SPECIFICATION

UWB FiRa Protocol

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Contents

1 Glossary

ADC
Analog Digital Converter

AEAD
Authenticated Encryption with Associated Data

AES
Advanced Encryption Standard

AoA
Angle of Arrival

AIDL
Android Interface Definition Language

AOSP
Android Open Source Project

APDU
Application Protocol Data Unit

API
Application Programming Interface

BPRF
Base Pulse Repetition Frequency

CAP
Contention Access Period

CCC
Car Connectivity Consortium

CCM
Counter with Cipher Block Chaining Message Authentication Code

CFO
Clock Frequency Offset

CFP
Contention Free Period

CIR
Channel Impulse Response

CM
Control Message

CMAC
Cipher-Based Message Authentication Code

CRUM
Control Update Message

DL-TDoA
Downlink TDoA

DPF
Data Packet Format

DRBG
Deterministic Random Bit Generator

DS
Device Specific

DS-TWR
Double-Sided Two-Way Ranging

DTM
Downlink TDoA Message

DUT
Device Under Test

ECB
Electronic Code Book

EVB
Evaluation Board

FBS
FiRa Based Session

FoM
Figure of Merit

FP
First Path

GID
Group IDentifier

GPIO
General Purpose Input Output

HAL
Hardware Abstraction Layer

HIE
Header Information Element

HPRF
High Pulse Repetition Frequency

I2C
Inter-Integrated Circuit

IE
Information Element

IFI
Inter-Frame-Interval

IFI_GT
Inter-Frame-Interval Guard Time

IFI_BGT
Inter-Frame-Interval Block Guard Time

KDF
Key Derivation Function

HUS
Hybrid UWB Scheduling

L1
Layer One

LNA
Low Noise Amplifier

LLHW
Low Level Hardware

LUT
Lookup Table

LO
Local Oscillator

IV
Initialization Vector

MAC
Medium Access Control

MCU
MicroController Unit

MHR
MAC Header

MRM
Measurement Report Message

MRP
Measurement Report Phase

MTI
Moving Target Indicator

NA
Not Applicable

NL
NetLink

NONCE
Number used Once

OID
Opcode IDentifier

OOB
Out-Of-Band

OUI
Organizationally Unique Identifier

OWR
One-Way Ranging

PA
Power Amplifier

PDoA
Phase Difference of Arrival

PHR
Physical Layer Header

PHY
Physical Layer

PIE
Payload Information Element

PRF
Pulse Repetition Frequency

PSDU
PHY Service Data Unit

PSR
Preamble Symbol Repetitions

RAM
Random Access Memory

RCP
Ranging Control Phase

RDS
Ranging Data Set

RFFE
Radio Frequency Front End

RFM
Ranging Final Message

RFP
Ranging Final Phase

RFRAME
Ranging Frame

RFU
Reserved for Future Use

RIM
Ranging Initiation Message

RIP
Ranging Initiation Phase

RP
Ranging Phase

RRM
Ranging Response Message

RRP
Ranging Response Phase

RRRM
Ranging Result Report Message

RSL
Received Signal Level

RSSI
Received Signal Strength Indicator

S1
ACPI power state corresponding to CPU Idle

S3
ACPI power state corresponding to suspend to RAM

Sample
One complex value from CIR array

SE
Secure Element

SHR
Synchronization Header

SIP
System In a Package

SNR
Signal to Noise Ratio

SOC
System On a Chip

SPI
Serial Peripheral Interface

SS-TWR
Single-Sided Two-Way Ranging

STS
Scrambled Timestamp Sequence

SUS
Secure UWB Service

SYNC
Synchronization Preamble Sequence

TDoA
Time Difference of Arrival

TLV
Type Length Value

ToA
Time of Arrival

ToF
Time of Flight

TWR
Two Way Ranging

UCI
UWB Subsystem Command Interface

UL-TDoA
Uplink TDoA

UWB
Ultra-Wide Band

UWBS
Ultra Wide-Band Subsystem

2 STS configurations

2.1 Overview

[IEE20b] introduces the concept of *STS* to authenticate the emitter of a frame, but it does not specifies how to authenticate and encrypt the content of the frame itself and how to make it change frame to frame. FiRa attempts to improve those points, and thus the security of the transactions, by regrouping the following two elements when it uses the concept of *STS* configurations:

- It specifies how to build the *STS* located in the *SHR* of a frame as described in [IEE20b]
- It specifies different mechanisms to guarantee the authenticity and confidentiality of the *HIE*/*PIE* parts of a frame.

Fig. 2.1 illustrates the interactions among the end-user and the software systems involved in a basic FiRa *TWR*.

The addition of the FiRa to the security of the exchanges is shown in the figure with the external attacker located to the right which is trying to eavesdrop the FiRa exchanges between the two authenticated participants. The encryption mechanisms brought by the FiRa *STS* configuration prevents this case.

The attacker might also try to replicate and inject *UWB* frames to perform man in-the-middle attack (a very common attack in *UWB* systems) where the unauthorized device shortens the expected distance between authenticated participants.

For more details about general *UWB* security mechanisms, please refer to general_functionalities/security/sts. For more details about FiRa *TWR* or *OWR* mechanisms and the frame exchanges they induce, please refer to *Two-Way Ranging (TWR)*.

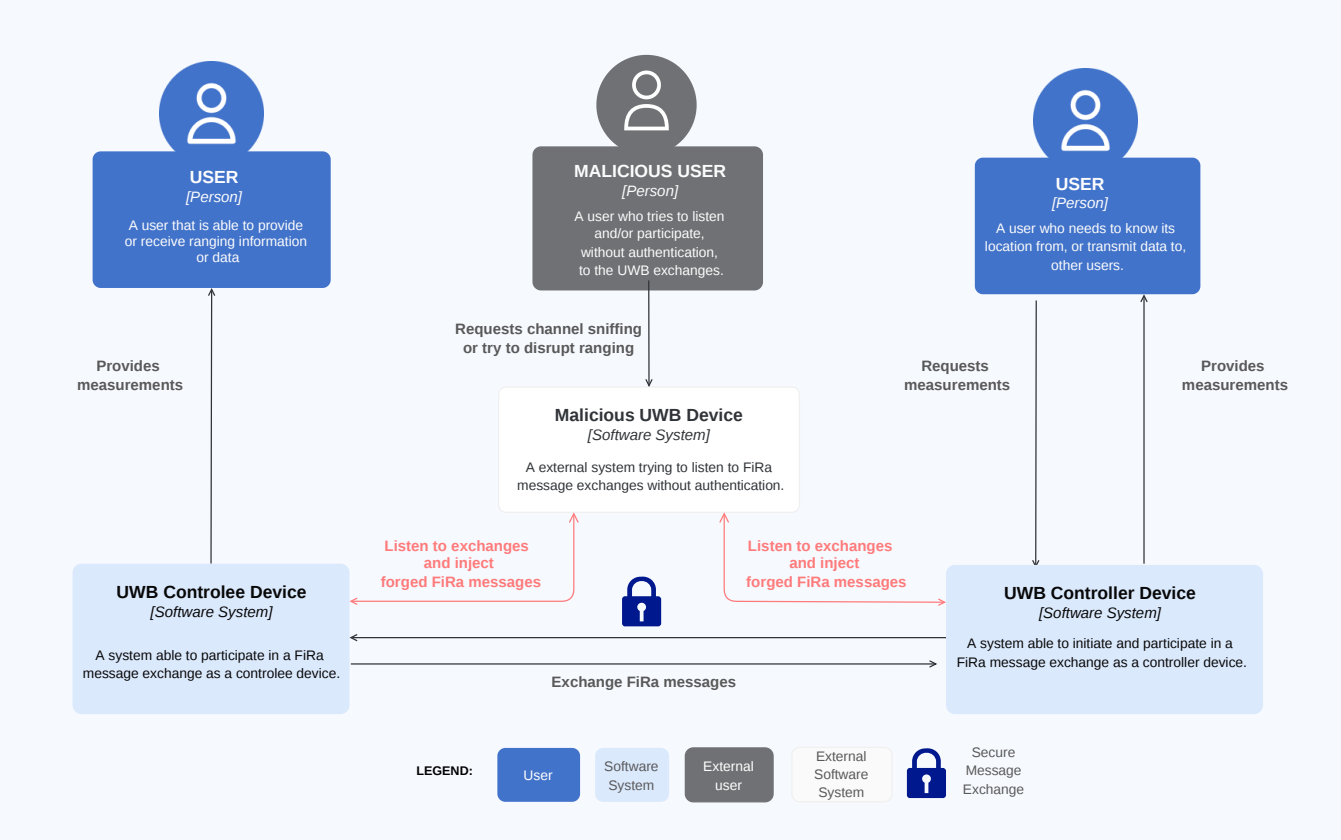

Fig. 2.1: FiRa *TWR* ranging system through context diagram

2.1.1 The different STS configurations specified by FiRa and supported by QM33.

FiRa has defined a set of standardized configurations that can be used to ensure different levels of protection against possible attacks. For *STS* generation, FiRa has defined a set of *AES* operations and crypto-derived materials used to provide *STS* variability by changing the 128b key and the 128b *IV* mentioned in general_functionalities/security/sts. The same set of cryptographic assets is used to perform *HIE*/*PIE* encryption and ensure slot synchronization between participants in a ranging session.

These specific *STS* configurations defined in [FiR23b] are:

Static *STS* (mandatory for any FiRa device)
: In this configuration, the system uses a pre-known static set of cryptographic assets for all participants and does not feature anti-rollback mechanisms neither strong encryption. This *STS* configuration is not considered secured and shall not be used for sensitive operations, but it allows a fast implementation and an immediate time synchronization.

Provisioned *STS*
: This configuration does not mandate the negotiation of cryptographic assets through a secured *OOB* channel, neither the direct connection between the *UWBS* and *SE*. The cryptographic keys are provided through *UCI* parameters. This *STS* configuration is considered as secure.

Provisioned *STS* with Responder-specific sub-session key
: This configuration shares the same principles as the Provisioned *STS* but it mandates the use of different cryptographic keys for each participant. This *STS* configuration is considered secured.

The *STS* configuration of a FiRa region shall be chosen depending on device capabilities and the desired level of security. This choice is usually made by an external system in charge of negotiating the session parameters. It

performs this operation through *OOB* communication and takes into account the level of security required by the service and the *STS* related capabilities of all the session participants.

2.2 Functional Description

2.2.1 STS configurations principles

Amongst the different *STS* configurations defined by FiRa (see *Overview*), the *UWBS* supports the following:

- Static *STS*
- Provisioned *STS*
- Provisioned *STS* with sub-session keys

In the following sections, some details about how the *STS* is handled by the stack are given. They shall be read in conjunction with [FiR23b] and [IEE20b].

2.2.1.1 Crypto assets management

In order to build *STS*, the *UWBS* uses three parameters, as explained in [IEE20b], that are needed by the *PHY* to trigger *STS* generation:

- `phyHrpUwbStsVUpper96`
- `phyHrpUwbStsVCounter`
- `phyHrpUwbStsKey`

However, the *PHY* chapter of this specification does not provide any information on how to compute those parameters and make them vary over time, this is left to protocol implementation.

In FiRa, those derivation mechanisms vary depending on the *STS* configuration. They are based on several crypto assets (keys, counters, etc.) which are computed during operation (Fig. 2.6 and Fig. 2.4 illustrate the computation of those assets in Provisioned *STS* and Static *STS* respectively). All the processes illustrated in those diagrams are performed by the *MAC* layer during the session starting phase or during controlee addition into the session if a sub-session has been requested. When these crypto assets are available and configuration is properly validated, the session is able to start.

Nevertheless, as each asset matches a specific purpose, if one of them fails during calculation, the remaining computation pipeline is aborted, the session is not started and the Host *UWB* service is informed.

2.2.1.1.1 Crypto keys

Amongst the needed crypto assets to build *STS*, there is several cryptographic keys that are described in the following sections.

2.2.1.1.2 SecSessionKey

It is an *AES* 128 bits or 256 bits key used to secure a *UWB* Session. It might be retrieved from different sources depending on the *STS* configuration chosen and it serves as a root key for all other crypto assets, hence, its confidentiality is vital if a secure approach is required.

2.2.1.1.3 SecDataProtectionKey

`secSessionKey` is never directly used in the key derivation process. Instead, an intermediate `secDataProtectionKey` is derived from it. This allows, for example, in certain *STS* configurations, to avoid storing the `secSessionKey` in the *UWBS*.

`secDataProtectionKey`, as shown in Fig. 2.2, is derived using the `CMAC-AES(secSessionKey, Counter|Label|Context|OutputLength)` function, where `Counter` is set to `0x01` or `0x02` depending on the iteration, `Label` is set to `DataPrtK` and `OutputLength` is set to either 128 or 256. `Context` is directly obtained from `configDigest`.

Note: `secDataProtectionKey` has the same length as the `secSessionKey`. If a 256 bits `secSessionKey` key is used, then two *KDF* iterations are required and the results are concatenated into one output key.

2.2.1.1.4 SecDataPrivacyKey

`secDataPrivacyKey` is obtained using the `CMAC-AES(secSessionKey, Counter|Label|Context|OutputLength)` function, where `Counter` is set to `0x01`, `Label` is set to `PrivacyK` and `OutputLength` is set to 128. `Context` is the same as the one used for `secDataProtectionKey` derivation.

2.2.1.1.5 SecDerivedPayloadKey

`secDerivedPayloadKey` is derived using the `CMAC-AES(secDataProtectionKey, Counter|Label|Context|OutputLength)` function, where `Counter` is set to `0x01`, `Label` is set to `DerPaylK` and `OutputLength` is set to 128. `Context` is built by concatenating the 96 less significant bits of `configDigest` with `cryptoStsIndex`.

2.2.1.1.6 SecDerivedAuthenticationKey

`secDerivedAuthenticationKey` is derived using the `CMAC-AES(secDataProtectionKey, Counter|Label|Context|OutputLength)` function, where `Counter` is set to `0x01`, `Label` is set to `DataAuthK` and `OutputLength` is set to 128. `Context` is the same as the one used for `secDerivedPayloadKey`.

2.2.1.1.7 SecDerivedAuthenticationIV

`secDerivedAuthenticationIV` is derived using the `CMAC-AES(secDataProtectionKey, Counter|Label|Context|OutputLength)`, where `Counter` is set to `0x01`, `Label` is set to `DerAuthI` and `OutputLength` is set to 128. `Context` is the same as the one used for `secDerivedPayloadKey` and `secDerivedAuthenticationKey`.

Note: Derived keys are updated either in a per-session or per-rotation increment basis depending on the chosen *STS* configuration. The update basis and the element impacted can be seen in Fig. 2.6 Refer to *Key Rotation* for more details.

2.2.1.1.8 FiRa key derivation function

Diving into the key derivation process, the first step is to take a closer look at the *FiRa key derivation function* widely used in the calculation pipeline of both Fig. 2.6 and and Fig. 2.4. Fig. 2.2 shows an operation block where *CMAC* is used as the underlying cryptographic primitive ([NIS05]) with *AES* as the block cipher ([NIS01a]). It features:

- 32 bits Counter: Its starting value is set to `0x00000001` and it is incremented by one for each *CMAC-AES* operation. If a 256 bits derived key needs to be obtained as output, two iterations are needed and the results are concatenated.
- 64 bits Label: Identifies the purpose of the derived key.
- 128 bits Context: Links the derived key to a specific session.
- 32 bits Output length: It defines the length of the derived key.
- 128 bits or 256 bits Root key: The key for the *CMAC* algorithm.

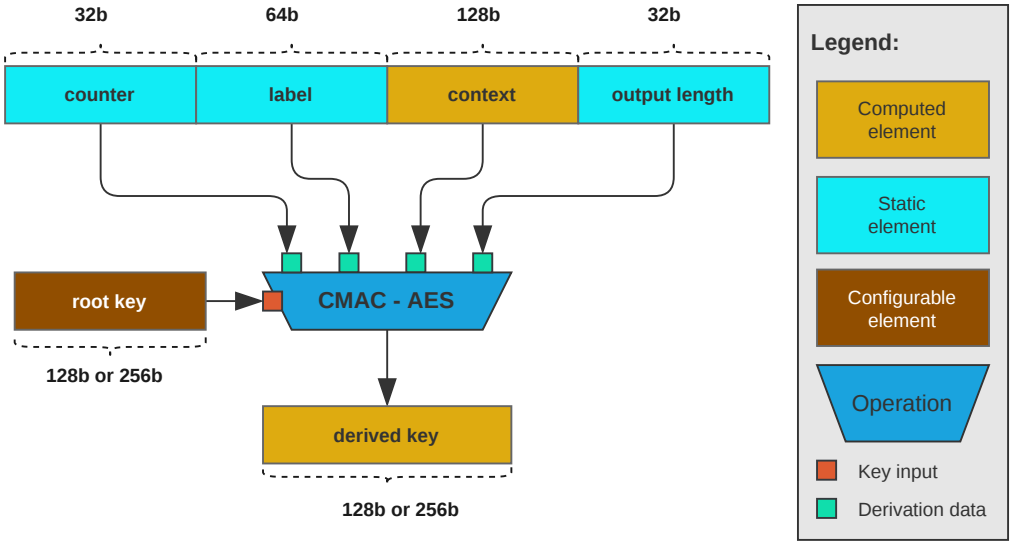

Fig. 2.2: FiRa Key Derivation Function

For more information about the key derivation process, please refer to [NIS09].

2.2.1.1.9 ConfigDigest

Disregarding the session, the *Host Application* shall provide a valid session configuration to the *UWBS* to enable its start. As mentioned earlier, a 128 bits context is needed to link the derived crypto assets to a given session. This context is named `configDigest` and it is built using different element of the session configuration. This mechanism forbids, even in Static *STS*, two different sessions to deduce the same crypto assets.

To build this crypto asset, a 17 bytes vector is built from the following list of concatenated configuration parameters. Strictly in the given order:

- `RANGING_ROUND_USAGE`: 1 byte
- `STS_CONFIG`: 1 byte
- `MULTI_NODE_MODE`: 1 byte
- `CHANNEL_NUMBER`: 1 byte

- SLOT_DURATION: 2 byte
- MAC_FCS_TYPE: 1 byte
- RFRAME_CONFIG: 1 byte
- PREAMBLE_CODE_INDEX: 1 byte
- SFD_ID: 1 byte
- PSDU_DATA_RATE: 1 byte
- PREAMBLE_DURATION: 1 byte
- CONSTANT = 0x03: 1 byte
- ID: 4 byte

Note: For non-slot-based ranging structures, SLOT_DURATION is set to 0x0000. For all other configurations, SLOT_DURATION is set to its value in microseconds.

Note: ID might represent either the session or the sub-session identifier depending on the *STS* configuration chosen.

Note: For multi-byte elements in the list, the most significant byte is placed first. Section D.2.1 in [FiR22] provides an example on how to build such a vector.

The 128 bits configDigest is finally obtained by applying the CMAC-AES(Key, Concatenated Parameters) function, where the Key is a 128 bits zero byte-string. configDigest is used during all other *CMAC-AES* operations as part of the context input parameter in the *KDF*.

2.2.1.1.10 Counters

2.2.1.1.11 PhyStsIndexInit

Going further in execution of the pipeline illustrated in Fig. 2.6 and Fig. 2.4, the phyStsIndexInit is computed using the CMAC-AES(secDataProtectionKey, Counter|Label|Context|OutputLength) function, where Counter is set to 0x01, Label is set to StsIndIn and OutputLength is set to 128.

2.2.1.1.12 PhyStsIndex

phyStsIndex is a 32 bits counter which initial value is initialized during the starting phase of the session with the result of the operation phyStsIndexInit & 0x7FFFFFFF. Then, during session execution, it is incremented by one after each slot and, as it is explained in *Slot Index Synchronization*, has a vital role in the slot time synchronization of controlees.

2.2.1.1.13 CryptoStsIndex

Similarly to `phyStsIndex`, `cryptoStsIndex` is another 32 bits counter used as part of the *NONCE* which is linking crypto assets to time during the life-span of a session providing replay protection. It mirrors `phyStsIndex` or `slotIndex` depending on the *STS* configuration.

Note: Derived counters are updated in a per-slot basis as shown by Fig. 2.6 and Fig. 2.4.

2.2.1.2 Frame protection mechanisms

Previous sections explained the computation of the different crypto assets needed to secure FiRa message exchanges. This section explains how to actually use them during an ongoing ranging session.

Explicit data contained in *UWB* frames shall be protected against eavesdropping. In the specific case of FiRa, the *MAC* layer is responsible for encrypting and authenticating different parts of the *PSDU*. In FiRa, while *PIE* encryption is mandatory, *HIE* encryption is optional and depends on the chosen *STS* configuration.

2.2.1.2.1 Authenticated Encryption with Associated Data

If a *PIE* is transmitted in the nested *IE*s field of the *UWB* frame, FiRa ensures confidentiality and authenticity by using *AES-CCM** as the underlying cryptographic primitive. *CCM** combines encryption, counter mode and authentication through variable-length authentication tags. After having encrypted the message, the *UWBS* concatenates both the cipher text and an encrypted 8-bytes authentication tag into the *PIE*s fields of the *MAC* payload.

As *AEAD* scheme is used, an Auxiliary Security Header (as described by section 9.4.2 in [IEE20a]) is included in the *MHR*. The required fields are set as follows:

- *Security Level* is set to `0b110` (`ENC-MIC-64`) as both encryption and 64 bits authentication tags are requested by FiRa.
- *Key Identifier Mode* is set to `0b00` as `secDerivedPayloadKey`, implicitly known by both parties, is used as an encryption key.
- *Frame Counter Suppression* is set to `0b1` as the frame counter is not directly carried in the *MHR* but it is set to the previously mentioned `cryptoStsIndex`.
- *ASN* is set to `0b0` as the *NONCE* is formed by concatenating `securityLevel`, `cryptoStsIndex` and `Source Address`:
  - `nonce[7:0]` is set to `0x06` (`ENC-MIC-64`).
  - `nonce[39:8]` is set to the `cryptoStsIndex` of the current frame.
  - `nonce[103:40]` is set to the corresponding extended-source-address of the device.

Note: If short-address is used instead of extended-address, most-significant-bytes of `nonce[103:40]` shall be padded with `0x00`.

Note: [IEE20a] and [NIS04] provide more details about *AES-CCM**.

2.2.1.2.2 Header IE Encryption/Decryption

To avoid a malicious agent to be able to track `phyStsIndex` as a simple incremental counter, some *STS* configurations require to encrypt FiRa *HIE*. When it is needed, this encryption is performed using an *AES*-*ECB* operation as described in [NIS01b] with `secPrivacyKey` as the encryption key and the concatenation of a known 64 bits padding field, `sessionId` and `phyStsIndex` as plaintext.

Note: To allow a non-synchronized device to decrypt *HIE* and retrieve `phyStsIndex`, `secPrivacyKey` does not change during the entire duration of the session.

2.2.1.2.3 MAC Payload Encryption bypass

While not compliant with FiRa protocol, *UWBS* provides a vendor-specific mechanism to avoid *AEAD* encryption on *PIE*s fields. Deactivating this encryption is achieved by setting the `UWB_STACK_MAC_ENCRYPTION_CONTROL` compilation flag.

2.2.1.2.4 Slot Index Synchronization

During FiRa ranging session using specific modes such as *TWR*, the Controller device is responsible for keeping track of time and to implement the necessary elements to enable the participants to synchronize with itself.

As explained in other chapters, FiRa divides the time into blocks, rounds, and slots, providing an incremental monotonic counter (also named `phyStsIndex`) to identify each slot during session's life-span.

Alongside FiRa's vendor *OUI* and session identifier, current `phyStsIndex` is broadcasted on each frame as part of FiRa *HIE*. Then, each controlee shall be able, using its own cryptographic secrets, to deduce `phyStsIndexInit` and, by using its session configuration, to calculate the current time. (2.1) illustrates this relation.

$$
\begin{aligned}
BlockIndex_i &= \lfloor \frac{AbsoluteSlotIndex_i}{SlotsPerBlock} \rfloor \\
RoundIndex_i &= \lfloor \frac{SlotInCurrentBlock_i}{SlotsPerRound} \rfloor \\
SlotIndex_i &= SlotInCurrentBlock_i \quad \% \quad SlotsPerRound \\
&\text{Where:} \\
SlotsPerBlock &= \lfloor \frac{BlockDuration}{SlotDuration} \rfloor \\
SlotInCurrentBlock_i &= AbsoluteSlotIndex_i \quad \% \quad SlotsPerBlock \\
AbsoluteSlotIndex_i &= PhyStsIndex_i - InitialPhyStsIndex \\
InitialPhyStsIndex &= PhyStsIndexInit \quad \& \quad 0x7FFFFFFF
\end{aligned}
\tag{2.1}
$$

2.2.1.2.5 STS Generation

The lower part of Fig. 2.6 and Fig. 2.4 shows the mapping between FiRa defined crypto assets (`cryptoStsIndex`, `phyVUpper64`, `secDerivedAuthenticationKey`, `secDerivedAuthenticationIV`) and the elements required by [IEE20b] (`phyHrpUwbStsVUpper96`, `phyHrpUwbStsVCounter` and `phyHrpUwbStsKey`) to build the *STS* of a frame.

During each `TX` or `RX` with a `SP1` or `SP3` frame, the *PHY* obtains the necessary seeds to perform its own *DRBG* and generate the expected sequence.

Note: *STS* variability is a fundamental aspect of a secure ranging protocol. The proposed FiRa configurations ensure different levels of variability frame-to-frame depending on the complexity of the use-case served by the *UWB* device.

2.2.2 Static STS

This chapter contains information about elements that are specific to the Static *STS*. Fig. 2.3 shows the container diagram for a *TWR* ranging session in Static *STS* between one Controller and one Controlee.

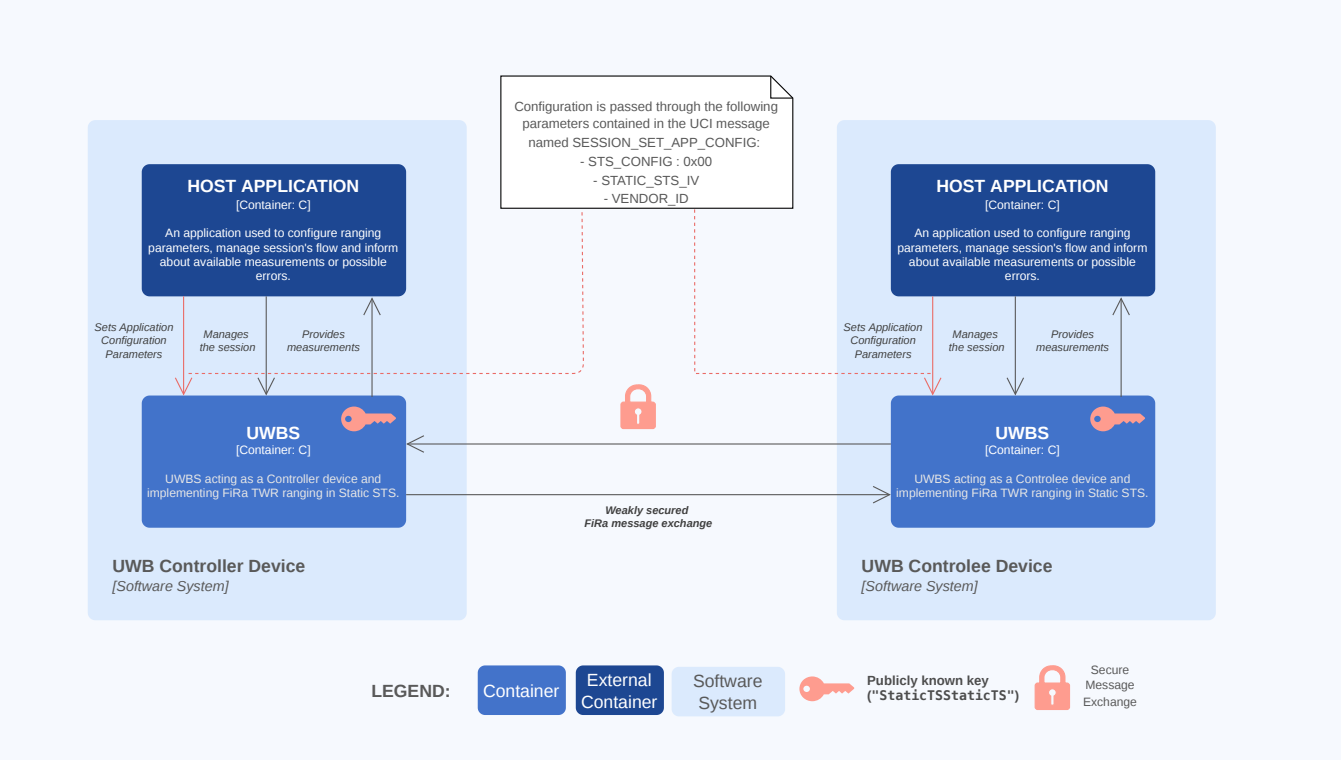

Fig. 2.3: Container Diagram for Static *STS*

Static is the simplest *STS* configuration, based on a publicly known `secSessionKey` and a group of crypto-derived materials that do not change during the whole session. This configuration is mandatory for those cases where prior knowledge of secrets is not possible or necessary. For example, in scenarios such as indoor navigation, scanning, information broadcast, or any other case where the exchanged data is not specifically considered sensitive.

Note: Some FiRa 2.x features, such as *DL-TDoA*, *UL-TDoA*, Contention-Based Ranging and *OWR* for *AoA* must use Static *STS*.

2.2.2.1 Crypto assets management

Static *STS* uses a simplified version of the key derivation pipeline previously described. These simplifications are illustrated in Fig. 2.4.

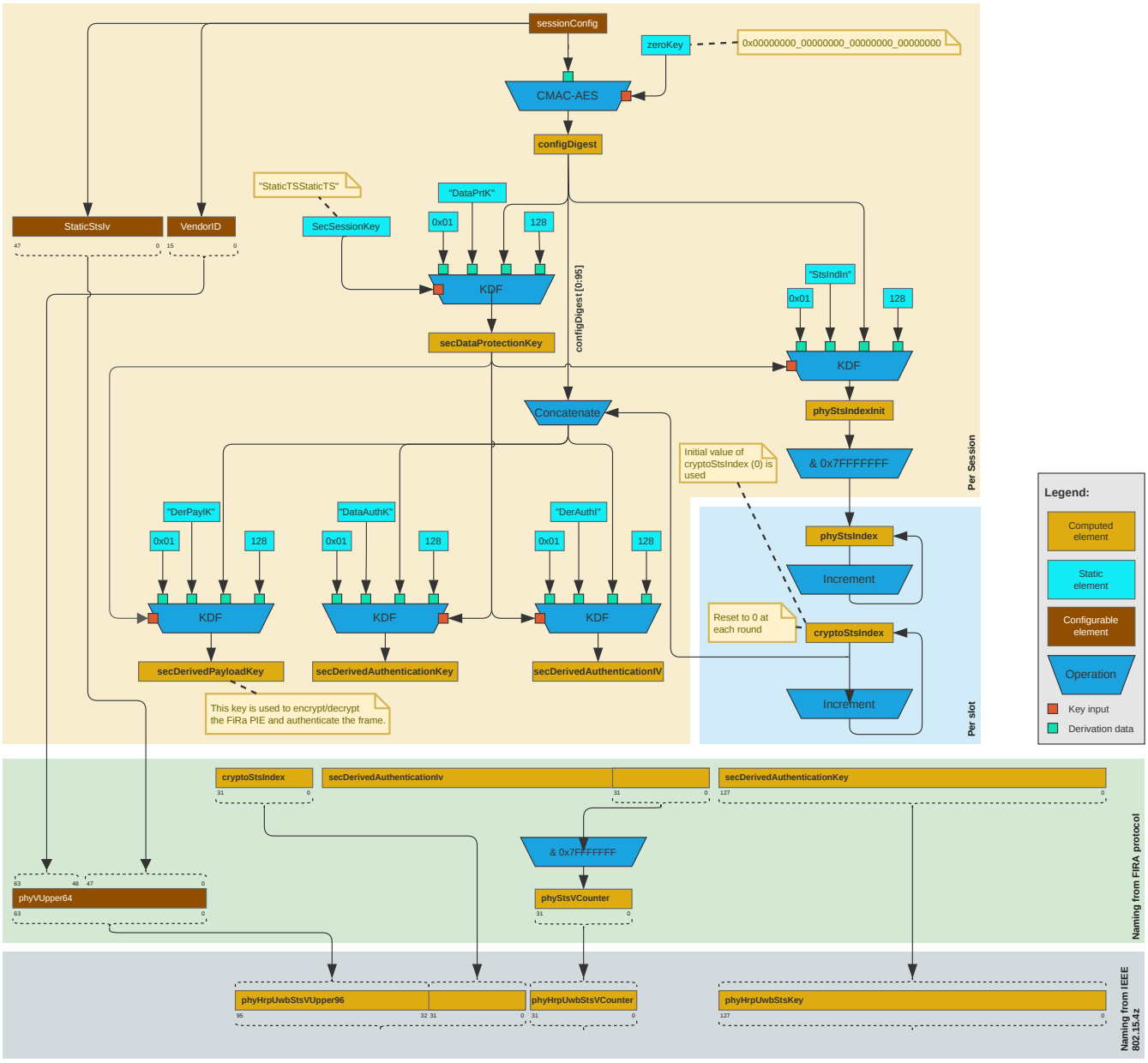

Fig. 2.4: Crypto assets computation pipeline for Static *STS*

2.2.2.1.1 Crypto keys

2.2.2.1.2 SecSessionKey

As shown in Fig. 2.4, the `SecSessionKey` in Static *STS* is publicly known and set to 128 bits string `StaticTSStaticTS`. This makes *Static* non-secure by design but allows for a simple and fast implementation.

2.2.2.1.3 Frame protection mechanisms

2.2.2.1.4 HIE and PIE Encryption/Decryption

In Static *STS*, only FiRa *PIE* is encrypted. *HIE* is transmitted as plaintext over the air. This allows any existing FiRa session to access current `phyStsIndex` and rapidly synchronize with the Controller device.

2.2.2.1.5 Slot Index Synchronization

Session slot synchronization is achieved by using the same mechanism explained in *Slot Index Synchronization*.

2.2.2.1.6 STS Generation

`phyVUpper64` is generated from the concatenation of `VendorId` and `StaticStsIv`, both set through *UCI* during session configuration. As these parameters are directly set by the application and agreed upon by *OOB*, they contribute to *STS* variability between two different sessions.

On the other hand, `cryptoStsIndex`, as part of `phyHrpUwbStsVUpper96`, takes its value from the current slot index; hence it is reset to `0x00` at the beginning of each round. This ensures that a different *STS* is generated inside each slot of the round, but not between different blocks of the same session.

2.2.2.2 Key Takeaways

To summarize, using a static *STS* has the following characteristics:

- The session key is publicly known.
- The same session key is used as a source to secure all the exchanges.
- Slot Index takes part in sequence generation and payload encryption, ensuring that a different *STS* can be generated at every slot of the round, but not providing block-to-block variability.
- Only *PIE* is encrypted, *HIE* is transmitted in plaintext.
- As key rotation is not supported, the same derived keys are used for the whole lifetime of the session, ensuring immediate resynchronization but compromising the overall confidentiality of crypto assets.
- Allows for low-cost and high-performance implementation.

2.2.3 Provisioned STS

This chapter contains information about elements that are specific to the Provisioned *STS*. Fig. 2.5 shows the container diagram for a *TWR* ranging session in Provisioned *STS* between one Controller and one Controlee.

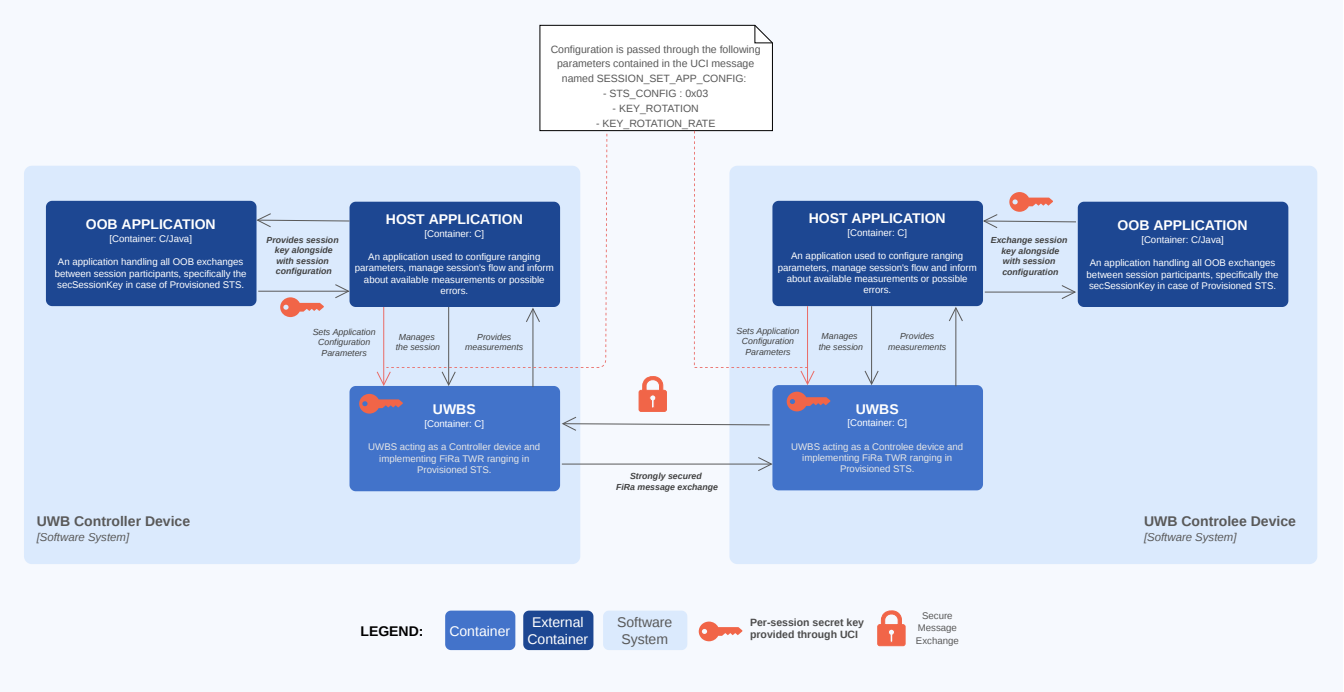

Fig. 2.5: Container Diagram for Provisioned *STS*

Apart from the *UWBS* device and the *Host Application* already mentioned in Static *STS* section, Fig. 2.5 also shows the *OOB* application handling *OOB* channels and providing session configuration. It also illustrates the session keys used to secure FiRa messages exchanges.

Note: *OOB* internal details and exchanges are out of the scope of this chapter so these are not shown in Fig. 2.5.

2.2.3.1 Crypto assets management

Provisioned *STS* uses a different version of the cryto assets computation pipeline previously described and is illustrated in Fig. 2.6.

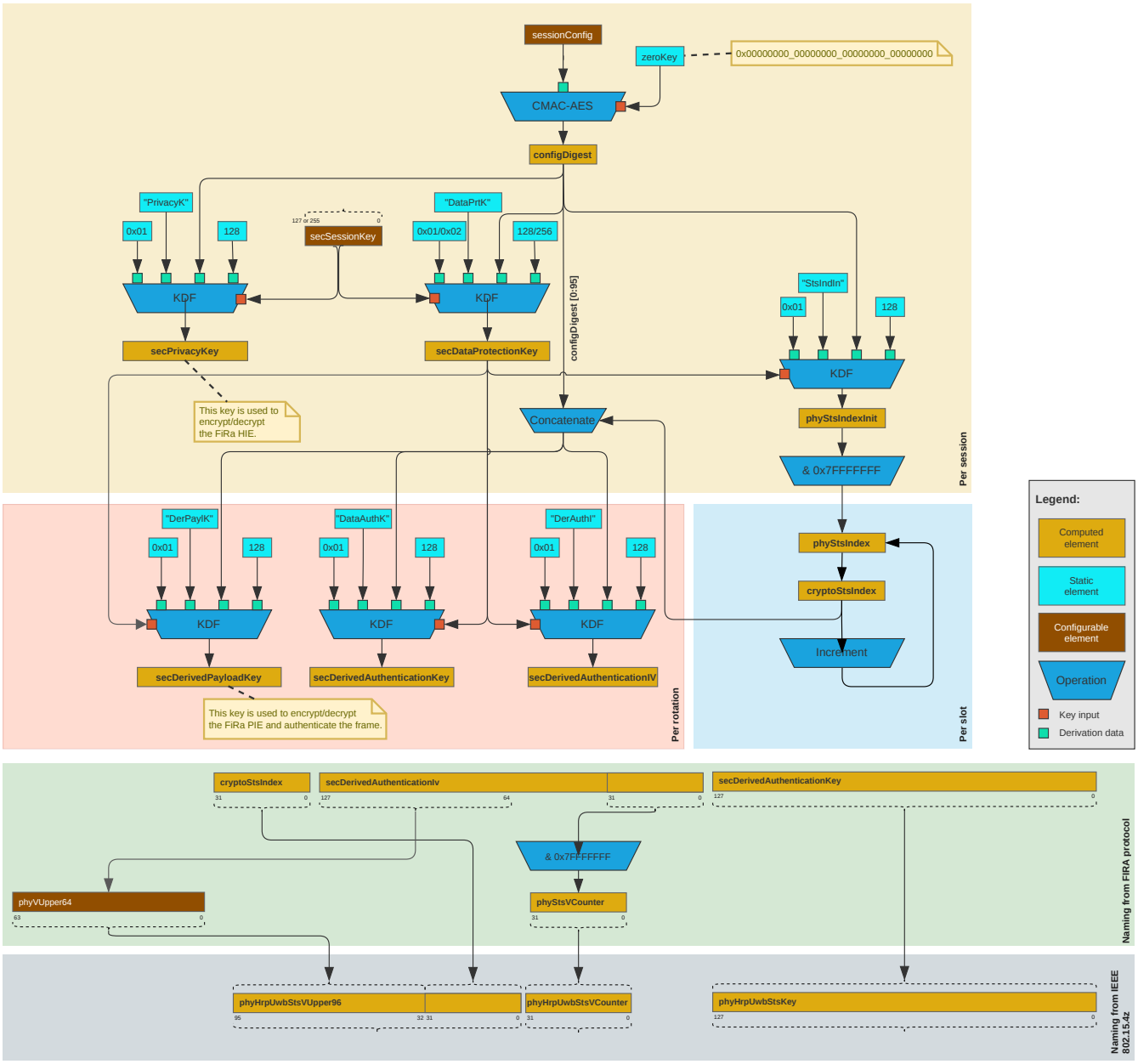

Fig. 2.6: Crypto assets computation pipeline for Provisioned *STS*

2.2.3.1.1 Crypto keys

2.2.3.1.2 SecSessionKey

`secSessionKey` is agreed upon during *OOB* exchanges and given to the *UWBS* in plaintext during session configuration phase. Two possible lengths are supported: 128 bits and 256 bits.

2.2.3.2 Frame Protection mechanisms

For all the following operations, `cryptoStsIndex` is taken from `phyStsIndex` instead from the current slot index as in Static *STS*.

2.2.3.2.1 Key Rotation

The set of cryptographic assets are expected to change at a given rate during the entire duration of the session, reducing the risk of side channel attacks. These assets are:

- `secDerivedPayloadKey`
- `secDerivedAuthenticationKey`
- `secDerivedAuthenticationIv`

Even though this key rotation procedure is required to be supported by Provisioned *STS*, its use is not mandatory. The session configuration allows to enable/disable it from application perspective and it allows to set the corresponding rotation rate:

- `KEY_ROTATION`, 1 byte: `0x00` to disable, `0x01` to enable [default: `0x00`].
- `KEY_ROTATION_RATE`, 1 byte: defining the `n` parameter [default: `0`].

A new set of keys are available every 2^n blocks and their *KDF*, according to Fig. 2.6, shall use `cryptoStsIndex` from the `phyStsIndex` value at the first slot of the block triggering the rotation.

2.2.3.2.2 HIE and PIE Encryption/Decryption

Alongside an encrypted *PIE*, Provisioned *STS* also encrypts *HIE*, ensuring `phyStsIndex` and `sessionId` are not transmitted in plaintext and are not easily identifiable over session lifetime as described in *Header IE Encryption/Decryption*.

Note: *HIE* encryption shall be performed before *AEAD* on *PIE*s fields, in other words, authentication tag shall be calculated on both encrypted *HIE* and *PIE*s.

2.2.3.2.3 STS Generation

STS generation in Provisioned *STS* follows exactly the same procedure as described in *STS Generation*. Instead of deducing `phyVUpper64` from session configuration, as in Static *STS*, its value is taken from the current state of the most significant 64 bits of `secDerivedAuthenticationIv`.

2.2.3.3 Key Takeaways

To summarize, using a provisioned *STS* has the following characteristics:

- `secSessionKey` is agreed upon during *OOB* exchanges.
- The same session key is used as a source to secure all the exchanges.
- `phyStsIndex` takes part in both *STS* generation and frame encryption.
- Both *PIE* and *HIE* are encrypted using different *AES* mechanisms.
- Key rotation of certain crypto assets is supported.

2.2.4 Provisioned STS with Sub-session Keys

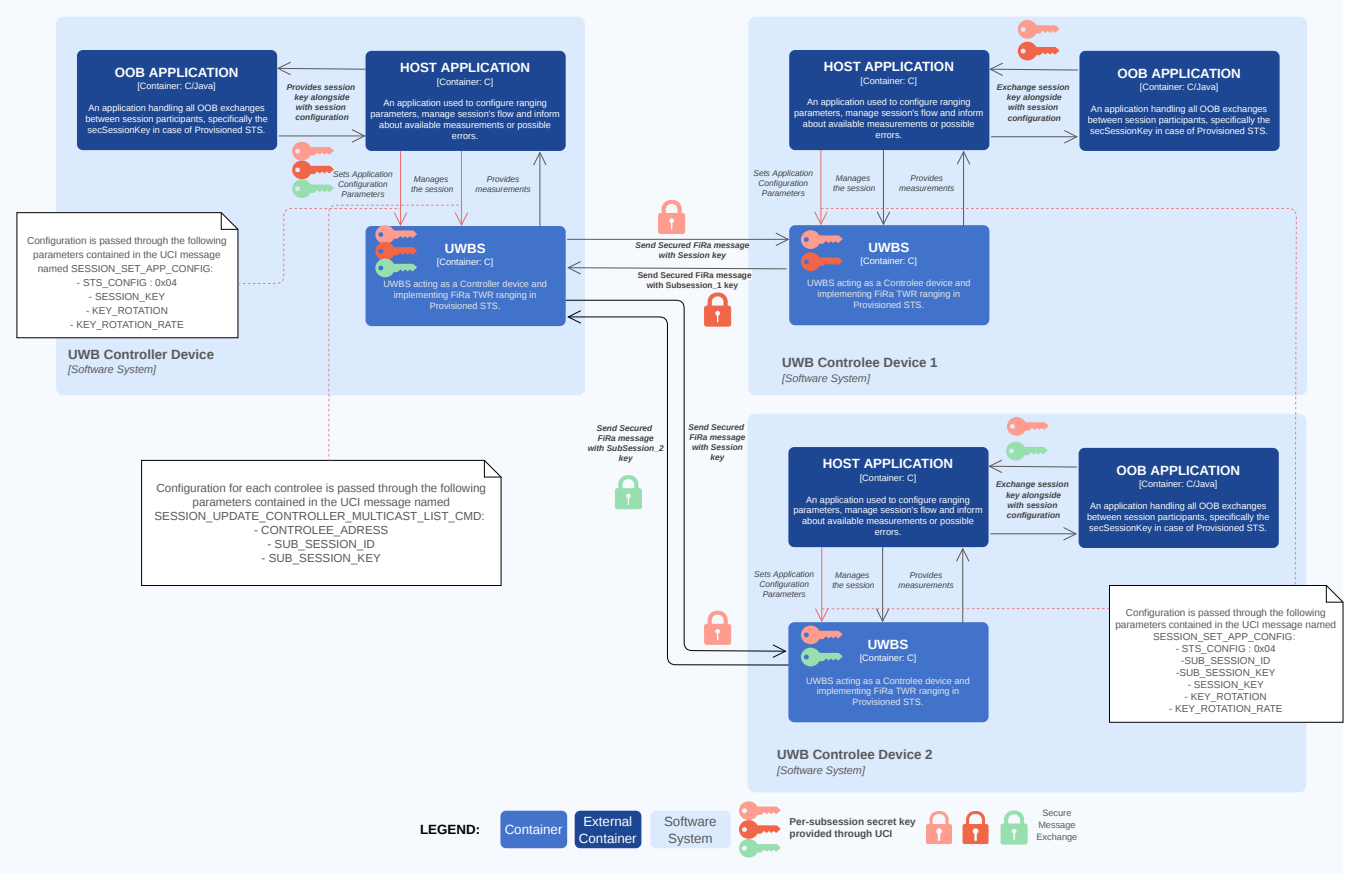

Fig. 2.7: Container Diagram for Provisioned *STS* for Responder Specific Sub-session Key

This *STS* configuration relies on the concept of sub-sessions. A FiRa session contains a set of cryptographically derived assets, all calculated from a root key and a group configuration parameters, including the session identifier. A sub-session symmetrically calculates its own set of assets from a sub-session key and a sub-session identifier. These secondary groups of derived keys are uniquely known by the Controlee defining the corresponding sub-session and the Controller device, helping to secure each link between two *UWB* devices in a *TWR* multicast ranging session.

2.2.4.1 Crypto assets management

2.2.4.1.1 Crypto keys

2.2.4.1.2 SecSessionKey

Depending on the chosen *STS* configuration, the `secSessionKey` follows the same rules as in Provisioned *STS* described in *Crypto assets management*.

2.2.4.2 Frame Protection mechanisms

As in Provisioned *STS*, frame protection procedures described in *Frame Protection mechanisms* still apply. Following FiRa ranging round structure in a *TWR* multicast session, all exchanges having the Controller as a source are secured with cryptographic assets derived from the session key. On the other hand, all exchanges having a specific Controlee as a source are secured with cryptographic assets derived from the corresponding sub-session key. This avoid a unintended Controlee to interfere, replay or eavesdrop on exchanges from other peers in the session. Fig. 2.7 illustrates this concept by having different root key for each exchange link.

2.2.4.3 Key Takeaways

This *STS* configuration inherits all the properties from Provisioned *STS* mentioned in this *section*. In addition, it also handles the problem of intra-session security between participants and features the following additional characteristics:

- Several keys are used to secure exchanges, each of them can either be configured through *UCI*.
- Exchanges having the Controller device as a source are secured with the `secSessionKey` as root key. Nevertheless, each Controlee uses its own `sub_session_key` to secure messages having the Controller device as destination.
- `phyStsIndex`, used for slot time synchronization, is individually derived from the corresponding key and used accordingly depending on the slot.
- As in Provisioned *STS*, key rotation is supported. In addition to crypto-derived assets coming from `secSessionKey`, the Controller device must rotate the ones coming from each `sub_session_key`.

3 FiRa Diagnostics

3.1 FiRa Diagnostics Overview

During FiRa ranging operation, the Qorvo UWB stack is able to gather various information about the received frames. This information can be considered as supplemental compared to the content of the standard range notification as it is not intended to be provided to upper layers.

The stack offers a feature named *diagnostics* allowing to surface this information when its FiRa ranging capability is used. This document describes the content of those diagnostics and how it shall be used.

3.2 Functional description

3.2.1 General description

By default, the FiRa region produces reports at the end of each round containing a summary of the measures it has been able to compute during the round. Those reports do not contain details about the frames exchanged during the round. The FiRa diagnostics feature of the Qorvo UWB Stack has been designed to solve this issue and to provide details about a round after its completion.

When activated, the stack stores additional information it gathers during the round. When the latter has been completed, it uses the stored information to produce a diagnostic report it attaches to the round. The diagnostic report is created disregarding the round validity status.

The diagnostics produced by the stack are composed of the following fields:

- **frame reports**: a set of different elements related to each frame exchanged during the round.

The diagnostic report is sent at the end of the ranging round, just after the standard ranging round report (`SESSION_INFO_NTF` *UCI* message). The session ID and sequence number of the round are included in the report to ease the correlation with the round.

The diagnostics can be activated through a FiRa session parameter. Parts of the report are also configurable through specific parameters.

3.2.2 Diagnostics content

The following chapter describes in more detail the content of a frame reports.

3.2.3 *Frame reports* field content

The *Frame reports* field contains the detail of all frames exchanged during the round. More specifically it provides for each frame:

- The action performed on the frame: TX or RX
- The antenna set used to transmit or receive
- The FiRa message ID of the frame
- The Emitter Short Address:
  - For TX frames, it contains the local MAC short address.
  - For RX frames, it contains the MAC short address of the emitter when the reception is successful, otherwise, it contains `0xFFFF`.
- A set of status related to the frame containing:
  - The status of the frame (successfully processed or not)
  - The status of the WiFi activation state during the frame
  - The status of the Max grant duration (exceeded or not)
- The *CFO* of the frame (only applicable to RX frames): clock offset between the transmitter and the receiver
- A list of Segment Metrics reports (only applicable to RX frames): Their number depends on the antenna sets used to perform the reception and the elements that were measured, there will be:
  - One Segment Metrics report per segment used to compute the *ToA* (i.e. one per receiver used, in case of simultaneous RX it will be >1)
  - One Segment Metrics report per segments used to compute each *AoA* supported by the antenna set. When the segment used for *ToA* is also used for *AoA* only one Segment Metric is given).

  Each Segment Metrics report contains:
  - The associated receiver ID and received segment index
  - The RF noise floor value during reception
  - The *RSL* of the global segment
  - The index of the first path in the entire *CIR* window
  - The *RSL* of the first path
  - The timestamp of the first path
  - The index of the peak path in the entire *CIR* window
  - The *RSL* of the peak path
  - The timestamp of the peak path

Note: the RF noise floor is not attached to a specific RX path (First path or Peak path), but is applicable to the entire received segment. It allows the computation of the *SNR* values corresponding to their relative *RSL*s, thanks to the following formula:

$$SNR = RSL - noise\_value$$

- A list of *AoA*s (only applicable to RX frames): one for each *AoA* the selected antenna set can compute containing:
  - The local *TDoA*
  - The local *PDoA*
  - The local *AoA*
  - The local *FoM* of the *AoA*
  - The type of *AoA* (Axis X, Y or Z)
- A list of *CIR* reports (only applicable for RX frames): Their number follows the same logic as the one for *Segment Metrics reports*.

  Each *CIR* report contains:
  - The associated receiver ID and received segment index
  - The offset of the first path in the sample window
  - The sample window around the first path

The following parts of the frame reports can be activated through a session parameter:

- Segment Metrics
- *AoA*s
- *CIR*s
- *CFO*
- Emitter Short Address

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