USER'S GUIDE

Apollo4 and Apollo4 Blue Secure Update

Ultra-Low Power Apollo SoC Family

A-SOCAP4-UGGA02EN v1.1

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Revision History

Revision	Date	Description
1.0	October 31, 2020	Initial Release.
1.1	February 23, 2021	▪ Removed duplicate figure in section 5.1.2 Connection Establishment (HELLO and STATUS) Messages. ▪ Updated Table 3-1 Common Field Definitions

Reference Documents

Document ID	Description
A-SOCAP4-WPNA01EN	Apollo4 and Apollo4 Blue SoC Security Features White Paper
A-SOCAP4-UGGA01EN	Apollo4 and Apollo4 Blue OEM Provisioning Tools User's Guide

Table of Contents

List of Tables

List of Figures

SECTION

1

Introduction

This document describes the methods, image formats, and protocols supported by the Apollo4 Secure Bootloader (SBL) for both secure image and wired updates.

1.1 Terminology

This section defines some of the terminologies used in this document.

Table 1-1: Terminology

Abbreviation	Definition
OTA	Over the Air
OTP	One Time Programmable
RSA	A public-key cryptosystem that is widely used for secure data transmission.
SBL	Secure Bootloader

SECTION

2

Security Features of Secure Bootloader

The following sections describe the specific features of the Secure Bootloader (SBL).

2.1 Integrity Check

Integrity Check using CRC32 (Ethernet FCS) function.

2.2 Authentication

Authentication uses RSA 3072 signature verification on the **Signature** field using the PK from the existing certificate chain. The **Auth Key Index** field (0-2) is specified to determine which PK is used based on the 3-stage pre-installed Certificate chain.

2.3 Decryption

Decryption is performed using AES-128 CTR and the **Encryption Info** field. The Encryption Info comprises of the Nonce/IV and the Encrypted Key. The Encrypted key is decrypted using the provisioned Key Encryption Key (KEK) on the device, and is thereafter used to decrypt the ciphertext in conjunction with the supplied Nonce/IV.

KEK Index determines which of the preinstalled keys is used to decrypt the Encrypted key. Values 0 and 1 correspond to the KCP and KCE respectively. Indices 0x80 onwards signify keys in the Key bank area, with each 128b key corresponding to one index.

2.4 Anti-Rollback

The SBL uses a combination of the OTP_HBK1MINVER words and the swVer in the OEM Content Certificate. This will prevent an OTA to upgrade to a OEM image with a version that is the same, or lower than that, of the current image. All the Certificates in a chain should all have the same version. Hence, to implement the anti-rollback, the full certificate chain needs to be refreshed with an updated version number.

2.5 Image Protection

SBL can be instructed to apply image protection features to assets in the MRAM. The MRAM blocks for protection are specified in 16K granularity.

The blocks can be marked as *Write-Protected* to prevent overwriting the images either intentionally using malicious programs, or unintentionally. Such Write-protected images can be upgraded only through SBL by maintaining the secure upgrade trust chain.

The blocks can be marked as *Copy-Protected* to prevent Read access to the pages. This can be used to avoid exposing sensitive algorithms or programs from prying eyes. Care must be taken when using this feature to protect executable code—so as to generate the code using appropriate tool options so that there are no data reads in the code memory.

Currently, the protection attributes are specified in the OTP, as part of provisioning, and hence are statically predefined.

In the future, there will be support for dynamic MRAM protection through content certificate. On successful installation/verification through SBL, the OEM Content Certificate can also be used to direct the SBL to apply specified protections.

SECTION

3

Image Formats

This section describes the generic format for all the OTA images.

- This is the format for both Secure (CC = 1) and Non-Secure (CC = 0) OTA Updates, as well as non-firmware updates.
  - The image format supports error detection, authentication, and decryption.
- The **Signature** field is optional, based on value of $\mathbf{A_{IN}}$ (Value of 0 implies no Authentication, and hence no signature).
- The **Encryption Info** field is optionally present, if the $\mathbf{E_{IN}}$ is non-zero.
- The image format and the offset of the fields will change if the optional **Signature** and/or **Encryption Info** is not present. The generic format in Figure 3-1 on page 11 and Figure 3-2 on page 12 depicts the case when both are present.

Figure 3-1: OTA Image Generic Format with Signature and Encryption Info - A

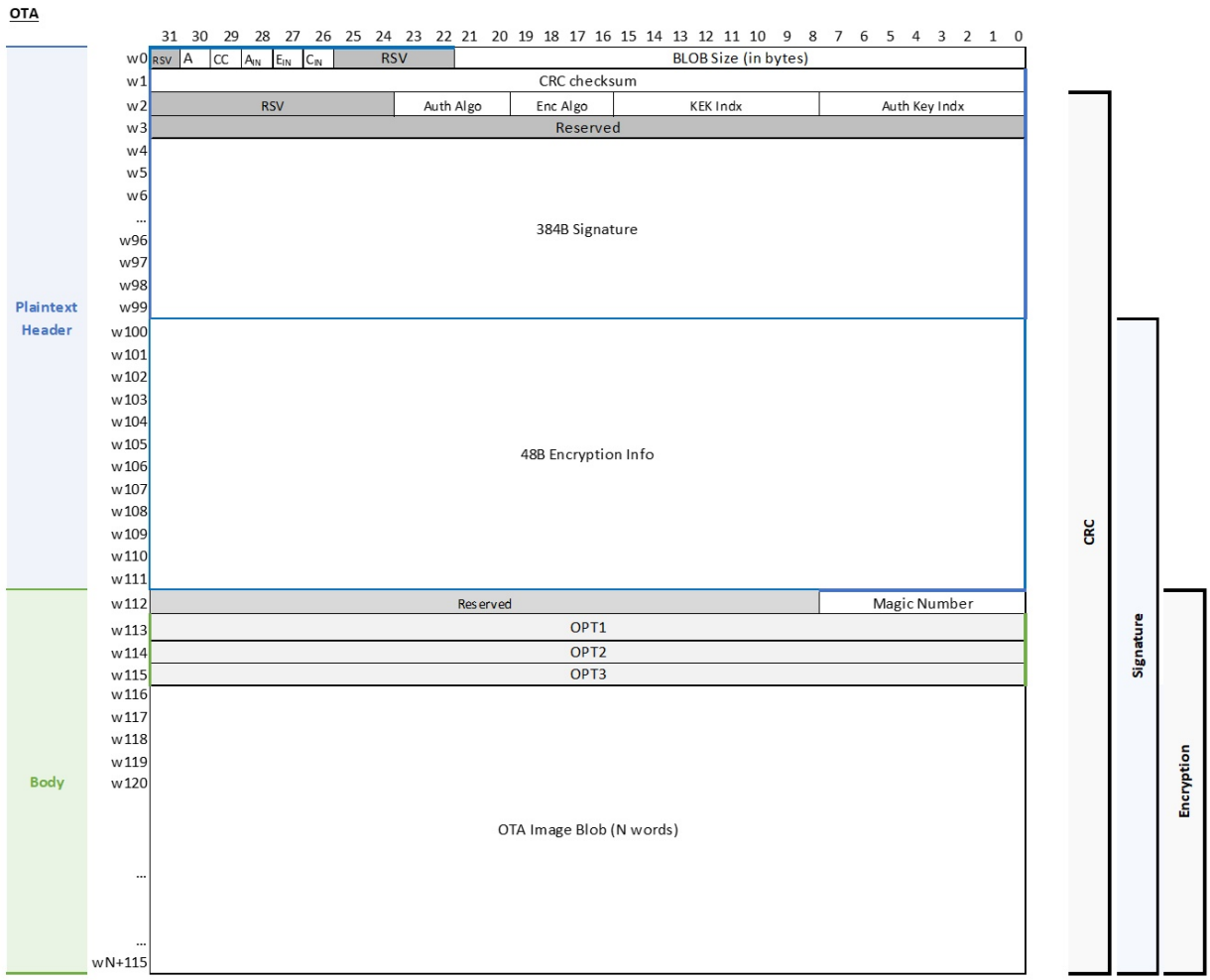
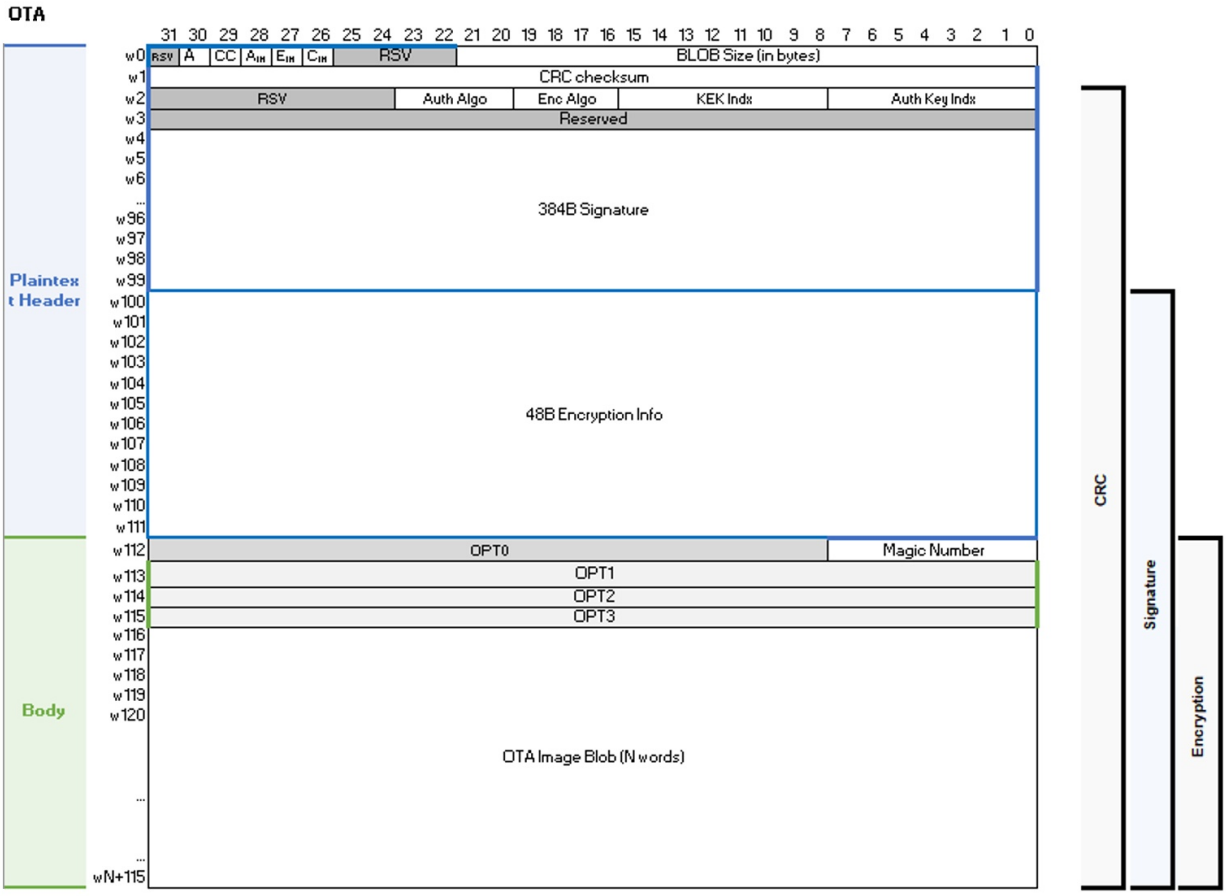
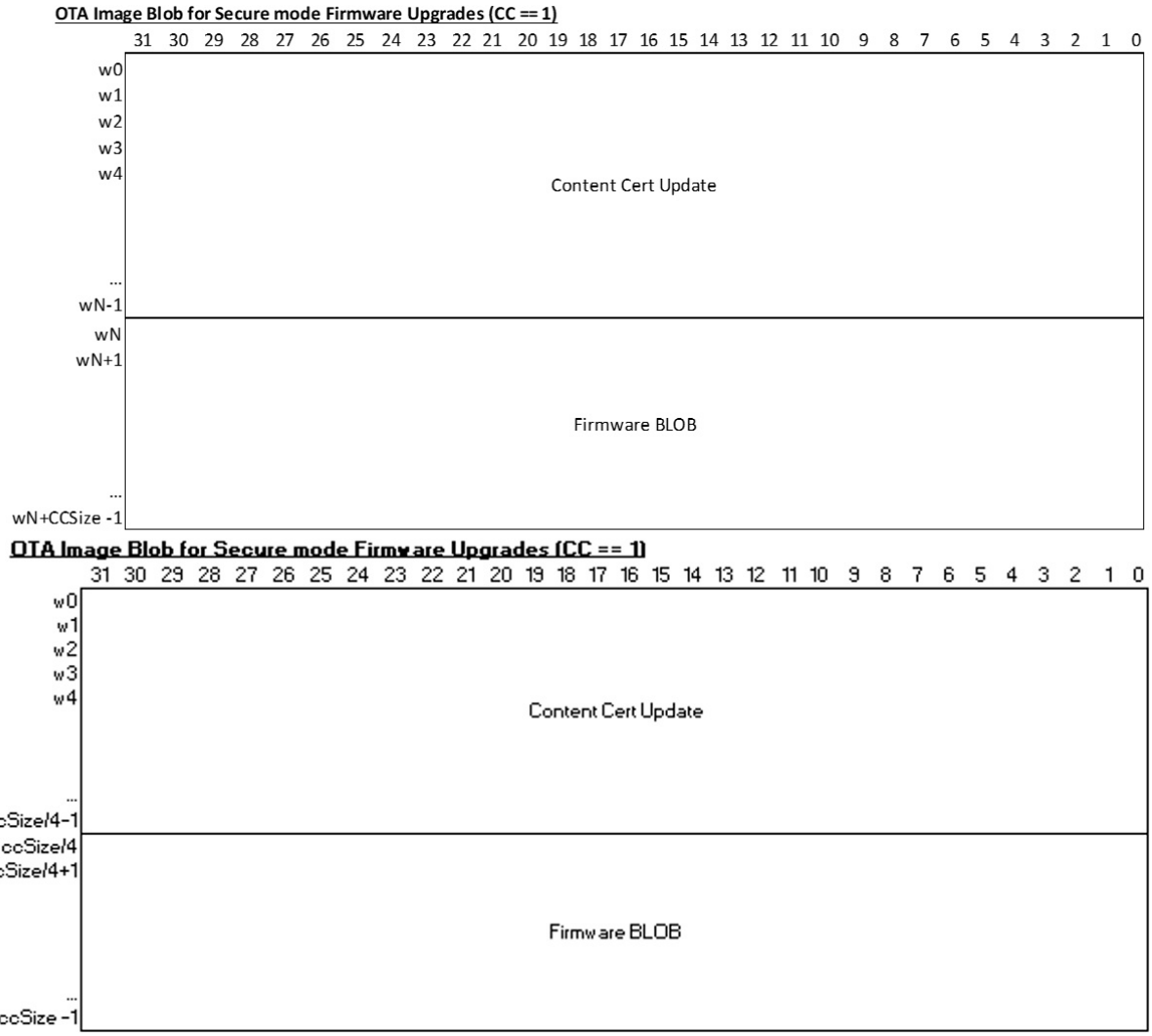


Figure 3-2: OTA Image Generic Format with Signature and Encryption Info - B



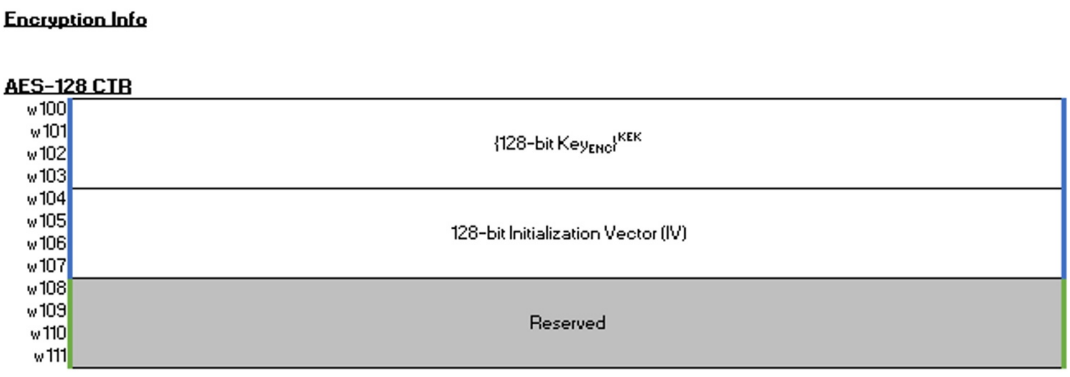
If the OTA Image Blob contains a Content Certificate, the format of the blob will be as shown in Figure 3-3—as the updated content certificate is also bundled along:

Figure 3-3: OTA Image Blob with a Content Certificate



If present, the **Encryption Info** field is formatted as shown in Figure 3-4.

Figure 3-4: OTA Image Blob with Encryption Info



3.1 Common Field Definitions

Table 3-1: Common Field Definitions

Field	Definitions
Magic Number	Unique 8-bit value used to reference a valid image type. 0xA3 = SBL, 0xAF = PATCH, 0xC0 = MAIN, 0xCC = CHILD, 0xCB = NONSECURE, 0xCF = INFO0
BLOB Size	Size of the image blob body (in bytes)
A	Ambiq Owned (Determines the restrictions on the magic#, and the keys to use for Authentication/ Encryption)
CRC Checksum	CRC checksum signature for the image. CRC is computed over the **CRC** region marked on the decrypted blob.
CC	Contains embedded Content Cert
A_{IN}	Install-Authenticate enable bit - If '1', the image must be authenticated on installation.
C_{IN}	Install-CRC enable bit - If '1', the image must be CRC verified on installation.
E_{IN}	Install-Decryption enable bit - If '1', the image must be decrypted on installation.
KEK Indx	Key-Encryption-Key Index. This index specifies which KEK should be used within the KEK bank for all key unwrap functions MSB indicates if it is a predefined key, or from key bank. Key bank keys are indexed in 128b increment.
Enc Algo	Encryption Algorithm - specifies which algorithm is to be used for decrypting the image. 0: N/A 1: AES-128 CTR others: not supported
Auth Key Indx	Authentication Key Index. This index specifies which authentication key should be used within the Auth Key bank for authentication of this image. Only three values are supported right now, which will be the PK of the existing Cert chain.
Auth Algo	Authentication Algorithm. Specifies which algorithm is to be used for authenticating the image. 0: N/A 1: RSA3072 others: not supported
Signature	384B RSA3072 signature of the Install Blob following.
128-bit IV	128-bit Initialization Vector used for seeding the encryption/decryption of the image.
$\{128\text{-bit Key}_{ENC}\}^{KEK}$	128-bit KEK wrapped encryption key.
Load Address	Specifies the address where the image is to be installed (applicable to OTA only).
OPT*	Optional parameters (depends on Magic #).

Table 3-1: Common Field Definitions *(Continued)*

Field	Definitions
Magic Number	Unique 8-bit value used to reference a valid image type. 0xA3 = SBL, 0xAC = ICV_Chain Update, 0xAF = PATCH 0xAE = ICV_KeyRevoke, 0xC0 = Secure-Firmware, 0xCC = OEM_Chain, 0xCB = NONSECURE Firmware, 0xCD = Download (Wired), 0xCE = OEM_KeyRevoke, 0xCF = INFO0
BLOB Size	Size of the image blob body (in bytes)
A	Ambiq Owned (Determines the restrictions on the magic number, and the keys to use for Authentication/Encryption)
CRC Checksum	CRC checksum signature for the image. CRC is computed over the "CRC" region marked on the blob.
CC	Contains embedded Content Cert
A_{IN}	Install-Authenticate enable bit - When "1", the image must be authenticated on installation
C_{IN}	Install-CRC enable bit - When "1", the image must be CRC verified on installation
E_{IN}	Install-Decryption enable bit - When "1", the image must be decrypted on installation
KEK Indx	Key-Encryption-Key Index - this index specifies which KEK should be used within the KEK bank for all key unwrap functions. MSB indicates if it is predefined key, or from keybank. Keybank keys are indexed in 128b increment.
Enc Algo	Encryption Algorithm - specifies which algorithm is to be used for decrypting the image 0: N/A 1: AES-128 CTR others: not supported
Auth Key Indx	Authentication Key Index - this index specifies which authentication key should be used within the Auth Key bank for Only three values supported right now, which will be the PK of the existing Cert chain.
Auth Algo	Authentication Algorithm - specifies which algorithm is to be used for authentication the image 0: N/A 1: RSA3072 others: not supported
Signature	384B RSA3072 signature of the Install Blob following
128-bit IV	128-bit Initialization Vector used for seeding the encryption/decryption of the image
$\{128\text{-bit Key}_{ENC}\}^{KKK}$	128-bit KEK wrapped encryption key
OPT*	Optional parameters (depends on Magic number)

3.2 Optional Field Definitions

Optional fields are interpreted based on the type of update (magic#).

Figure 3-5: Optional Field Definitions for Firmware Updates

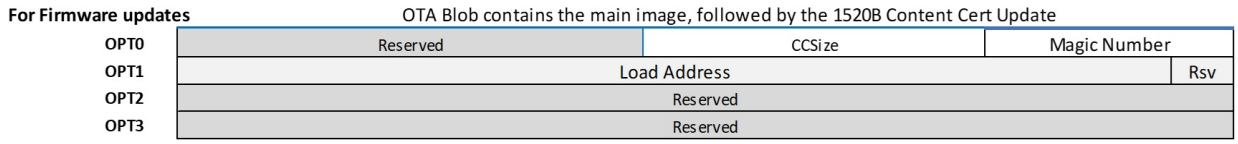


Table 3-2: Field Definitions for Firmware Updates

Field	Definitions
CCSize	Size of the bundled Content Certificate (only relevant if CC is set in W0).
Load Address	msb of Address to which the image should be installed.

Figure 3-6: Optional Field Definitions for INFO0 Update

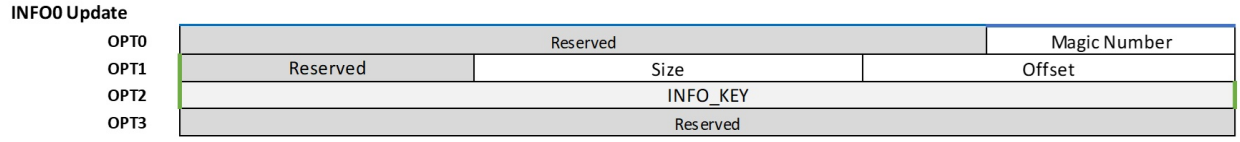


Table 3-3: Field Definitions for INFO0 Update

Field	Definitions
INFO_KEY	32-b key required for programming the INFO0.
Size	The size of the update.
Offset	The offset in the Infospace where the update needs to happen.

Figure 3-7: Optional Field Definitions for Patch Update

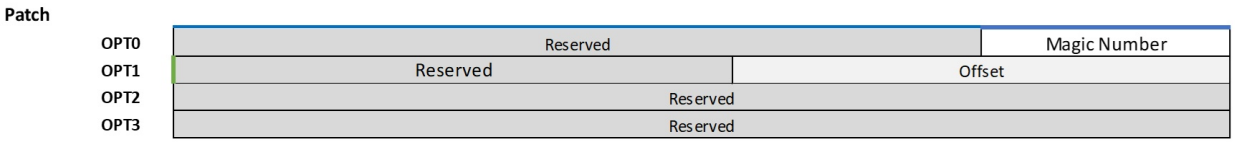


Table 3-4: Field Definitions for Patch Update

Field	Definitions
Offset	Specifies the offset of the patch function within the blob.

Figure 3-8: Optional Field Definitions for Wired Update

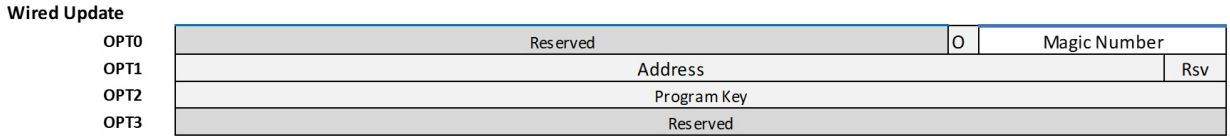


Table 3-5: Field Definitions for Wired Update

Field	Definitions
O	Implying an OTA process request.
Program Key	32-b key required for programming the MRAM (PROG_KEY)
Address	msb of Address in flash to load the image to

Figure 3-9: Optional Field Definitions for SBL Update

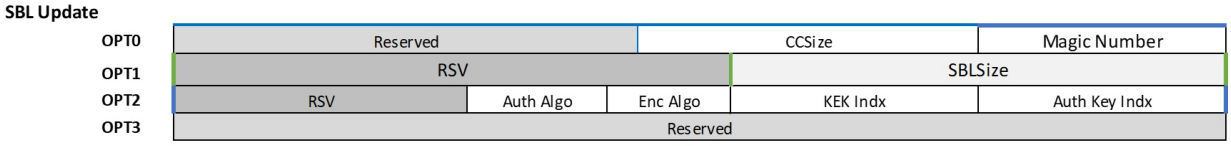


Table 3-6: Field Definitions for SBL Update

Field	Definitions
CCSize	Size of the bundled Content Certificates
SBL Size	Size of the SBL image at the staging area
KEK Indx	Key-Encryption-Key Index used for encrypting the SBL image. This index specifies which KEK should be used within the KEK bank for all key unwrap functions. MSB indicates if it is a predefined key, or from a key bank. Key bank keys are indexed in 128b increment.
Enc Algo	Encryption Algorithm. Specifies which algorithm is to be used for decrypting the SBL image. 0: N/A 1: AES-128 CTR others: not supported
Auth Key Indx	Authentication Key Index. This index specifies which authentication key should be used within the Auth Key bank for authentication of the SBL image. Only three values are supported right now, which will be the PK of the existing Cert chain.
Auth Algo	Authentication Algorithm. Specifies which algorithm is to be used for authentication on the SBL image. 0: N/A 1: RSA3072 others: not supported

Figure 3-10: Cert Chain Updates

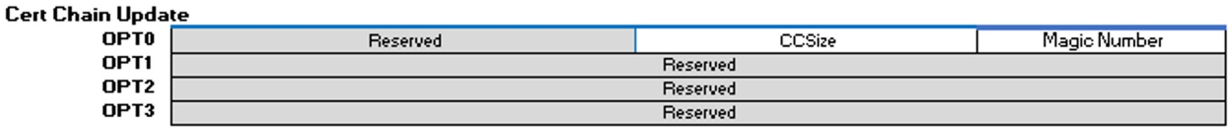


Table 3-7: Optional Field Definitions for Cert Chain Updates

Field	Definitions
CCSize	Size of the bundled Content Certificate

Figure 3-11: Optional Field Definitions for AES-128 CTR Updates

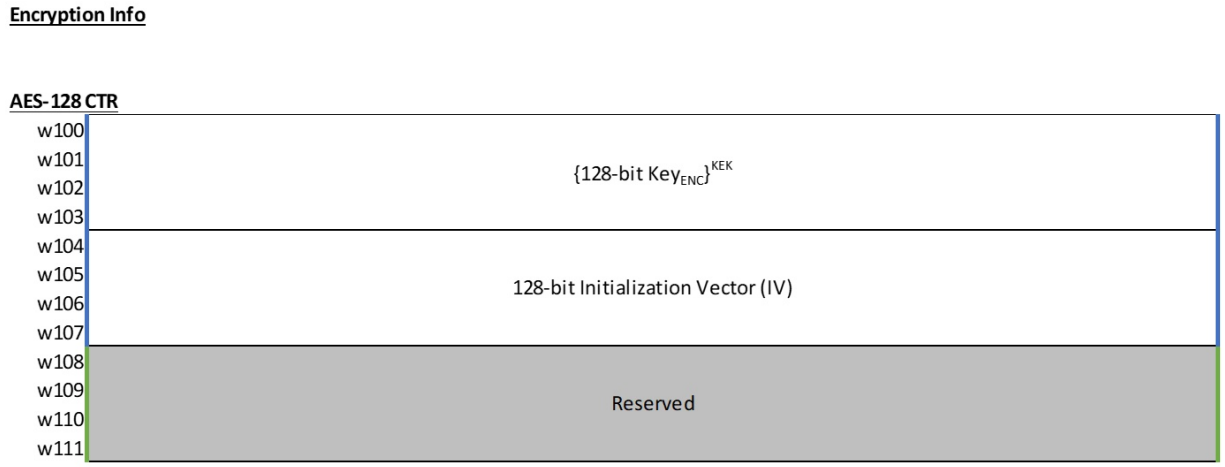


Table 3-8: Optional Field Definitions for AES-128 CTR Updates

Field	Definitions
128-bit IV	128-bit Initialization Vector used for seeding the encryption/decryption of the image.
{128-bit Key_{ENC}}^{KEK}	128-bit KEK wrapped encryption key.

SECTION

4

Secure Image Upgrade Flow

Apollo4 SoC supports a secure in-field image upgrade flow using the Secure Bootloader (SBL). The Secure Bootloader has access to the key storage in the OTP memory and can be used to optionally decrypt, authenticate and validate upgrade images before installing them. If configured so (based on the security policy configurations in OTP), only properly signed and protected images will be allowed in an update.

The Secure Bootloader can be used to securely update itself, the customer application image, or a customer secondary bootloader. The following sections lists out steps in the secure in-field image update flow.

4.1 Image Download

The In-Field upgrade process is initiated by a user application downloading an image blob to the MRAM. This part of the upgrade process is specific to individual deployment scenarios and the implementation is left to the customers. The Secure Upgrade framework does not mandate any specifics for this process. Depending on the deployment model, the image download could happen over traditional wired interfaces (e.g., I^2C, SPI, or UART), or wirelessly OTA (Over the Air) using BLE, or other wireless protocols. The Upgrade application running on Apollo4 SoC and its counterpart on the host/cloud side could implement their own protocol to ensure integrity, secrecy, and authenticity of the image blob itself.

4.2 OTA Descriptor and OTA Pointer

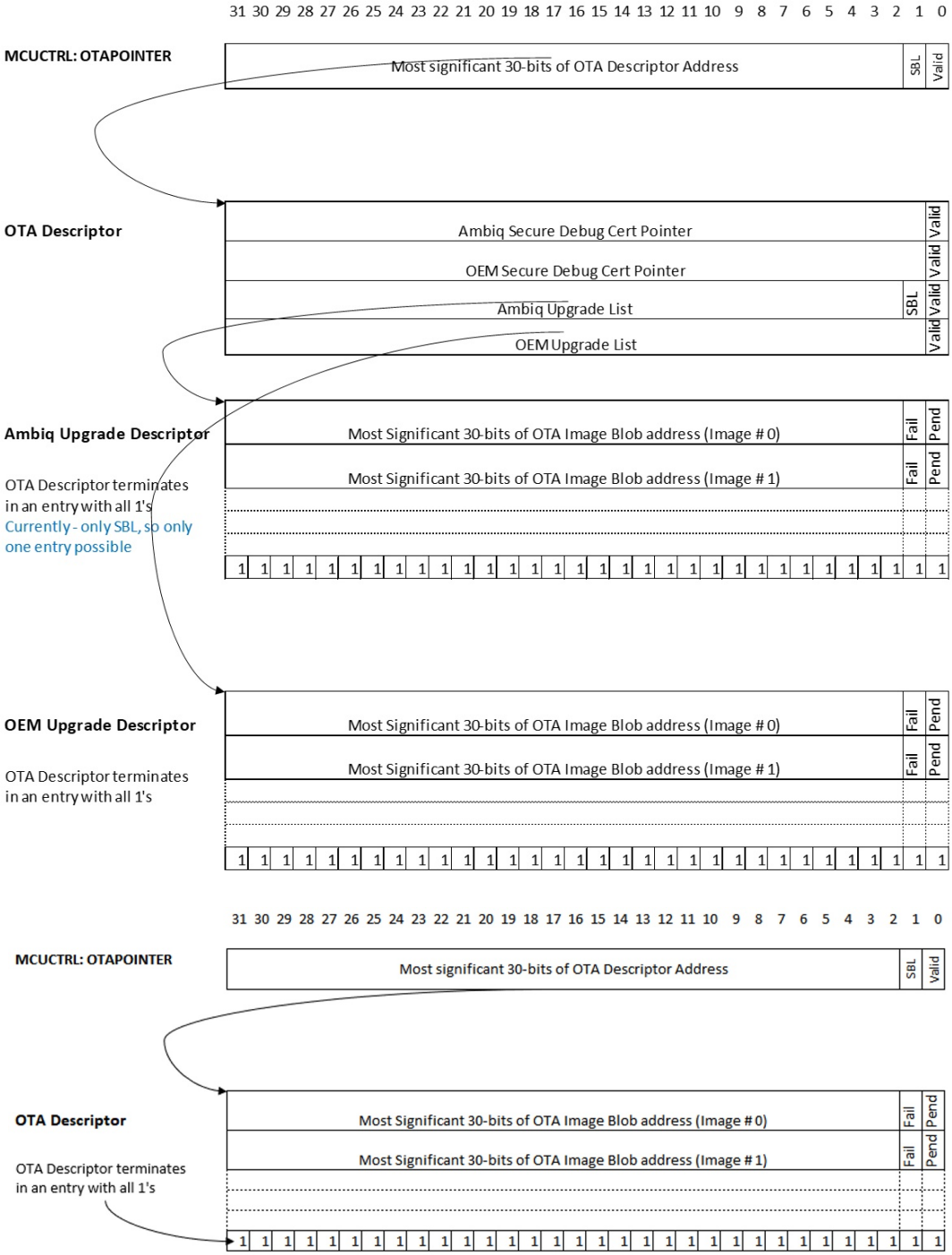
The customer application builds an OTA Descriptor containing the information about the upgrade image blob(s) corresponding to the update requests.

OTA Descriptor needs to be built in MRAM. The framework supports multiple updates in same operation. The OTA Descriptor consists of a list of upgrade image blobs, with a special End of

List Marker. This allows the upgrade application to update more than one images in one boot cycle. For example, the upgrade application could construct a single OTA Descriptor to upgrade main firmware as well as certain third-party library images located separately in the MRAM.

The download application communicates the OTA Descriptor information with the Secure Bootloader by initializing a special register, MCUCTRL:OTAPOINTER.

Figure 4-1: OTA Descriptor and OTA Pointer



OTAPOINTER will be initialized as follows:

- Most significant 30-bits will correspond to most significant 30-bits of OTA Descriptor.
- Least Significant bit (bit 0) should be initialized to 1 to indicate a valid OTA Descriptor.
- Bit 1 should be initialized to 1 if the list contains an SBL OTA.

The **OTA Descriptor** contains a list of entries, each corresponding to an OTA blob, list terminating in 0xFFFFFFFF. Each list entry word are comprised of following:

- Most significant 30-bits will correspond to most significant 30-bits of OTA blob pointer.
- Least Significant 2-bits should be initialized to '11' to indicate a valid OTA Pending.

Note that the OTA Image Blobs needs to be aligned at a 16-byte boundary to ensure that the encryption portion falls at 128b alignment (block size).

4.3 Reset

After accepting the required updates, the download application constructs the OTA Descriptor and initializes the **MCUCTRL:OTAPOINTER** register accordingly. The actual Update is only initiated on the next Reset, which kicks in the bootloader.

4.4 Upgrade Verification

As part of boot process, the SBL inspects **MCUCTRL:OTAPOINTER** for any updates to be processed. If present, each update blob is processed as per the configured security policy.

- The security policy can be configured (via OTP memory) to mandate Authentication to ensure only properly signed images will be accepted.
- The Secure Bootloader also supports encrypted image blobs, and the same can also be mandated by the security policy.

The SBL enforces the configured security policy and validates the image blobs against the security assets in OTP memory, and/or pre-installed certificate chain in the MRAM. After optional decryption and authentication, if the image is found to be good, the SBL then proceeds with installation of the image. In the case of secure firmware upgrade, SBL also verifies the bundled content certificate update, and installs the new content certificate along with the new image, only if the content certificate checks out (which implies all the images in the content certificate need to match up, if there are more than one).

4.5 Installation

A validated OTA image is installed to its designated place by the Secure Bootloader.

4.6 Feedback

The OTA flow also allows for a feedback to the user application using the same OTA Descriptor to communicate the OTA status of individual images, back to the initiating application. This is accomplished using the same OTA Descriptor.

- General OTA descriptor errors are communicated back to the application using the high order bits in the **MCUCTRL:OTAPOINTER** register. Details can be found in **am_hal_secure_ota.h**.
- After the Secure Bootloader processes an OTA, it clears the least significant bit (bit 0).
  - Bit 1 indicates the status of the OTA: 0 for Success, 1 for Failure
    - Some of the higher order bits of the Upgrade Descriptor are used to return failure cause. Details can be found in **am_hal_secure_ota.h**.
  - If Bit 0 is still set to 1 (Pending) after the OTA, this implies some other error (e.g., invalid or improperly formed OTA descriptor list) caused SBL to not process this OTA. The OTA can be retried after clearing the issue.

SECTION

5

Wired Update Flow

Apollo4 SBL provides support for an external host to connect during bootup to upgrade images, or to recover a failing device. Essentially, the SBL proxies as the “download application” for the Update process, if required. SBL initiates Recovery if any of the boot time validations fail, or if there is no valid image to boot to. In addition, there is an Override feature (configurable through OTP), which allows a forced image upgrade to be initiated using specific GPIO settings during the boot up.

The SBL uses the OTP configuration to determine the interfaces to examine (see **OTP_SEC_WIRED:IFC**). It first looks for UART connection, then the IOS connection of either SPI then I^2C (these are mutually exclusive). The UART connection is associated with the timeout (see **OTP_SEC_WIRED_UART: TIMEOUT**), while the SBL waits for the initial HELLO packet from the Host. The IOS interface is polled and the SBL uses the Slave Interrupt pin (see **SEC_WIRED: SLVINTPIN**), to indicate to the host that it is ready to receive packets. In this case, it only waits for a fixed timeout of 500 msec before exiting the update process.

In all cases, an external host needs to follow a predefined messaging protocol to instruct SBL to upgrade assets on the device. Figure 5-1 on page 24 illustrates a high level message exchange to initiate an “upgrade” using prevalent security policies of the device when using the UART. In this case, the **DATA** packets are sent as up to 8KB packets. The process starts with a **HELLO/ STATUS** exchange within the timeout period. It ends with the **RESET/ACK** exchange which sends the SBL into SWPOR or SWPOI reset.

Figure 5-1: Message Exchange Using Prevalent Security Polices of Device

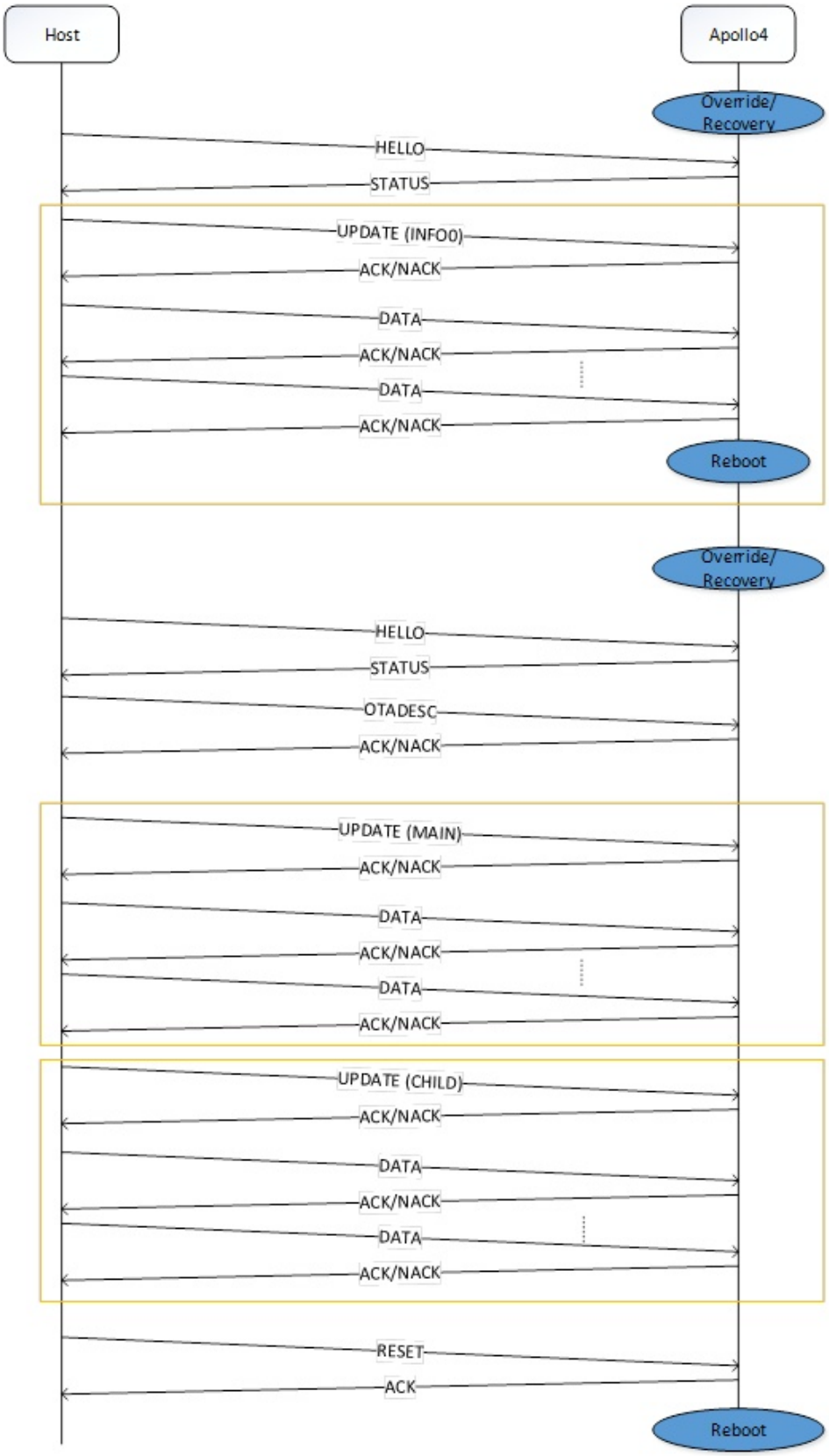


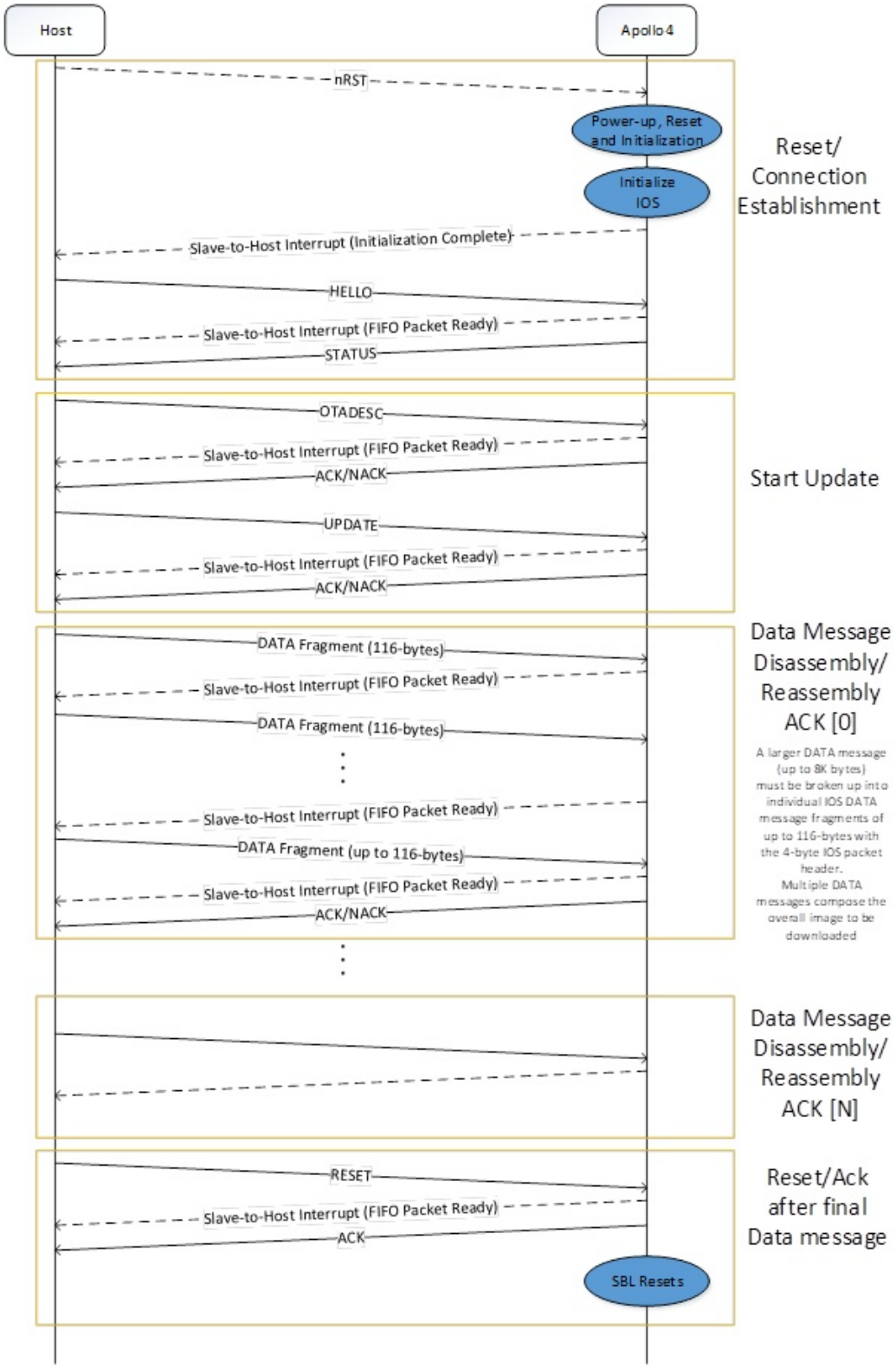
Figure 5-2 on page 26 shows the process for update/recovery when using the IOS as SPI or I^2C interface. The process starts with the Host resetting the Apollo4-Blue using nRST signal. Once initialization of the configured interface is complete, the SBL raises the Slave Interrupt pin to indicate it is ready to accept packets over the IOS Direct memory interface. All packets from the Host to the SBL are limited to 120 bytes due to the maximum LRAM memory size. This means the packets from the Host must be disassembled, and then reassembled by the SBL. Disassembly is done by adding a 32-bit header to each packet as follows:

```
typedef struct
{
      uint32_t length : 16;
      uint32_t resv : 14;
      uint32_t bEnd : 1;
      uint32_t bStart : 1;
} am_secboot_ios_pkthdr_t;
```

The start and end flags indicate the packets that represent the first and last of an original SBL wired protocol packet. The original packet data follows up to 116 bytes. The 116-byte Data Fragments compose an entire original DATA message and are stored by SBL up to 8KB. There is limited error checking except that the total bytes received must equal the length in the original message, or it will be rejected.

Note that because the FIFO mode is used for Slave to Host transfers, the message size limit is 1023 bytes so disassembly/reassembly is not required.

Figure 5-2: Process for Update/Recovery Using IOS as SPIC or I^{2}C Interface

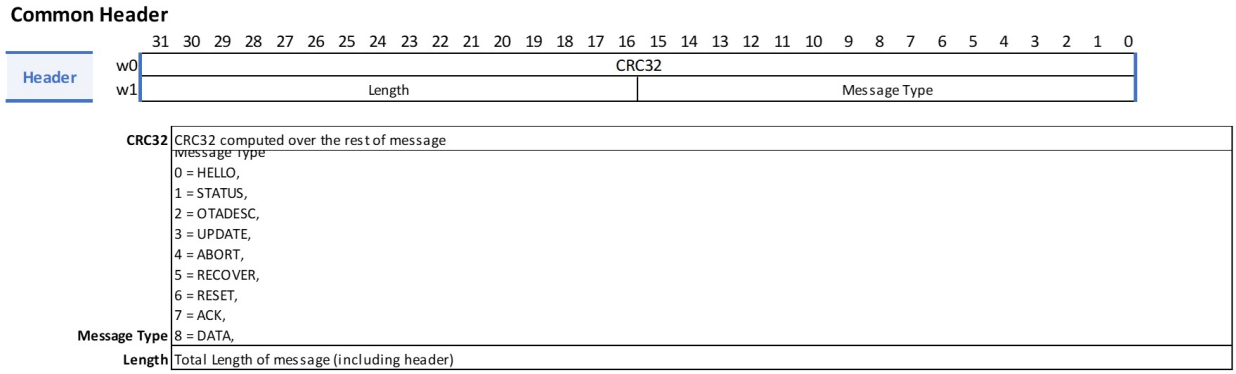


5.1 Wired Update Messages

All the message formats below assume little-endian byte order.

Each message starts with a common header which defines the following message type and length, along with a CRC for error checking.

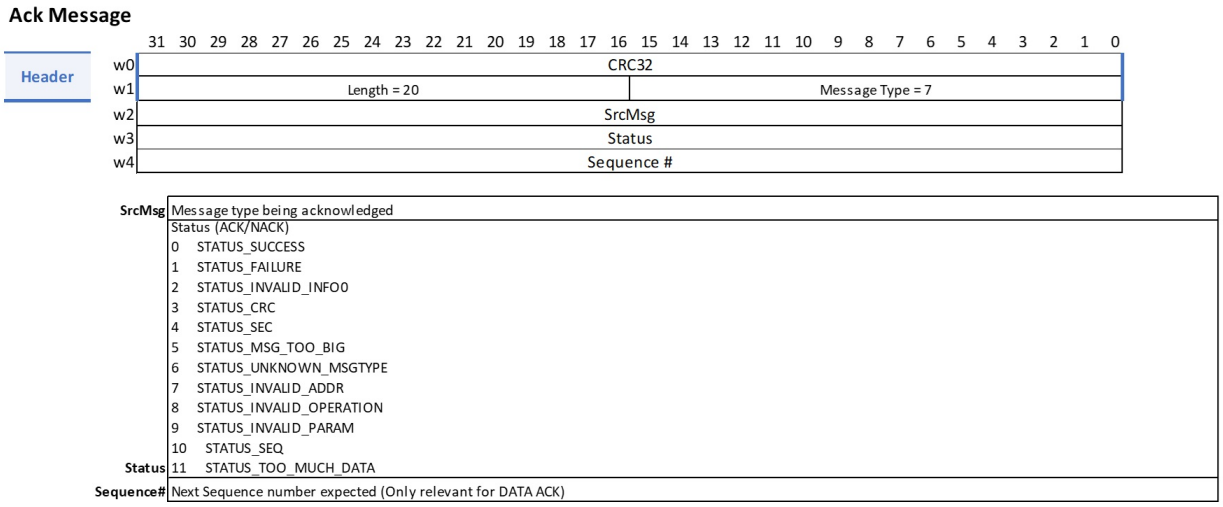
Figure 5-3: Wired Update Messages



5.1.1 Acknowledgment (ACK) Message

The SBL acknowledges most of the messages received using an ACK message (except for RECOVER, which is not acknowledged unless encountering a failure, and HELLO, which is acknowledged using STATUS message). Acknowledgments for DATA messages (described later), also include a sequence number, which can be used to implement a retransmission mechanism at host side if the connection medium is lossy.

Figure 5-4: Acknowledgment (ACK) Message



5.1.2 Connection Establishment (HELLO and STATUS) Messages

There is a initial handshake between the host and SBL, which can assist in determining the reason why SBL got into the wired update mode. A HELLO message is sent from host, to which the SBL responds with a STATUS message. The STATUS message also provides information about the largest size of the image blob that can be downloaded using SBL, along with other useful information about the device.

Figure 5-5: Connection Establishment (HELLO and STATUS) Messages

Hello Message

	31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
Header w0	CRC32	
w1	Length = 8	Message Type = 0

Status Message

	31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16	15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
Header w0	CRC32	
w1	Length = 88	Message Type = 1
w2	Version	
w3	Max Download Image Size	
w4	Current Status	
w5	Current State	
w6	ChipId0	
w7	ChipId1	
w8	SD Cert Location	
w9	Resv	
w10 w11 w12 w13 w14 w15 w16 w17	SOC ID	
w18 w19 w20 w21 w22 w23 w24 w25 w26 w27 w28 w29 w30 w31 w32 w33	AMInfo	

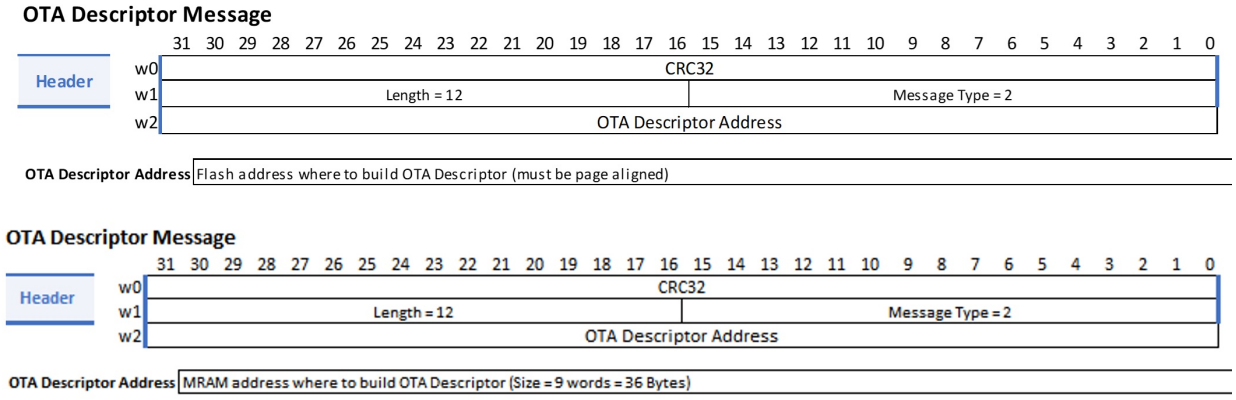
Version	Bootloader Version information
Max Image Size	Maximum size of blob that can be transferred using UPDATE command
Status	Current Boot Status
State	Current Bootloader state
ChipId0	Child Id 0 for the device
ChipId1	Child Id 0 for the device
SD Cert Location	Address at which the Secure Debug Cert needs to be loaded
SOC ID	256b SOCID for the device (Only valid if in Secure LCS)
AMInfo	Aux information - only for Ambiq usage

5.1.3 Secure Upgrade (OTADESC) Message

Upgrade for the firmware images using wired update undergoes the same secure OTA flow as applicable to wireless OTA. SBL just provides means to do wired download for the image blobs. So, in accordance, there are messages which instruct SBL to create an OTA Descriptor, followed by download of one or more image blobs (using UPDATE and DATA messages).

SBL reserves a fixed size in the MRAM starting at the specified address for the purpose of building the OTA Descriptor (to allow for up to 8 update images).

Figure 5-6: Secure Upgrade (OTADESC) Message

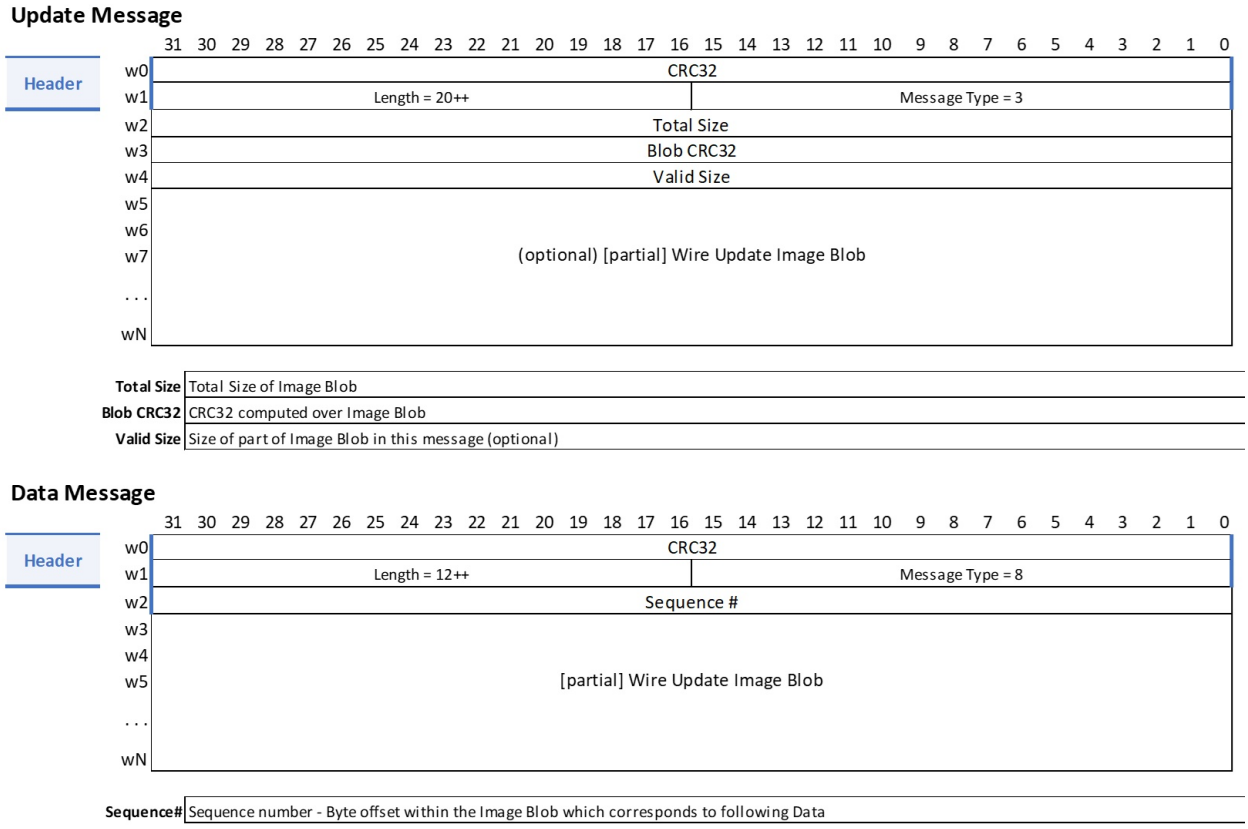


5.1.4 Wired Download (UPDATE and DATA) Messages

Any upgrade on the device comprises of an UPDATE message, which describes the nature and size of an upgrade. It also contains the required security information for verification of the image. The UPDATE message is then followed by zero or more DATA messages to send the actual image blob. After all the data is received, SBL verifies the integrity and validates per prevalent security policy.

To avoid corrupting existing MRAM space with corrupted downloads, the image blobs are downloaded to SRAM, and written to MRAM only after verification for integrity and authentication. This implies that individual wired downloads are limited in size based on the available SRAM. SBL only uses DTCM for this purpose, and the amount of available memory for this could be further reduced, if some part of the same is being reserved by the application (using INFO0). Bigger size blobs can still be transferred by splitting them accordingly.

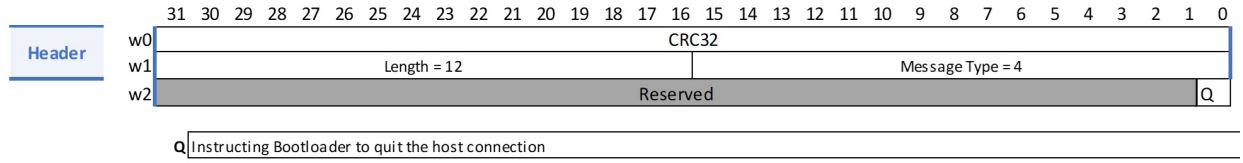
Figure 5-7: Wired Download (UPDATE and DATA) Messages



5.1.5 Termination (ABORT) Message

A Download in progress can be aborted using ABORT message. Host has a choice to continue the connection, or instruct SBL to quit the connection.

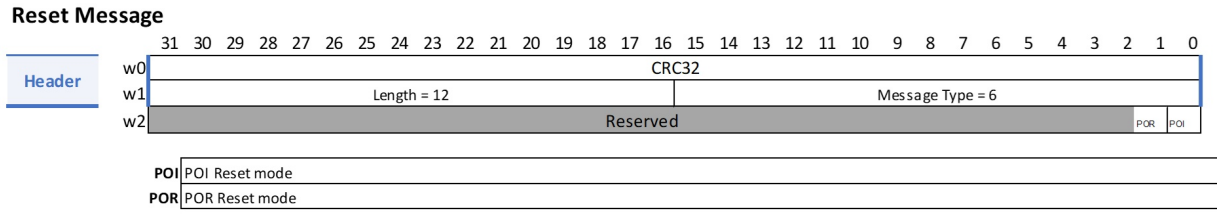
Figure 5-8: Termination (ABORT) Message



5.1.6 Reboot (RESET) Message

The Image blobs downloaded through UPDATE/DATA messages will have 'O' bit set to instruct SBL to schedule an OTA using the downloaded image. Multiple images can be combined together for the download step using this process. Actual Image upgrade is only initiated when a RESET message is received, as part of regular OTA processing by SBL.

Figure 5-9: Termination (ABORT) Message



SECTION

6

OEM Secondary Bootloader

Apollo4 Secure Boot/Update flow allows the provision to incorporate an OEM secondary bootloader. A secondary bootloader can be used to supplement the core capabilities of the native Apollo4 SBL. Potential reasoning for implementing one can be:

- Need to support different authentication/encryption algorithms
- Need to support external memory device
- Other vendor specific enhancements

For designs incorporating a secondary bootloader, the latter replaces the OEM's main image. SBL treats the secondary bootloader as the main image and verifies/updates the same using native boot/update flow. The secondary bootloader can then implement the additional features before passing control to the OEM's main application image.

6.1 Device Programming Considerations for Secondary Bootloader

There are certain considerations while OEM programming a design with a secondary bootloader.

- Ensure **OTP_SECURITY:PLONEXIT** field is set to 1 during OEM provisioning in DM LCS.
  - Ensures OTP key bank will remain accessible to be used for image verification purposes.
  - Allows Secondary bootloader to implement page lockouts for Read/Write protection by clearing additional bits in the **MCUCTRL:FLASHWPROT*** and **MCUCTRL:FLASHRPROT*** words.

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6500 River Place Boulevard, Building 7, Suite 200, Austin, TX 78730
www.ambiq.com
sales@ambiq.com
+1 (512) 879-2850

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