key storage, customers are advised to make modifications to the KeyBox program and consider the following suggestions:

- The usage environment of KeyBox must be within a secure environment and should be used together with FIT security solutions or AVB security solutions.
- TA files can be signed according to Chapter 5, **`TA Signing`**, in the Rockchip_Developer_Guide_TEE_SDK_CN.pdf document. After signing, third parties will not be able to run custom TAs on the customer's device.
- Strictly limit the CA usage environment to prevent the key from being read out in other non-secure environments after the CA is copied. In the default code, KeyBox can perform key writing operations under any circumstances but can only read keys in the Ramdisk and within a program with PID=1.
- Modify CA-TA interaction. In the default code, some simple random verifications are performed in the CA-TA interaction. If there is an error in the CA-TA interaction, random keys are directly output.

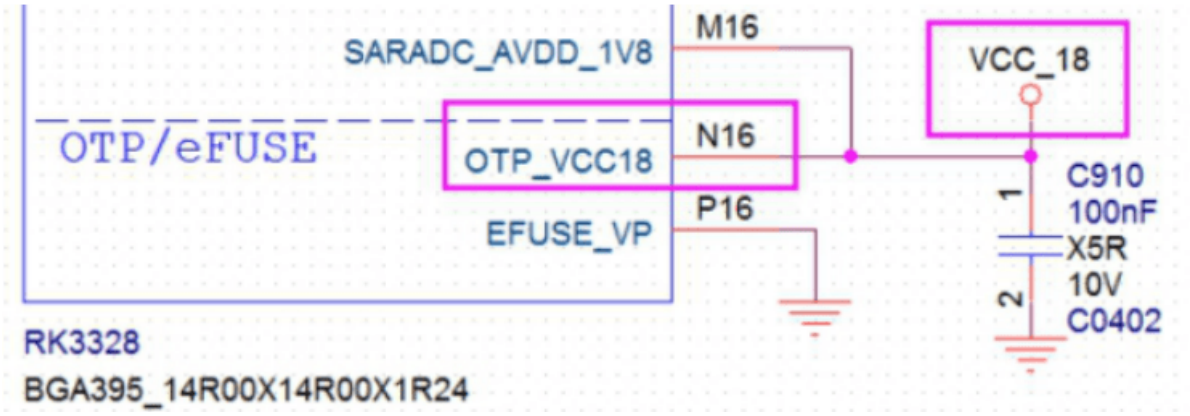
5. Secure Information Burning

5.1 Key Hash

Different chips use different media for secure storage. Confirm the storage media used by the chip based on the Product Version and follow the required steps.

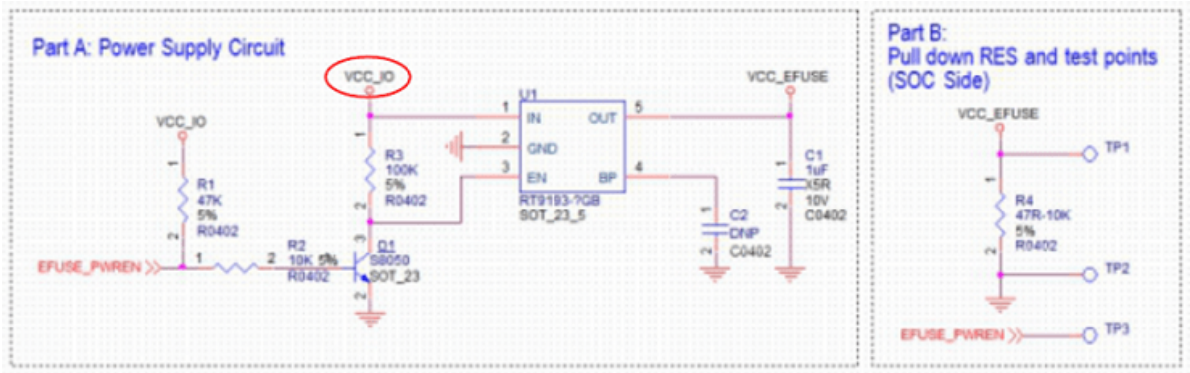
5.1.1 OTP

If the chip uses OTP to enable Secure Boot functionality, ensure that the OTP pins of the chip are powered during the Loader phase. Download the firmware using AndroidTool (Windows) / upgrade_tool (Linux). Upon the first reboot, the Loader will be responsible for writing the Key's Hash into OTP, activating Secure Boot. Upon the next reboot, the firmware will be in protection mode.



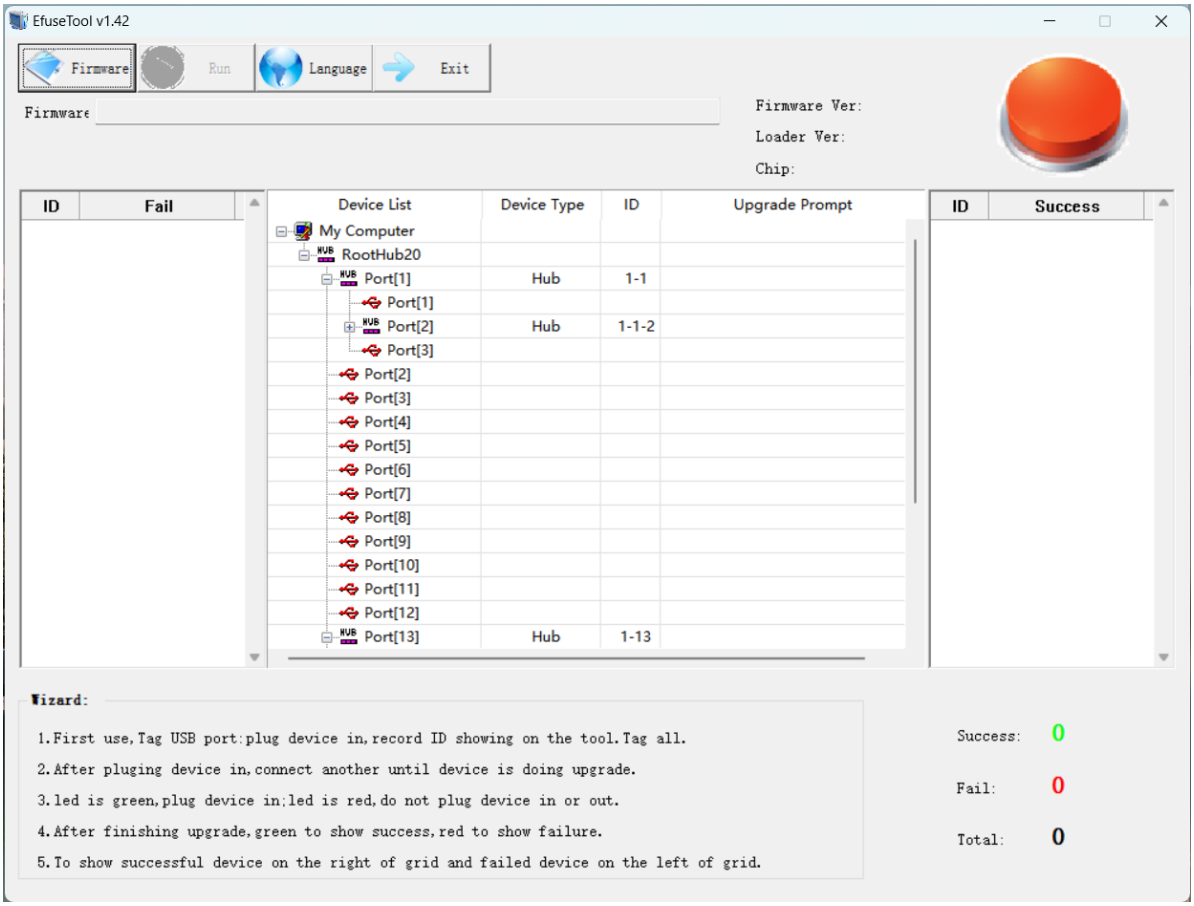
5.1.2 eFuse

If the chip uses eFuse to enable Secure Boot functionality, ensure that VCC_IO has power in the MaskRom state (default hardware state), and VCC_EFUSE requires the following power control circuit.



Use tools/windows/eFusetool_vXX.zip to put the board into MaskRom state.

Click "Firmware," select the signed update.img or Miniloader.bin, click "Start" to begin burning eFuse.



After successfully burning eFuse, power off and restart the board, enter MaskRom mode, and download other signed firmware to the board.

5.2 Custom Security Information

For custom security information, it is recommended to use OPTEE storage. Please refer to the Rockchip_Developer_Guide_TEE_SDK_CN.pdf document for details.

6. Security Demo

The previous sections described how to build a firmware security solution from scratch. To simplify the setup process, the SDK provides several management scripts that are integrated into the common compilation script `build.sh`. With a few simple configurations, you can achieve system encryption or system verification.

Note: This section does not provide detailed explanations of the principles and operations. If you need to understand the details of your operations, please refer to the above sections. Regarding the simplified scripts, they are developed based on a common SDK. However, because the SDK is update iteratively, and some SDK versions may conflict with the common SDK, it cannot be guaranteed that the simplified scripts will work correctly for every SDK version. If you encounter errors with the simplified scripts, please refer to the earlier sections and try debugging.

Due to the sensitivity of firmware security, and because this solution is open-source for all customers, it is recommended that customers, while quickly setting up a system, thoroughly analyze its principles, modify and optimize the solution to create secure firmware that meets their own standards.

6.1 SDK Configuration

In the SDK root directory, you can use `make menuconfig` for SDK compilation configuration. Security-related configurations are centralized under `RK_SECURITY`:

```
[*] security feature
      *** Security check method (system-verity) needs squashfs rootfs type ***
      Secureboot Method (avb)  --->
      Optee Storage (rpmb)  --->
      security check method (base|system-encryption|system-verity) (base)  --->
[ ]   burn security key (NEW)
```

The sdetailed configuration is as follows:

```
RK_SECURITY                             # Security function is enabled

RK_SECUREBOOT_FIT                       # Basic security function mode, choose
one of FIT / AVB
RK_SECUREBOOT_AVB

RK_SECURITY_OPTEE_STORAGE_RPMB          # OPTEE Secure Storage Medium, choose one
between the two
RK_SECURITY_OPTEE_STORAGE_SECURITY      # Choose RPMB for eMMC storage and
SECURITY for flash storage.

RK_SECURITY_CHECK_SYSTEM_BASE           # Just check loader + uboot + boot
RK_SECURITY_CHECK_SYSTEM_VERITY         # Add rootfs verification to the base
RK_SECURITY_CHECK_SYSTEM_ENCRYPTION     # Add rootfs encryption to the base

RK_SECURITY_INITRD_BASE_CFG             # When there is rootfs verification or
encryption, ramboot needs to be configured
RK_SECURITY_INITRD_TYPE
RK_SECURITY_FIT_ITS

RK_SECURITY_BURN_KEY                    # Enable public key hash burning function
```

> **Pay attention to RK_SECURITY_BURN_KEY. For the sake of convenience during debugging, it is closed by default. When it is closed, the Key Hash will not be written to OTP, the loader.bin is considered secure by default, does not require verification, and can be replaced. But starting from the loader, strict verification will be applied to u-boot, following a process similar to that of burning OTP. When producing official production products, please open this option and burn the Key Hash.**

After configuring the options mentioned above, you can use `./build.sh` or `make` to build. During this process, there may be errors, which can be resolved based on the error messages and prompts. Alternatively, you can continue to make modifications according to the documentation. The error checking during compilation only checks critical configurations, and default configurations may vary between SDKs. It cannot guarantee that the resulting firmware will have fully functional security features, so the final verification is essential. If there are issues, first check which part of the firmware verification is problematic, and then refer to the documentation for specific debugging steps.

6.2 Detailed Configuration

6.2.1 Key Generation

- Key generation

```
./build.sh createkeys
```

- If system encryption is used, store the user password with root permissions in U-Boot

```
echo "Password for sudo" > u-boot/keys/root_passwd
```

> When building an encryption system, the loopback feature of the system will be used. This requires users to have root operation permissions on the compilation computer, which means that this method cannot be compiled in a server environment (unless user has root permissions).

6.2.2 U-Boot Modification

According to the "Kernel verification method" of Product Version, U-Boot configuration is divided into:

- FIT solution needs to be added:

```
CONFIG_FIT_SIGNATURE=y
CONFIG_SPL_FIT_SIGNATURE=y
```

- AVB solution needs to be added

  There are quite a few modifications to U-Boot for AVB, please refer to AVB U-boot Configuration for details.

6.2.3 Kernel Modification

Kernel needs to add OPTEE and Device Mapper configuration:

```
CONFIG_BLK_DEV_DM=y
CONFIG_DM_CRYPT=y
CONFIG_BLK_DEV_CRYPTOLOOP=y
CONFIG_DM_VERITY=y

CONFIG_TEE=y                    # It is required in encryption system
CONFIG_OPTEE=y                  # It is required in encryption system
```

DTS files need to add OPTEE nodes:

```
        optee: optee {
                compatible = "linaro,optee-tz";
                method = "smc";
                status = "okay";
        }
```

6.2.4 Buildroot Modification

Buildroot system configuration needs to be added:

```
BR2_ROOTFS_OVERLAY+="board/rockchip/common/security-system-overlay"
```

6.2.5 Ramdisk Modification

The configuration of Ramdisk is configured according to system verification by default. If you need to change it to system encryption, you need to add the following configuration

```
BR2_PACKAGE_TEE_USER_APP=y                    # Refer to the KeyBox chapter
configuration. Some SDKs can directly include "tee_aarch64_v2.config"
BR2_PACKAGE_TEE_USER_APP_COMPILE_CMD="6432"
BR2_PACKAGE_TEE_USER_APP_TEE_VERSION="v2"
BR2_PACKAGE_TEE_USER_APP_EXTRA_TOOLCHAIN="$(PATH_TO_CROSS_COMPILE)"

BR2_PACKAGE_RECOVERY=y
BR2_PACKAGE_RECOVERY_UPDATEENGINEBIN=y     # The encryption key is stored in
misc, and the Recovery option is to add the misc parser
```

6.3 Verification Method

The security solution outlined in the document protects several levels: loader, trust, U-Boot, boot, and system.

Following the document's method, build a secure firmware, download the keys correctly, and start up the system normally. If there are any abnormal boot-up issues, please troubleshoot them first.

Next, prepare a non-secure firmware or a firmware that has had its keys replaced. Replacing any image from the second firmware set with the protected partitions of the secure system will render the system unable to start.

During the replacement process, if you find that protection has been compromised in a certain partition, refer to the Partition Security Process diagram to identify which part of the verification has failed. Then, review the specific sections of the documentation to check the configuration.

6.4 Debugging Method

If the `init` process cannot transition to the system properly, you can enable debugging and use the `DEBUG` function to add some private prints. Follow the instructions in Ramdisk Initial Script Configuration to determine its runtime status.

```
diff --git a/board/rockchip/common/security-ramdisk-overlay/init.in
b/board/rockchip/common/security-ramdisk-overlay/init.in
index 756d0b5375..c3267e28b1 100755
--- a/board/rockchip/common/security-ramdisk-overlay/init.in
+++ b/board/rockchip/common/security-ramdisk-overlay/init.in
@@ -16,7 +16,7 @@ BLOCK_TYPE_SUPPORTED="
 mmcblk
 flash"

-MSG_OUTPUT=/dev/null
+MSG_OUTPUT=/dev/kmsg
 DEBUG() {
        echo $1 > $MSG_OUTPUT
 }
```

7. References

Rockchip_Developer_Guide_UBoot_Nextdev_CN.pdf

Rockchip-Secure-Boot-Application-Note-V1.9.pdf

Rockchip-Secure-Boot2.0.pdf

Rockchip_Developer_Guide_TEE_SDK_CN.pdf

SDK/kernel/ Documentation/device-mapper/

https://android.googlesource.com/platform/external/avb/+/master/README.md

https://source.android.google.cn/security/verifiedboot/dm-verity