System Specification

Security of EnOcean Radio Networks

V 2.6

San Ramon, CA, USA, 2020

Executive Summary

Ver.	Editor	Change	Date
1.0	MF	Creation	05.03.2012
1.1	MF	Inclusion of AES CBC. Secure telegrams with/without non-secure RORG.	03.07.2012
1.2	MF	Page numbering	31.07.2012
1.3	AP	Removing ARC4 and editorial changes	31.10.2012
1.4	MH	Editorial on CMAC computing	22.11.2012
1.5	MH	Added PSK Teach In and VAES extensions above 16 bytes.	17.06.2013
1.6	MF	Abstraction from telegram to message	03.07.2013
1.7	MF	Teach-in unidirectional/bidirectional procedure described	10.07.2013
1.8	MF	RLC synchronization. Message-to- ERP1 and ERP2 conversion	11.07.2013
1.9	MF	PSK CRC explained. Description of teach-in procedure improved	26.07.2013
2.0	MH	Added High Security definition - renamed public key to VAES INIT Vector - CMAC in teach-in telegram eliminated	11.08.2014
2.1	FG	Added Test vectors	09.11.2016
2.2	MF	Test vectors encryption and CMAC calculations described in detail	12.07.2017
2.3	MH	Best practice examples, Secure chaining, 32 bit RLC. Removed Mutual authentication with RLC as NONCE from high security.. Changed RLC description.	09.05.2018
2.4	TM	Add secure chaining example, updated the sec_cdm mechanism	27.11.2018
2.5	TM & MH	Based on Alliance TTG Fedback: Recommendations Chapter changed to implementation aspects. Formatting, and wording. Removed AES CBC.	15.01.2019
2.51	MH & FS	Re-enabling the SLF RLC option 0b011 (3) 16 bit RLC explicit with window algorithm and roll over - PRELIMINARY	17.04.2019
2.6	AP	Replaced secure chaining test vector in A.4.3	03.12.2020

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1 Introduction

This document specifies the security concept for ERP (1/2). This concept was specially designed for devices powered by energy harvesters and is based on the ERP. The objective of the design was to keep the energy requirements and µC resources for the implementation of the security as low as possible.

The implementation aspects, which describe which security shall be used, are listened in the chapter 8. Chapter 2 – 5 goes into technical details describing the scenario against which the EnOcean security protocol protects, technical background and possible security formats. Most of the possibilities are not recommended and new design shall follow the SLF described in chapter 8. Chapter 6 describes EnOcean High Security which uses challenge and response. Chapter 7 explains the usage of Secure Chained messages, which shall be used to send data longer than one telegram.

1.1 Terms & Abbreviations

Term / Abbr.	Description
µC	Microcontroller (external)
API	Application Programming Interface
APP	Application
Data	Payload of ERP telegram
EEP	EnOcean Equipment Profile
ERP 1/2	EnOcean Radio Protocol 1 or 2. If no number is used, the argument is valid for both versions.
EO	EnOcean
ESP3	EnOcean Serial Protocol V3
RLC	Rolling Code
CMAC	Cipher Based Message Authentication Code
Gateway	Module with a bidirectional serial communication connected to a HOST
Device	Customer end-device with an integrated EnOcean radio module
Nonce	Number which is used once
SLF	Security Level Format, describes the used security parameters

Table 1. Abbreviations used in this document.

1.2 Definition of requirements levels

The usage of the keywords “must”,“shall”,”should” and so on follow the ones of the RFC 2119.

1. MUST This word, or the terms "REQUIRED" or "SHALL", mean that the definition is an absolute requirement of the specification.

2. MUST NOT This phrase, or the phrase "SHALL NOT", mean that the definition is an absolute prohibition of the specification.

3. SHOULD This word, or the adjective "RECOMMENDED", mean that there may exist valid reasons in particular circumstances to ignore a particular item, but the full implications must be understood and carefully weighed before choosing a different course.

4. SHOULD NOT This phrase, or the phrase "NOT RECOMMENDED" mean that there may exist valid reasons in particular circumstances when the particular behavior is acceptable or even useful, but the full implications should be understood and the case carefully weighed before implementing any behavior described with this label.

5. MAY This word, or the adjective "OPTIONAL", mean that an item is truly optional. One vendor may choose to include the item because a particular marketplace requires it or because the vendor feels that it enhances the product while another vendor may omit the same item. An implementation which does not include a particular option MUST be prepared to interoperate with another implementation which does include the option, though perhaps with reduced functionality. In the same vein an implementation which does include a particular option MUST be prepared to interoperate with another implementation which does not include the option (except, of course, for the feature the option provides.)

2 Scenarios

The ERP is used in a variety of applications. However, the major usage is in products within building automation. Some typical situations where a secure protocol can be required are:

- Thermostat vacation mode - A family leaves their home for several weeks. They set their thermostat in vacation mode. Obscuring data from the thermostat will prevent an intruder to know the occupancy state of the house.
- Window control – A building has a window installed whose opening is controlled by temperature and CO2 sensors. Applying a secure radio protocol the window receiver should ignore messages that have been already used. This will prevent an intruder to gain unauthorized access to the building by recording packets and replaying them.

  Automated meter reading – Polling a thermostat per radio enables the collection of meter information without the necessity of a person entering the house. By obscuring data from the thermostat it will be prevented that an intruder obtains private information from the transmitted data. To prevent an intruder forging the heating consumption the system must resist reply-attacks.

2.1 Attacker scenarios

In such fashions could be compromised the normal operation of an EO radio system:

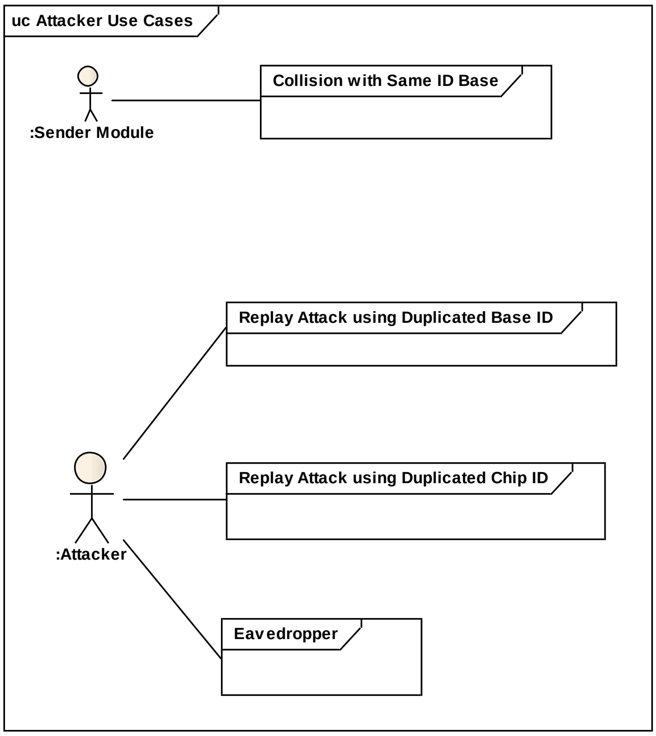

Figure 1. The picture shows the possible interferences and attacks in the actual EO radio communication. Attacks other than the ones shown in this figure will not be considered in this documentation and in the implementation of a secure radio protocol. Attacks not considered include, for instance, the physical manipulation of a sender or a receiver module; continuous wave sending;

power-supply sabotage. From the four scenarios depicted, the first (Collision with the same ID base) corresponds to an unintentional control of a receiver by another EO user. The last three scenarios represent, however, an intentional attack. Unauthorized listening of information that is being transmitted is called *eavesdropping*.

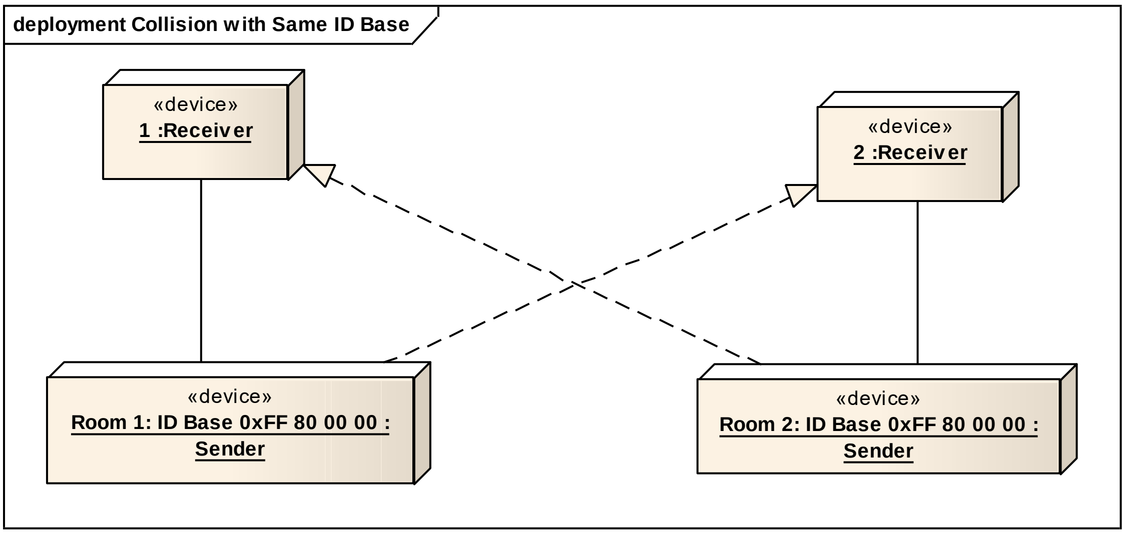

Figure 2. This scenario is not a proper attack. It's simply an ID duplication within the range of the base ID (see what is EnOcean Base ID). The duplication happens because two different users programmed their sender modules with identical ID within the base ID range. When the user in room 1 sends a signal with Sender 1 he controls unluckily also Receiver 2, in room 2. A symmetrical situation happens when the Sender 2 in room 2 is operated.

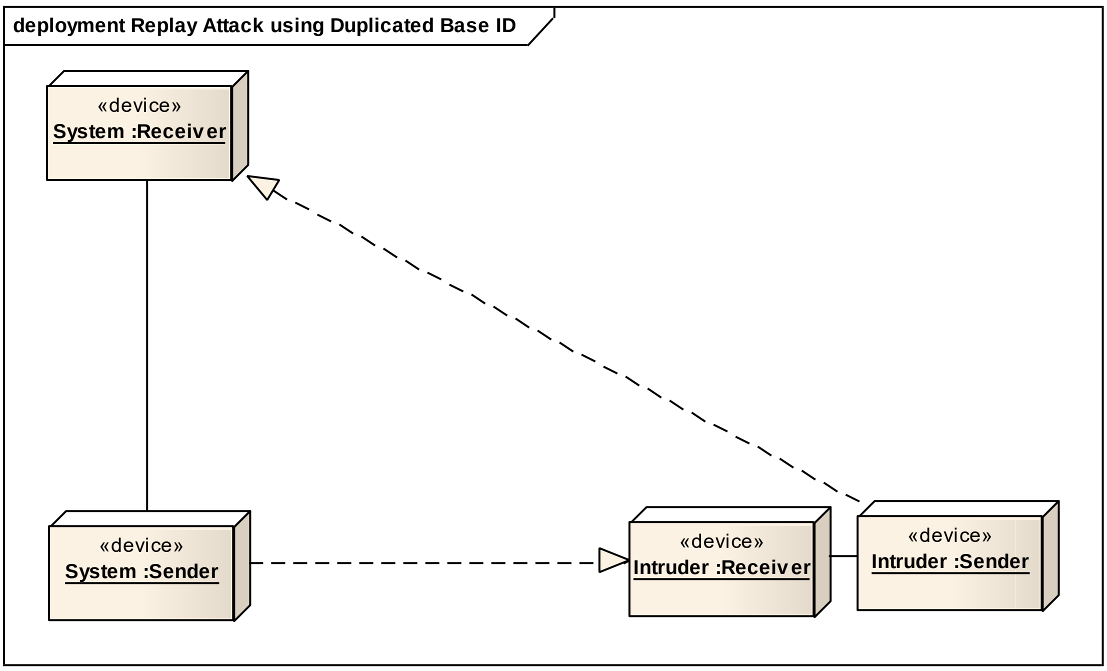

Figure 3. In this scenario an attacker programs the ID base taking intentional control of the system receiver. To do this, the intruder simply listens to the sender ID. It programs then this same Base ID in his sender module, and controls the system receiver. All this is possible using EO tools without performing reverse engineering.

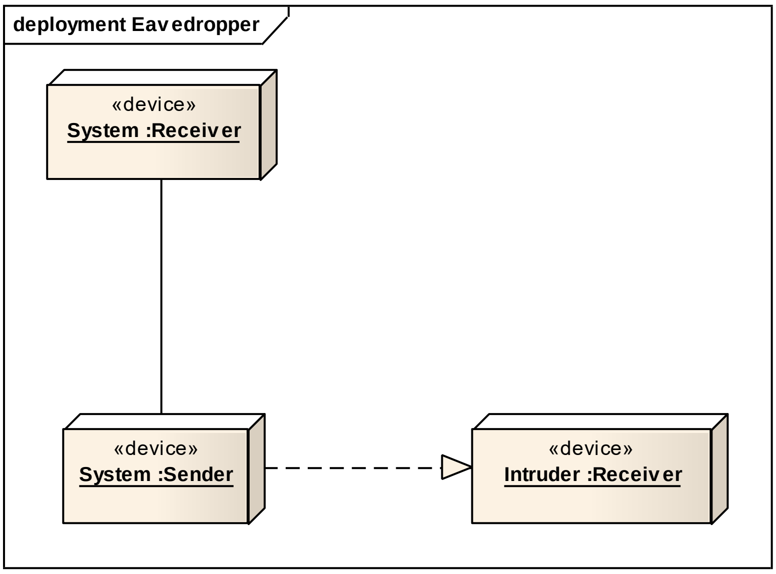

Figure 4. With the only help of an EO receiver it is possible to hear the communication between an EO sender and a receiver. This is undesired if the information being transmitted is private. This is the case of metering reading systems.

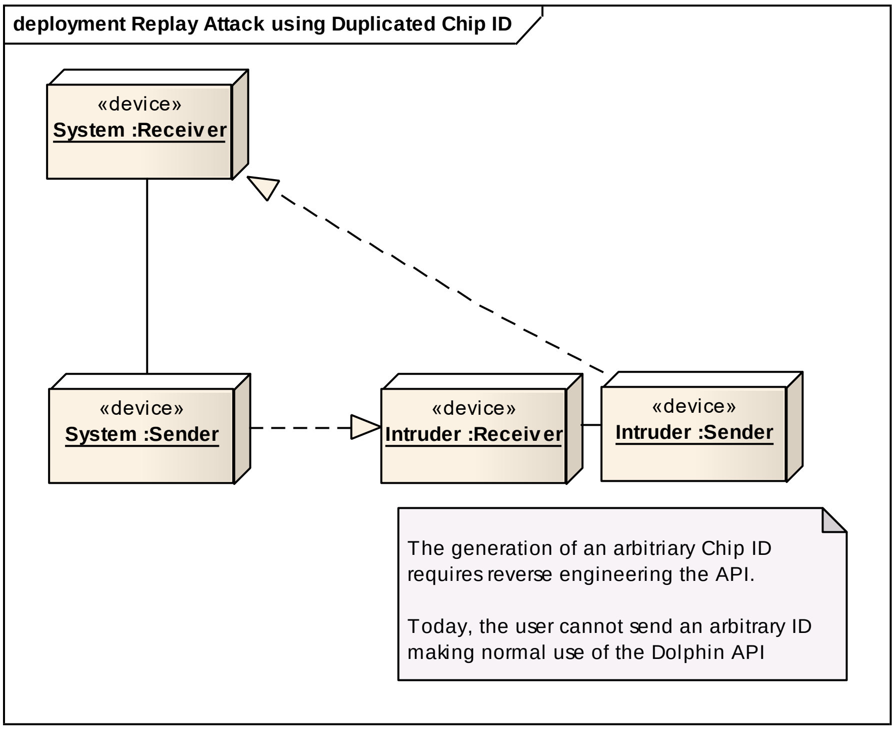

Figure 5. In a more sophisticated attack version the attacker listens to the telegrams in the air. The attacker sends a telegram with the same chip ID (replay) as the one in the system sender.

2.2 System Architecture

A typical system architecture using ERP is shown on the figure below:

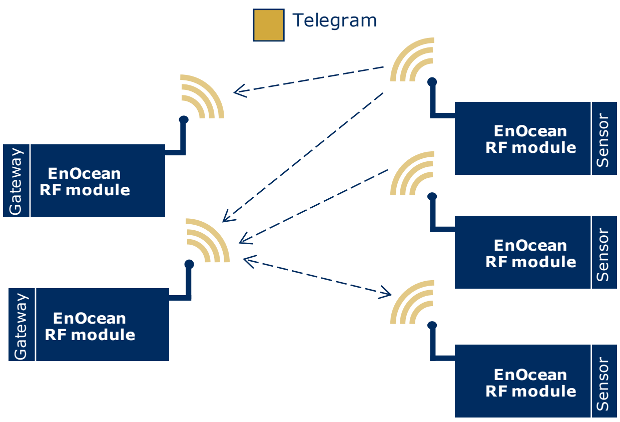

Figure 6 ERP system architecture

In an ERP system most common communication pattern is unidirectional. However there are installations where bi-directional communication is required for instance between two Gateways, in SmartACK or in Remote Management concept. Thus the security concept has to be designed in a way that it can be applied to N:M communication patterns.

3 Security for operation mode

RORG	Description
0x30 SEC	Secure telegram. This message was not created from a non-secure counterpart. A message with this RORG was created by the secure application and the data may interpreted by a Teach-In-Process outside of this specification (i.e. EEP or GP).
0x31 SEC_ENCAPS	Secure message that transport the original R-ORG non secure code.
0x32 SECD	Non-secure message type that results from the decryption of a secure message with R-ORG 0x30.
0x33 SEC_CDM	Secure chained Messages
0x35 SEC_TI	Secure Teach-In telegrams transmit private key and rolling to the communication partner

Table 2. Secure RORGs

The ERP security is implemented on the OSI presentation layer of the ERP protocol stack.

The security strategies discussed in the next chapters are applied to messages. Messages abstract the concept of telegrams. Messages do not specify a certain byte order. They are to be imagined as C structures with all necessary members to contain the information stored in a telegram. A message is a generalisation of serial and radio telegrams.

A message contains all fields that a telegram may have: the R-ORG, DATA, Sender ID, receiver ID, repeater counter as well as the security specific members like RLC, CMAC, SLF that will be explained in the next chapters.

EO secure messages follow a flexible schema made up of different freely combinable security mechanisms. The Security level formats described in chapter 8 should be used. The description of other combination still exists for legacy products and may be still used[1].

The security mechanism may transform the DATA and R-ORG fields of the non-secure message. Other fields like the message sender ID, receiver ID, repeater counter are not affected or altered. The RLC and CMAC should be added. Not modified fields like sender ID, received ID or repeater counter are not depicted through the chapter when a message is represented.

The following figure depicts the relevant secure radio message structure members, together with examples of application scenarios, attacks that can be blocked.

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[1] As the different SLF allow significant freedom, and not all combinations can be seen as optimal secure solutions, and some solutions could cause different problems the SLF should be selected accordingly to chapter 8.

MESSAGE	Scenario	Replay Attacks	Eaves-dropping
R-ORG DATA	Unsecured	Yes	Yes
R-ORG S DATA	Deprecated	Yes	No
R-ORG S DATA RLC CMAC	Deprecated	No	Yes
R-ORG S DATA RLC CMAC	Shall be used	No	No

Table 3. The table shows the different secure messages structures for typical EnOcean applications. . A secure message is identified by specific R-ORG codes represented as R-ORG S. Obscured will be only the DATA of the message and optionally the original R-ORG. Any combination of DATA encrypted/not encrypted, RLC present/not present, and CMAC present/not present is technical possible. But only the one mentioned in chapter 8 should be used.

The structure of the secure telegram is negotiated between the devices within the teach-in procedure. See 4.

3.1 Message structure

R-ORG | DATA | RLC | CMAC

Figure 7. Relevant message members In the following chapters, whenever DATA is written, DATA includes OPTIONAL DATA.

3.1.1 R-ORG

The message R-ORG identifies the type of message that is being sent or received. The message R-ORG is 1-byte long. Secure messages are identified by the codes 0x30, 0x31,0x33 or 0x35, denoted generally *R-ORG S* in the Table 3.

A code different from those identifies a non-secure message.

3.1.2 DATA

Under DATA will always be understood the telegram DATA field and the OPTIONAL DATA, if it exists. The DATA is a byte concatenation of both DATA + OPTIONAL DATA.

The data is encrypted using any of the encryption algorithms described in section 5.

The DATA encryption algorithm is indicated to the receiver during the teach-in procedure.

The length of the DATA and the interpretation is defined by the application.

3.1.3 RLC (ROLLING CODE)

This field contains a code that changes according to a predefined algorithm (see 5.5). If the RLC is not transmitted, sender and receiver must keep this code synchronize. The code increases every time a message is sent by the radio transmitter. If a message RLC does not coincide with the expected RLC value the receiver rejects the message.

- If the RLC is transmitted via a message, it must be higher than the previous received RLC.
- If the RLC is not transmitted, the RLC shall be in RLC window range.

RLC is MSB first.

The teach-in procedure may synchronize the RLC in the receiver with the one in the receiver.

The RLC field should be transmitted but can be omitted. Although the RLC may not be sent by the transmitter it is used internally in the transmitter and receiver modules to perform the calculation of the CMAC code and DATA field encryption (see 5.6). By reception of the CMAC the receiver indirectly test the correctness of the RLC.

RLC field format: RLC byte length, RLC algorithm and RLC presence in the telegram- are communicated to the receiver during the teach-in procedure using the SLF.

Details of the RLC algorithm are explained in section 5.5

3.1.3.1 Synchronizing RLC when synchronization window is lost

If the receiver misses more messages then the defined RLC window, no additional messages will be decrypted by the receiver. In this case the receiver needs to resynchronize the RLC. Different approaches can be used for this, one is that the sender retransmits a Teach-IN telegrams which includes the current RLC. The receiver will resynchronize itself after receiving this Teach-IN. Another possibility is e.g. if the receiver is a line powered device and did suffer a power loss to increase the RLC window to a very large number one time – for one incoming telegram. In this case it is recommended to ensure that not a duplicated RLC has been received.

3.1.4 CMAC

The CMAC is the cipher-based message authentication code field –with MSB first. Its mission is to guarantee that the message has not been tampered with. This confirms that the sender is the stated one.

The CMAC is dependent on the private key (see 4.1.5), a public vector, the message bytes and, if it exists, the rolling code (see 3.1.3).

The MAC field code changes for every sent message. The CMAC changes unpredictable, unless the key and the RLC state are known.

The algorithm to calculate CMAC is explained in the chapter 5.6

3.2 Transforming secure and unsecure messages

This chapter explains how to create secure messages taking as basis an unsecure message and vice versa.

In the explanation message fields such as sender ID, receiver ID and other message fields, not modified by the security transformations, will be not indicated. The reader must suppose that these fields are part of the message.

3.2.1 Transforming an unsecure message into a secure message with R-ORG encapsulation

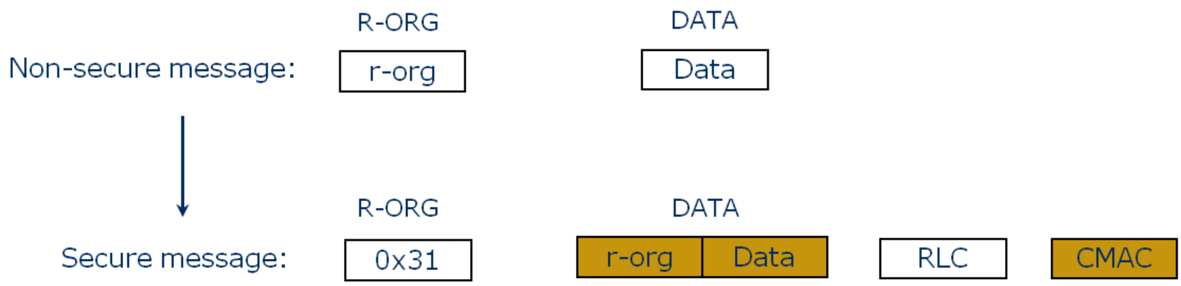

Figure 8. An unsecure message is transformed into a secure message that includes the original R-ORG by 1- transforming the message R-ORG code to 0x31. 2- The unsecure R-ORG field code and the unsecure DATA fields are concatenated and then encrypted. 3- The result of the encryption is stored in the most significant bytes of the secure message DATA field. 4- A rolling code, RLC, might be calculated (section 5.5). 5- Finally, it is possible to add a CMAC code (chapter 5.6). Other message fields like sender ID, receiver ID or repeater counter are not modified.

3.2.2 Transforming a secure message with R-ORG encapsulation into a non-secure message

In this case, a secure message with R-ORG 0x31 is transformed into a non-secure message. The transformation implies decrypting the encrypted R-ORG and Data information which is to be found concatenated in the DATA field of the message.

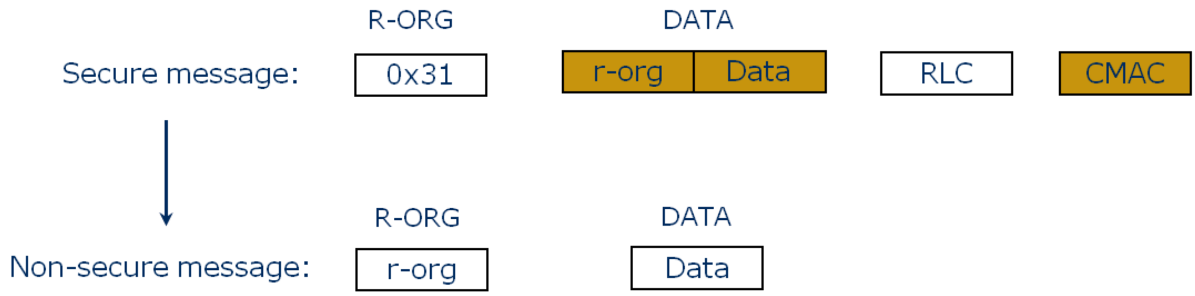

Figure 9. A secure message with R-ORG 0x31 contains the unsecured R-ORG encrypted in the DATA field. The DATA field of the message must be decrypted, maybe with the help of the RLC. The first decrypted byte represents the message R-ORG of the unsecure message. The rest of the decrypted DATA field bytes represent the unsecure message DATA bytes. CMAC does not play a role in the decryption. This field will be checked for authentication of the telegram.

3.2.3 Transforming an unsecure message without R-ORG encapsulation into a secure message

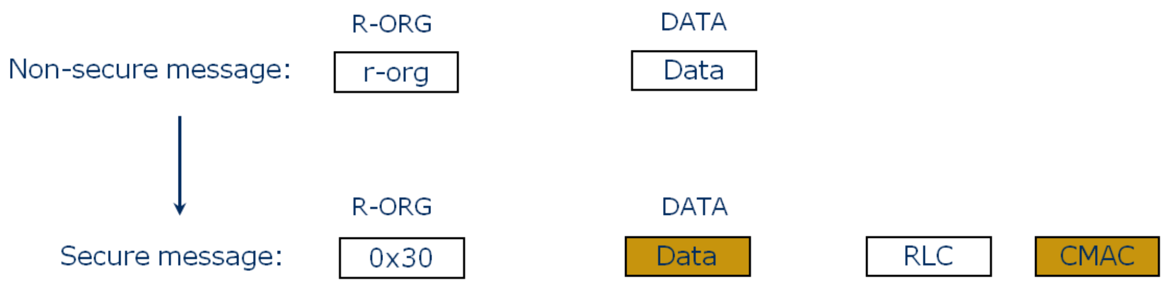

Figure 10. An unsecure message is transformed into a secure message that does not include the original R-ORG by 1- rewriting the message R-ORG code to 0x30. 2- The unsecure DATA field is encrypted. 3- The result of the encryption is stored in the secure message DATA field. 4- A rolling code might be calculated. 5- Finally, it is possible to add a CMAC code. The purpose of not including the original unsecure message in the secure message DATA field is to save energy at transmission time.

3.2.4 Transforming a secure message without R-ORG encapsulation

In this case, a secure message with R-ORG 0x30 is transformed into a non-secure message. The transformation implies decrypting the DATA field information.

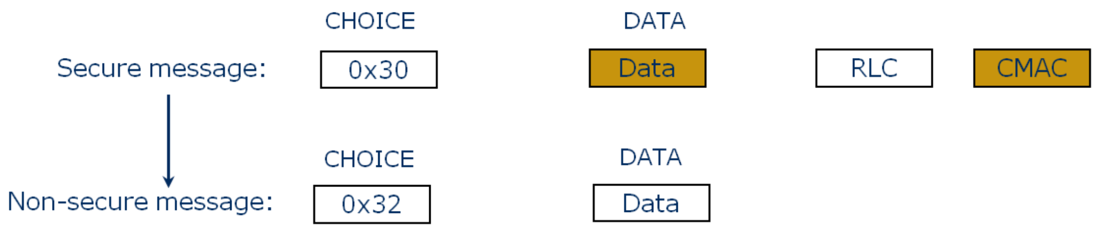

Figure 11. The secure message with R-ORG 0x30 does not include the non-secure R-ORG information in any form. In the conversion from secure to non-secure message the latter becomes the R-ORG = 0x32.The DATA field is decrypted, maybe using the RLC field. The CMAC does not play a role in the decryption. It is only used for authentication purposes.

4 Security for teach-in mode

This chapter explains the exchange of the security information via the radio interface, which may be omitted. Especially sending the AES-Key in clear text should be omitted and at least a PSK should be used. The exchange of the security information may be done by using other interfaces, and then be added into the device. This is not explained in details here. (E.g. ReCom, Serial interface or IP Gateway)

To configure the details of the secure communication in operation mode a teach-in procedure mode must be executed. Within the teach-in procedure the parts involved in the communication transmit to each other the encryption method, key, rolling code, rolling code size and CMAC size that will be used during the operation mode.

The teach-in procedure can be set up to be a unidirectional or bidirectional process. See 4.1.2 to learn how to configure this option.

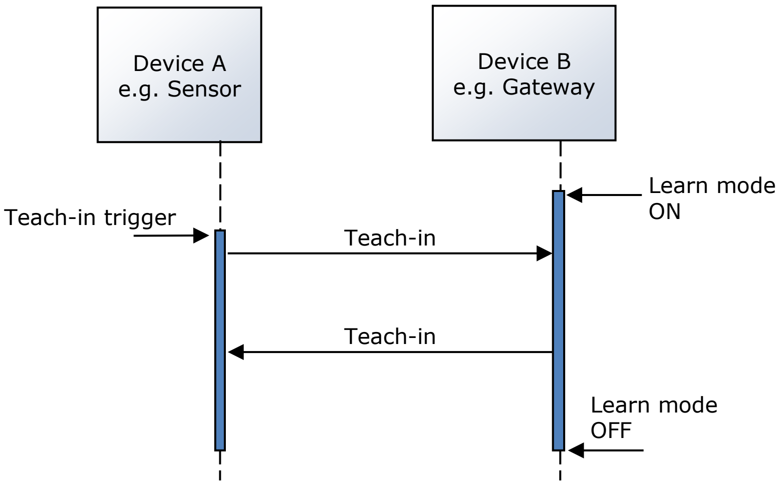

Figure 12. Schematic representation of the most general bidirectional teach-in procedure. In the case of unidirectional security teach-in Device B does not send a teach-in message.

Firstly, the Device B must be set in learning mode to accept the teach-in messages from Device A. The Device A sends the security teach-in message (are described in chapter 4.1) whenever its specific trigger is activated. After reception of the teach-in message the Device B stores the security parameters of Device A: these parameters include the Device's A private key, KEY, current RLC, RLC, RLC size and CMAC size and way of encrypting information. The KEY and RLC can be sent encrypted by the sender using the so called pre-shared key, PSK. More details under chapters 4.1.2.3 and 4.2.

If the process is bidirectional the Device B, a gateway, for instance, answers back with a security teach-in message. This teach-in message contains as receiver-ID the ID of the Device A. If the Device B encrypts its teach-in message it will make use of the same PSK key of the Device A. In the second security teach-in depicted in the picture the Device B informs the Device A of its own KEY and RLC and CMAC. The format of the teach-in messages sent by Device A and Device B are the same.

The teach-in delivered by Device B must occur in worst case 500ms after the reception of the teach-in sent by Device A. The Device's A time-out for the reception of a teach-in is 750ms.

Before Device A sends the security teach-in message, the receiver is put into teach-in mode – active listening for teach-in messages. The teach-in method is limited typically to 30 seconds. After this time-out the module leaves its teach-in mode, and returns typically to its operation mode. Teach-in messages are not accepted until the next activation of the teach-in mode.

The possible methods for the teach-in execution are:

- Via wireless from the transmitter to the receiver
- Via serial interface to the receiver through a third party
- Via ReCom
- Others

Execution via serial interface or other methods are not part of this specification and are rather application / use case specific.

The execution of the teach-in process via wireless leads to two possibilities:

- Teach-in message is sent in plain text (no encryption in the information is performed).. This should not be used, as a third party could sniff the key and listens to all later communication.
- Parts of the teach-in message are encrypted. For the encryption a pre-shared key is used. Encrypted are the RLC and KEY. Message structure is listed below. Details about this execution can be found in chapter 4.2

4.1 Message structure

The teach-in message has the following secure-specific fields:

R-ORG TS	TEACH_IN_INFO	SLF	RLC	KEY

Figure 13. Secure teach-in message. Teach-in Info field contains information relative to the teach-in message itself. The SLF field indicates the format of the security parameters in operation mode. The RLC is the current RLC in the transmitter. The KEY contains the private key used for encryption in operation mode. RLC and KEY may be encrypted with a pre-shared key

This secure teach-in message only transfers the security specific data. This message does not contain the information about how the data has to be interpreted (except for field type PTM) in operation mode.

To enable profile interpretation a profile-teach-in message (EEP or GP) has to be transmitted after the secure teach-in. This profile teach-in is conducted already secured (encrypted) using the decrypted key that the secure teach-in transmitted.

4.1.1 R-ORG TS

The one byte secure teach-in R-ORG is 0x35.

4.1.2 TEACH-IN INFO

7	6	5	4	3	2	1	0

IDX	CNT	PSK	TYPE	INFO
		0 - No PSK 1 – PSK	0 – No PTM 1 – PTM	Interpretation depends on Type. See 4.1.2.5

Table 4. Teach-in info byte fields

4.1.2.1 Field IDX

A tech-in message can be divided in several telegrams. This field indicates the order of those telegrams. The first telegram receives the IDX = 0. In the case that the teach-in message is not divided the IDX shall be set to 0 and this message is the only one.. Chaining is explained in chapter A.1.2

4.1.2.2 Field CNT

If IDX = 0

CNT indicates the number of telegrams that the message is divided into

If IDX not 0

This field is reserved

4.1.2.3 Field PSK

If IDX = 0

0 The RLC and the KEY are not encrypted

1 The RLC and the KEY are encrypted with the pre-shared key. See 4.2

If IDX not 0

This field is reserved

4.1.2.4 Field TYPE

If IDX = 0

Indicates if the application is a PTM or not

1) Non-specific type
2) PTM

If IDX not 0

This field is reserved

4.1.2.5 Field INFO

The interpretation of this field depends on the code in Field (4.1.2.1)

If IDX = 0 and TYPE = 0

0 Unidirectional security teach-in procedure

1 Bidirectional teach-in procedure

If IDX = 0 and TYPE = 1

0 ROCKER A normal Teach In

1 ROCKER B normal Teach In

In other cases this field is reserved

4.1.3 SLF (Security level format)

With the information contained in the teach-in SLF byte the receiver is informed about the details of the secure messages in operation mode: what fields, how long they are, and what are the applied security algorithms. [2]

7	6	5	4	3	2	1	0
RLC_ALGO[3]			**MAC_ALGO**		**DATA_ENC**		
0: No RLC *1: Reserved for future use* *2: 16 Bit implicit RLC Roll Over/ Window Algorithm* *3: 16 Bit explicit RLC Roll Over/ Window Algorithm* *4: 24 Bit implicit Roll Over/ Window Algorithm* 5: 24 Bit explicit RLC [24 Bit transmitted] No Roll Over / No Window Algorithm **6: 32 Bit explicit RLC [24 Bit transmitted] No Roll Over / No Window Algorithm** **7: 32 Bit explicit RLC [32 Bit transmitted] No Roll Over / No Window Algorithm**			*0 – No MAC* 1 – AES128 3 byte **2 – AES128 4 byte** *3 – N/A*		*0 – No data encryption* 1 – See chapter 6 2 – N/A **3 – VAES – AES128** *4 – N/A*		

Table 5. Security Level Format fields and its interpretation. When RLC_ALGO is 1 or 2 the secure teach-in message contains the rolling code whose size corresponds to the one described by that bit field.

4.1.3.1 Field RLC_ALGO

Defines the type of the rolling code algorithm used during secure communication. More details under Rolling Code .

0 No RLC

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[2] The codes 6 & 7 should be used in new designs.

[3] In older specification the RLC_ALGO field was split into RLC_ALGO + RLC_TX. The same functionality of the old specification is still possible, case 0,2,3,4,5. Only case 6,7 are actually new and defined a new behaviour

1 *Reserved for future use*
2 *16 Bit implicit RLC which allows a roll over and uses a window algorithm at the receiver side to ensure that both devices are in sync.*
3 *16 Bit explicit RLC which allows a roll over and uses a window.*
4 *24 Bit implicit RLC which allows a roll over and uses a window algorithm at the receiver side to ensure that both devices are in sync. See Rolling Code .*
5 24 bit explicit RLC, the RLC will be transmitted. Roll over is not allowed and no window algorithm is used
6 32 bit explicit RLC only 24 bit of it will be transmitted. Roll over is not allowed and no window algorithm is used
7 32 bit explicit RLC, the full RLC will be transmitted. Roll over is not allowed and no window algorithm is used

4.1.3.2 Field MAC_ALGO

Defines the type of algorithm for the CMAC calculation

0 *No MAC included in the secure telegram*
1 CMAC is a 3-byte-long code. MAC is calculated using AES128 as described in the 5.6 chapter
2 MAC is a 4-byte-long code. MAC is calculated using AES128 as described in the 5.6 chapter
3 N/A

4.1.3.3 Field DATA_ENC

Defines the type of algorithm for DATA encryption during secure communication in operation mode.

0 *DATA not encrypted*
1 Challenge - Response
2 Reserved. Not defined
3 DATA will be encrypted/decrypted XORing with a string obtained from an AES128. See 5.1
4 *Reserved.* Not defined

4.1.4 RLC

Contains the rolling code needed for the transmitter-receiver RLC synchronization.). See chapter 4.1.3.

4.1.5 KEY

Contains the private key used for the encryption of DATA and CMAC generation in operation mode.

4.2 Teach-in with pre-shared key

In case a teach-in is executed with a pre-shared key the fields RLC and KEY are encrypted. For the message structure of a teach-in please refer to the Figure 13.

The pre-shared key of the sender module must have been communicated to the receiver (a gateway) via serial interface in advance. The pre-shared key is typically written on a sticker on the sender module. The pre-shared key is not transmitted through the EnOcean air interface.

When TEACH_IN_INFO.PSK = 1 the fields RLC and KEY will be encrypted using the VAES encryption. See chapter 5.1 for details. The following parameters are used in the VAES algorithm:

- VAES DATA = concatenation of RLC + KEY bytes

- VAES RLC = 0x0000 (Rolling code is not exchanged at this moment, therefore it must be initialized to a default value)
- VAES PRIVATE KEY = PRE-SHARED KEY

4.2.1 PSK checksum

The PSK code (16 bytes) comes together with an extra byte, CRC checksum, which is used to verify that the installer/user writes correctly the 16-byte PSK code into the Device B (see Figure 12). The checksum uses a CRC8 algorithm that is explained in chapter A.3.

5 Security algorithms

This section describes the security algorithms for the ERP that are used to secure the telegram content.

5.1 VAES (variable AES) encryption

A more secure way to encrypt data is using the 128-bit AES algorithm(1) in combination with the rolling code. The mechanism described here allows DATA lengths from 1 to N, where N does not have to be necessarily a multiple of 16. Thanks to the rolling code the generated encrypted code varies, although the DATA input is constant. This feature improves the obscurity of the original information and avoids replay attacks. Encryption is done in 16 bytes chunks, similar to the previous algorithm. But the length of the resulting cipher text is the same as the length of plain text. After transmitting each message the RLC is increased.

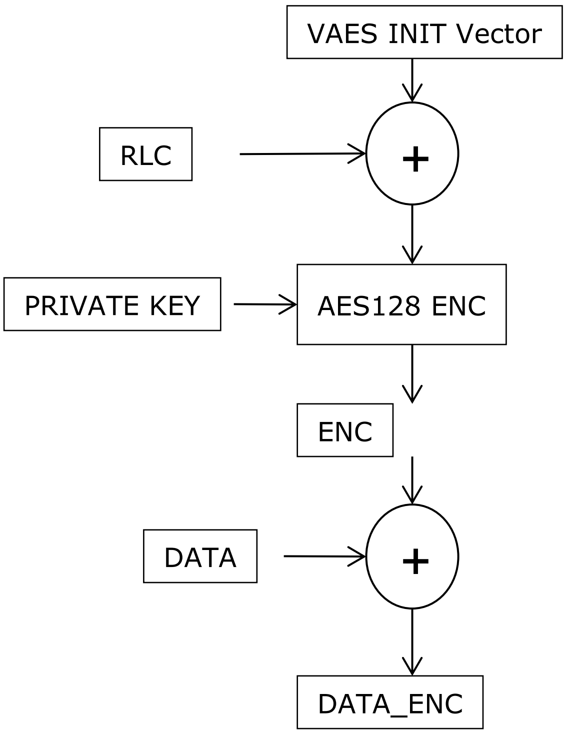


Figure 14. Encryption of telegram DATA using variable XOR AES128 for DATA equal or less than 16 bytes. The AES128 is used to perform a pseudo random generator. The plus symbol within a circle represents a bitwise XOR operation. One DATA chunk can have a maximum of 16 bytes. The length of DATA_ENC is equal to the length of DATA. VAES INIT Vector is a constant 16-byte hexadecimal string array. The RLC is XORed with the VAES INIT Vector before entering the AES128 algorithm. The VAES INIT VECTOR byte array first element, VEAS_INIT_VECTOR [0], is XORed with the RLC most significant byte. VEAS_INIT_VECTOR [1] is XORed with the RLC 2nd most significant byte and so on. The RLC is padded with 0 until a full 16 byte block is reached. In the same way DATA and ENC arrays are XORed to produce the output code.

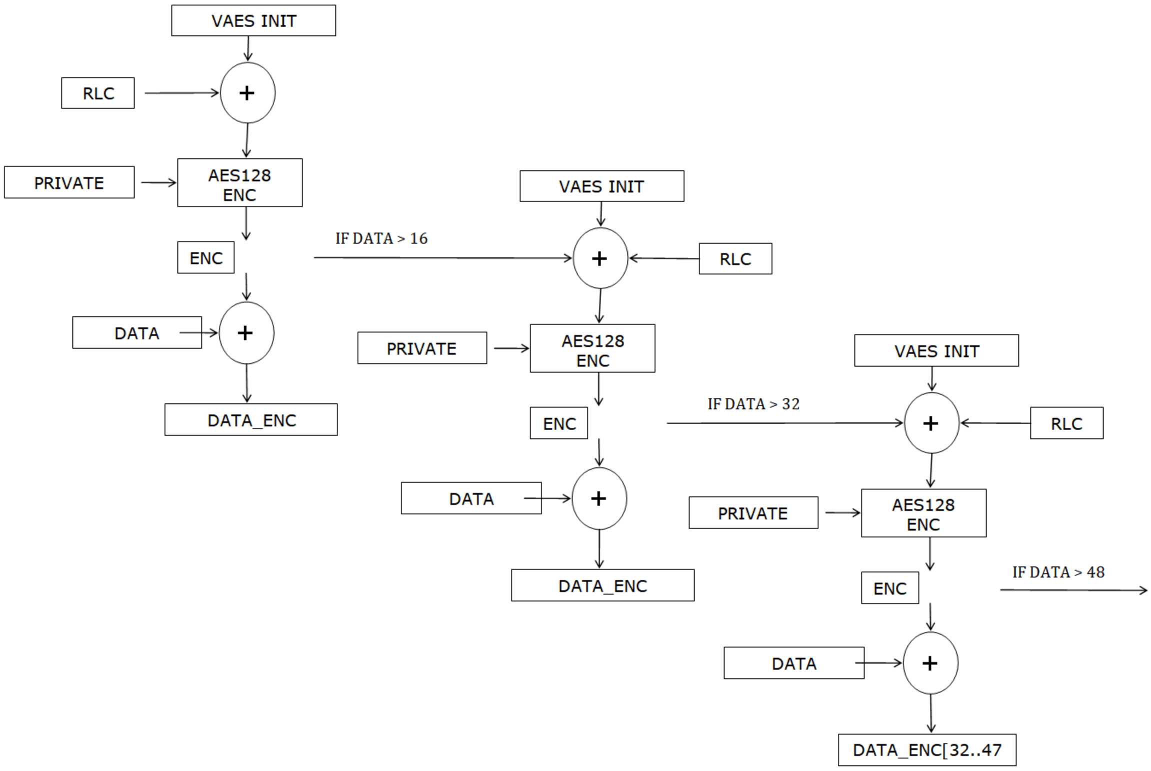


Figure 15. Encryption of telegram DATA using variable XOR AES128 for DATA longer than 16 bytes. Encryption is repeated but in all following cycles the ENC field from previous cycle is XORed with the encryption input for the actual cycle. The Rolling Code is the same for all cycles. By using the ENC field in all following cycles the encryption input will change and so the ENC field for DATA. Otherwise same rules apply as in encryption with less than 16 bytes.

5.2 VAES (variable AES) decryption

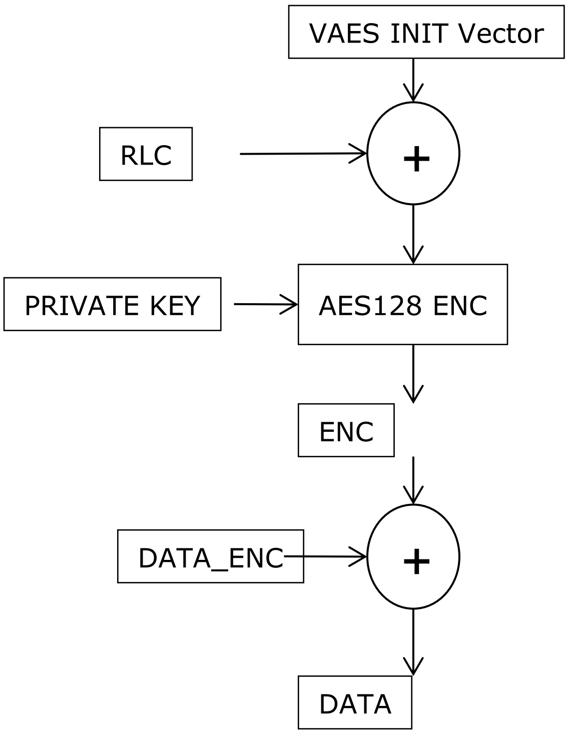


Figure 16. Decryption algorithm of the received telegram. DATA_ENC is the received encrypted DATA. DATA is less than 16 bytes. Note: The AES algorithm required is the same as in the encryption algorithm. The RLC value in the receiver must be the same as in the transmitter module. Otherwise the decrypted DATA will not correspond to the DATA in the transmitter. The DATA has the same length as the DATA_ENC. The XOR bit alignment follows the ideas described in

Figure **14**.

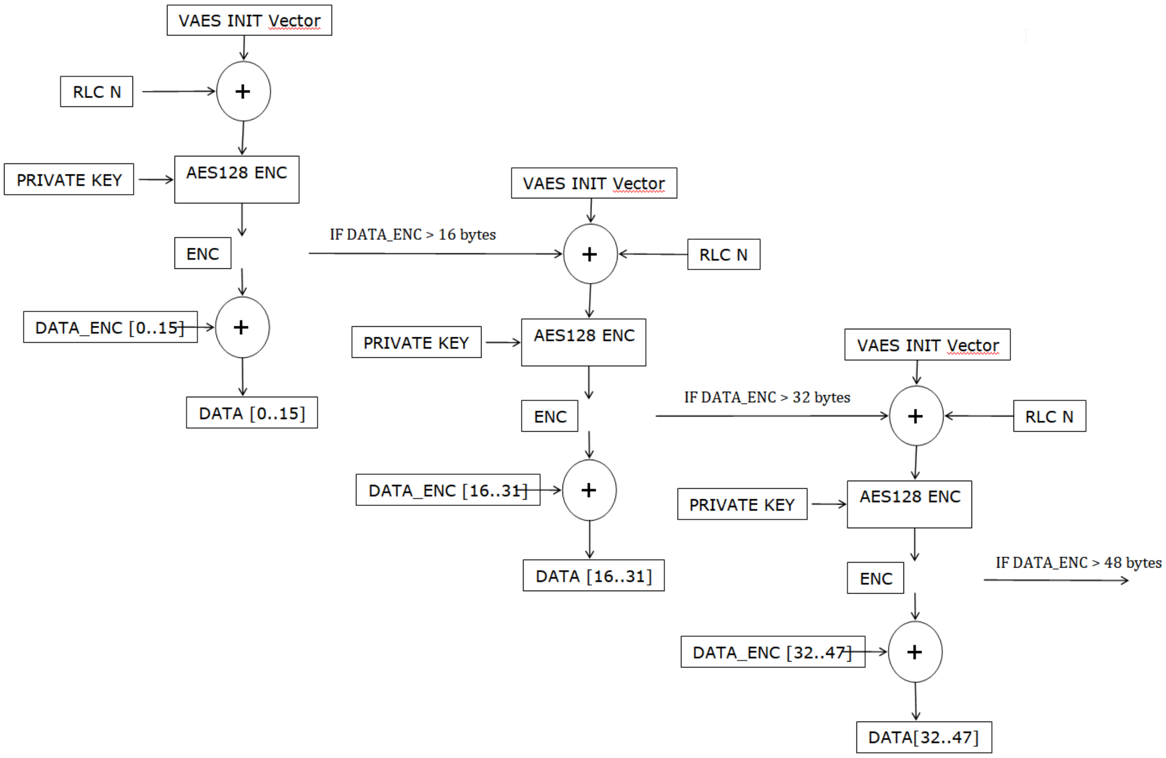


Figure 17. Decryption algorithm of the received telegram. DATA_ENC is the received encrypted DATA from the transmitter. DATA is more than 16 bytes.

For this algorithm to work correctly the receiver must check first that its internal RLC is correct. This can be done by comparing the internal RLC against the telegram RLC or, if there is no transmitted RLC, by comparing the MAC (see 5.6).

5.3 VAES INIT Vector

The VAES INIT Vector is a known constant value used as input to the AES algorithm.

Its value is the hex **3410de8f1aba3eff9f5a117172eacabd.**

Seen as a 16-byte array, the VEAS_INIT_VECTOR first element, VEAS_INIT_VECTOR [0] = 0x34.

The array last element is VEAS_INIT_VECTOR [15] = 0xbd.

5.4 Private Key

The private key is a secret constant value used as input to the AES algorithm. Its length is 128 bits (16 bytes).

5.5 Rolling Code

The rolling code is a value stored in the sender and transmitter module independently. The code changes for every sent/received telegram according to a predefined algorithm. The rolling code is used as to obtain different CMAC codes (5.6) and VAES encryption values (5.1) although telegram DATA remains constant.

Explicit RLC strategy - The RLC shall be transmitted as part of the telegram information.

Implicit RLC strategy - It is possible for the transmitter module not to send RLC in the telegram (See 5.6) to decrease the needed energy.

If the RLC is transmitted or not is indicated by the SLF (Security level format)

The rolling code algorithm is the simplest possible: it is a **counter that is incremented by 1** when the transmitter/receiver sends/receives a telegram. A RLC value shall not be duplicated. To ensure this the following strategies shall be used.

- If the RLC is send, rollover of the RLC is not allowed and window algorithm is not used. A receiver shall block messages with a lower RLC. The RLC shall only be reset when a new key is used.
- If the RLC is not send, the RLC window shall be used. A receiver may store the first received RLC and inform the user if same values are used again.

If the implicit RLC strategy is used, a window is used to ensure synchronization between receiver and transmitter.

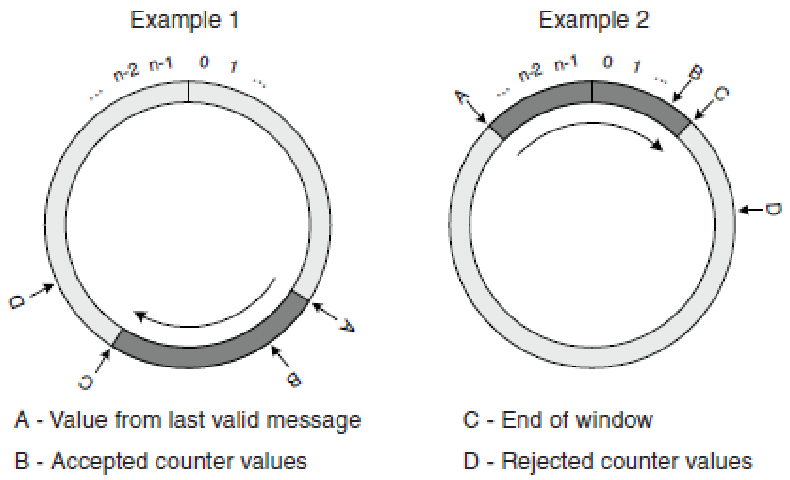


Figure 18. Rolling Window of Acceptance for Counter Values *(AVR411: Secure Rolling Code Algorithm)*.

The RLC window is a mechanism that ensures that even if the transmitter and receiver lost their synchronization (transmitter was operated outside the range of the receiver or telegrams were lost), telegrams will be still accepted. The difference between the rolling code counters in the sender and receiver must not be bigger than the rolling code window size. When the receiver module receives a wrong RLC it tests the next rolling code. If this test fails again, it tests the next rolling code. These tests continue until the RLC match, or a number of RLC window size tests were performed. In this last case the receiver returns to its original RLC and rejects the telegram.

Once the receiver cannot match the transmitter rolling code in the range of the window size it may block the TXID of the transmitter.

If sender and receiver RLC were desynchronized with a RLC difference bigger than the RLC window size, they can be synchronized again by means of the teach-in procedure (section 4) or writing the RLC directly into the receiver.

The window size for incorrect RLC should be 128. Other values may be used.

5.6 CMAC algorithm

The general algorithm (see [3]) to calculate the CMAC of a message to send is the following.

```
+-----+     +-----+     +-----+     +-----+     +-----+     +---+----+
| M_1 |     | M_2 |     | M_n |     | M_1 |     | M_2 |     |M_n|10^i|
+-----+     +-----+     +-----+     +-----+     +-----+     +---+----+
   |           |           |   +--+    |           |           |   +--+
   |     +--->(+)    +--->(+)<-|K1|    |     +--->(+)    +--->(+)<-|K2|
   |     |     |     |     |   +--+    |     |     |     |     |   +--+
+-----+  |  +-----+  |  +-----+     +-----+  |  +-----+  |  +-----+
|AES_K|  |  |AES_K|  |  |AES_K|     |AES_K|  |  |AES_K|  |  |AES_K|
+-----+  |  +-----+  |  +-----+     +-----+  |  +-----+  |  +-----+
   |     |     |     |     |           |     |     |     |     |
   +-----+     +-----+     |           +-----+     +-----+     |
                           |                                   |
                        +-----+                              +-----+
                        |  T  |                              |  T  |
                        +-----+                              +-----+

          (a) positive multiple block length         (b) otherwise
```

If messages payload is aligned by 16 bytes, the case (a) is used. Subkey K1 is used in this case. See 5.6.2 for details about the subkey generation. The case (b) applies for messages that are not multiple of 16 bytes. Subkey K2 is used then.

M_i are 16-byte long array of the message bytes whose CMAC is to be calculated. M_1..M_n-1 are 16-byte long arrays. In case of (b) the last byte of the message is concatenated with the bit sequence 10…0, to obtain a 16 byte-long array.

The AES_K uses as input the 16-byte M_i array and the K key.

The last 16-byte M_i array requires the subkey K1 –case (a)- or the subkey K2 -case (b).

The message is composed of the RORG-S field, the DATA field and optionally the RLC (in case it is being used explicitly in the telegram or implicitly).

5.6.1 CMAC calculation for operation mode telegrams

To illustrate the CMAC calculation a message <=16 bytes will be used:

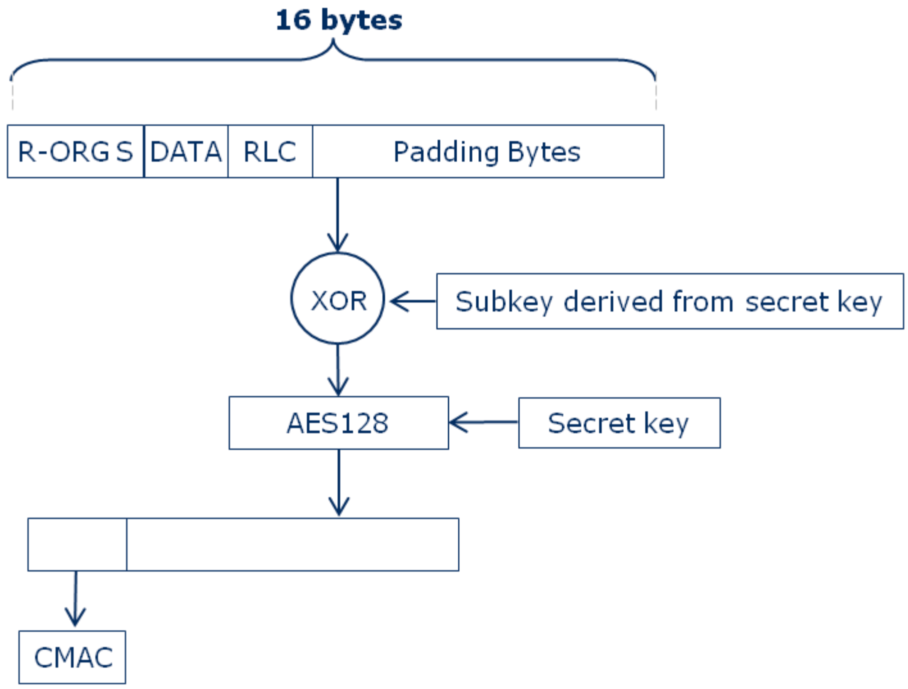


Figure 19. CMAC generation algorithm for a message <= 16 bytes. The R-ORG-S is the secure radio message R-ORG code. DATA is the secure message DATA field. When R-ORG S= 0x31, DATA includes the encrypted non-secure R-ORG as most significant byte. When R-ORG S= 0x30, DATA does not include the encrypted non-secure R-ORG. If no RLC is used (either in the message or internally) the field RLC is not included for the CMAC calculation. IMPORTANT: if the RLC is used but not transmitted with the telegram then the RLC is included in the CMAC calculation. In this way the CMAC changes for each transmitted message. From the AES-generated array the bytes with index 0, 1, ... ,(CMAC_size-1) are taken as CMAC. The padding bytes are only necessary for the case that the input information is < 16 bytes.

When the message fields (R-ORG S, DATA -and optionally RLC-) does not add 16 bytes for applying the AES128 algorithm, a bit sequence 100…0 (padding bits) is concatenated to form a total bit string of 16 bytes.

The R-ORG S, DATA –optionally RLC and PADDING BITS- are XORed with the 16-byte *Subkey derived from the private key*. R-ORG S XORs Subkey_Kn[0] and so on.

If the R-ORG S + DATA + RLC fields add 16 bytes then the subkey K1 will be used.

Otherwise the subkey K2 is used.

When performing AES, the byte R-ORG S corresponds to the string array byte with index 0.

A four byte CMAC corresponds to the string array bytes 0 (MSB), 1, 2, 3 (LSB) generated by the AES128 algorithm. A three byte CMAC corresponds to the string array bytes 0(MSB), 1, 2 (LSB) generated by the AES128 algorithm.

Note: When the R-ORG S + DATA + RLC > 16 byte the message has to be spitted like indicated in 5.1. The R-ORG will only be present as first byte in the M_1 while the RLC will only be present only within M_n.

5.6.2 Calculation of the subkey (AES-CMAC, RFC4493)

```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+                   Algorithm Generate_Subkey                       +
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+                                                                   +
+   Input     : K (128-bit key)                                     +
+   Output    : K1 (128-bit first subkey)                           +
+               K2 (128-bit second subkey)                          +
+-------------------------------------------------------------------+
+                                                                   +
+   Constants: const_Zero is 0x00000000000000000000000000000000     +
+              const_Rb   is 0x00000000000000000000000000000087     +
+   Variables: L          for output of AES-128 applied to 0^128    +
+                                                                   +
+   Step 1.  L := AES-128(K, const_Zero);                           +
+   Step 2.  if MSB(L) is equal to 0                                +
+            then    K1 := L << 1;                                  +
+            else    K1 := (L << 1) XOR const_Rb;                   +
+   Step 3.  if MSB(K1) is equal to 0                               +
+            then    K2 := K1 << 1;                                 +
+            else    K2 := (K1 << 1) XOR const_Rb;                  +
+   Step 4.  return  K2;                                            +
+                                                                   +
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

Algorithm Generate_Subkey

- In step 1, AES-128 with key K is applied to an all-zero input block
- In step 2, K1 is derived through the following operation:
  - If the most significant bit of L is equal to 0, K1 is the left-shift of L by 1 bit
  - Otherwise, K1 is the exclusive-OR of const_Rb and the left-shift of L by 1 bit
- In step 3, K2 is derived through the following operation:
  - If the most significant bit of K1 is equal to 0, K2 is the left-shift of K1 by 1 bit

    - Otherwise, K2 is the exclusive-OR of const_Rb and the left-shift of K1 by 1 bit.
- In the case that padding bits where necessary use the K2 as subkey. Otherwise K1

6 EnOcean High Security

EnOcean High security is an extension of the existing security concept. Its main aim is to:

- Enable protection against special man-in-middle attack (relay attack)
- Enable more flexible handling for devices communicating bidirectional with encryption

To handle first requirement is it suitable to apply the challenge & response process with time limited authentication. This implies that both communication devices are bidirectional. All the following definitions are based on that constrain.

6.1 Use Case definition

High security specification is developed for specific designed applications where this kind of security is required (e.g. doorlock, access control, safety applications). It is not the baseline for security application but the highest grade and should be applied only in applications where it is a valid use case.

For high Security these use cases are defined:

1. Bidirectional data flow – both devices are line-powered

Both devices have enough computing capabilities and energy to perform security relevant tasks. Data telegrams are exchanged in both ways e.g. communication between smart plug and gateway.

2. Bidirectional data flow – one device is energy autarkic and one is line-powered

One device is doing energy harvesting and the second is line-powered. Data flow is executed in both directions. The autarkic device initializes the communication and then expects a response from the line-powered device i.e. Smart Acknowledge process.

3. Unidirectional data flow (both devices have bidirectional capabilities) – one device is energy autarkic and one is line-powered

One device is energy harvesting and the second is line-powered. Data flow is executed in one direction – from the autarkic device to the line-powered. Bidirectionality is only required to execute high security features not for actual application use case. In this case Smart Acknowledge will be used too.

6.2 Protection against Relay Attacks

Relay attacks are special man-in-the-middle attack scenarios. The intruder intercepts the communication and blocks the targeted receiver. Then he can replay the communication to a later moment. With this scenario he will even bypass the RLC Counter checking, because the receiver has not updated his counter and so accepts the replayed message.

To prevent this attack scenario the message validity must be time limited and/or the receiver must be aware of transmission process ongoing. Time limitations are ensured by performing an authentication by challenge and response which valid only limited time (500 ms). During challenge and response a Nonce is used as challenge.

6.2.1 Authentication based on CMAC

Authentication can be:

- Unilateral – only one of the communication partners is authenticated and his outgoing communication is protected against replay attacks – one Nonce is exchanged
- Mutual – both communication partners are authenticated and both communication ways are protected against replay attacks – two Nonce are exchanged

For CMAC computing the EnOcean security concept uses the Payload of telegrams. The Nonce is used during CMAC computing too and so ensures that the Nonce is connected with the exchanged message and its data content. So becomes the data content also valid for limited time.

EnOcean Security concept uses the VAES for data encryption. The Nonce can be also used for the initialization vector for the VAES process. This way a random element is added to the VAES process. This is required if Nonce is a random number and no RLC is used.

The Nonce can be:

- Used during CMAC counting
- Used as initialization vector for VAES counting

Nonce represents the challenge and has to be therefore exchanged between the communication partners via air interface. The Challenge and Response does not have to encrypt and can be transferred plaintext. The CMAC algorithm represents the securing element.

During data communication following constrains are applied:

- Bidirectional communication can be only executed after mutual authentication. Both parties can trigger the authentication
- Unidirectional communication is unilateral authenticated. The emitter of the data flow is authenticated and only the emitter can trigger the communication. The challenge is provided by the consumer of the data

For Nonce we can use:

- Random number 32 bit – here is critical that the generator process is not predictable, does not repeat same sequences and is equally spread on the defined range
- Simple incrementing, non-repeating sequence 32-bit number

6.2.2 Communication scenarios

To protect against relay attacks we define three new security communication approaches. They differ in aspect of the Use Case definition made in chapter 6.1:

1. Mutual authentication with RND as NONCE
2. Unilateral authentication with RND as NONCE

In following definitions the DEVICE A is the sensor / autarkic device which initialize the communication. DEVICE B is the line-powered device which is receiving the communication. The definitions also apply for Use Case 1, then DEVICE A is also an line powered device.

The link between A to B is unique, because of used keys. No other device can listen and decrypt the communication. The communication is unicast – and has to be eventually addressed in one or both directions, depending if device A or device B has other communication partners.

Device A

KEY A – key used by device A to encrypt communication, used for communication from A to B

RND A – random number generated by device A - 32 bits

TIMEOUT A – timeout on device A till next message from device B should be received

Device B

KEY B – key used by device B to encrypt communication, used in for communication from B to A

RND B – random number generated by device B - 32 bits

TIMEOUT B – timeout on device B till next message from device A should be received

Fields

In the following description we use these fields:

ENC: Encryption method - NA / VAES

VAES IntV: Content of the Initialization Vector of VAES, for Details see 5.1.

PAYLOAD: Content of the data field used in the telegram

CMAC: Content which is the CMAC calculated on – complete expiation see 6.3.3.1

RORG-MS Telegram payload length – in case of MS Telegram is used, we specify the length.

6.2.2.1 Mutual authentication with RND as NONCE

In this scenario the NONCE is represented by random sequences. No RLC is used. This solution might be useable for autarkic devices.

Failures like timeouts are not considered. Only the ideal case is described. On any failure e.g. CMAC not validated or timeouts the whole process is discarded and needs to start from beginning or other measures e.g. resynchronize must be taken. The communication will be executed in these steps.

1. A sends Challenge to B. and starts timeout A.

Message parameters:

- ENC: NA
- RORG: RORG-MS
- DATA: RORG-MS Header (RND), RND A
- RORG-MS telegram payload length = 5 bytes

2. B receives Challenge. Sends Response with next Challenge to A. B starts communication timeout B.

Message parameters:

- ENC: NA
- RORG: RORG-MS
- DATA: RORG-MS Header (DATA / RND / CMAC), RND B
- CMAC: DATA, RND A
- RORG-MS telegram payload length = 9 bytes

3. A receives Challenge and successfully authenticates it with help of both RNDs. A sends Response with payload data to B. Optionally - Starts timeout A.

Message parameters:

- ENC: VAES
- VAES INT: VAES INIT Vector + RND B
- RORG: RORG-SEC
- DATA: application payload
- CMAC: DATA, RND B, RND A

4. B receives Response with payload within timeout B. Validates it with help of both RNDs. Optionally – continues with communication and send another payload message.

Message parameters:

- ENC: VAES
- VAES INT: VAES INIT Vector + RND A
- RORG: RORG-SEC
- DATA: application payload
- CMAC: DATA, RND A, RND B

5. Optionally A receives message from B within timeout A.

No further communication with same RND A and RND B can be executed, because no Sequence number is present and replay attacks could be executed. To transmit bigger data quantities at once use message chaining.

Please see the process description in the sequence diagram below.

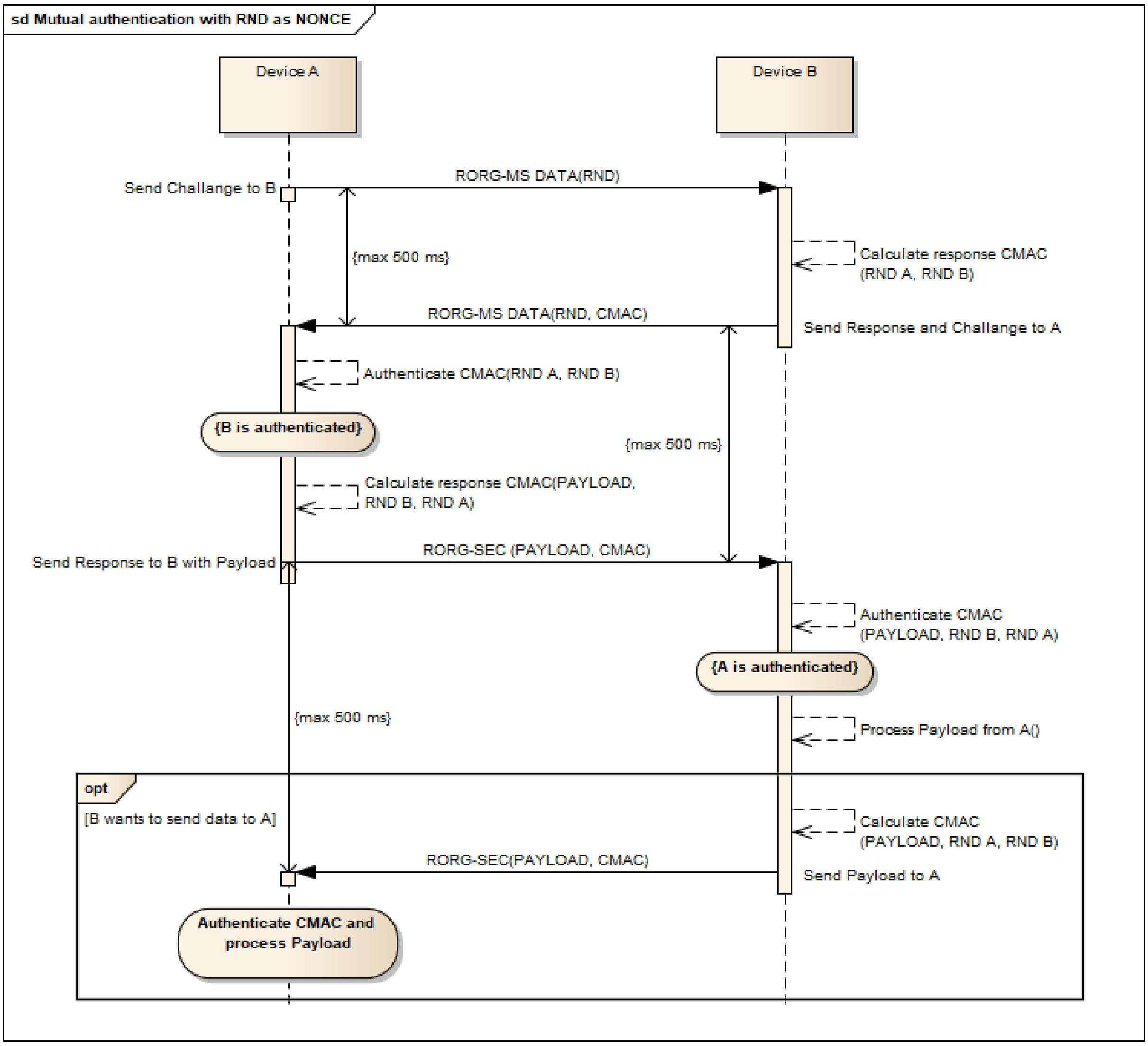


Figure 20 Mutual authentication with RND as NONCE.

SLF:

DATA ENC – VAES + RND

6.2.2.2 Unilateral authentication with RND as NONCE

In this scenario the HASH is represented by one random sequence. No RLC is used. This is the solution which requires the least amount of resources and ensures relay attack protection.

Failures like timeouts are not considered. Only the ideal case is described. On any failure CMAC not validated or timeouts the whole process is discarded and needs to start from beginning or other measures e.g. resynchronize must be taken. The communication will be executed in these steps.

1. A sends Request for Communication Message to B and start timeout A.

Message parameters:

- ENC: NA
- RORG: RORG-MS
- DATA: RORG-MS Header 0x00
- Payload length = 1 byte

2. B receives Request for Communication. Sends Challenge to A. B starts communication timeout B.

Message parameters:

- ENC: NONE
- RORG: RORG-MS
- DATA: RORG-MS Header (RND) + RND B
- Payload length = 5 bytes

3. A receives Challenge and successfully decodes it. A sends response with payload data to B. Starts timeout A.

Message parameters:

- ENC: VAES
- VAES INT: VAES INIT Vector + RND B
- RORG: RORG-SEC
- DATA: application payload
- CMAC: DATA + RND B

4. B receives message within timeout B. Decodes the message and authenticates with help of RND B.

No further communication with same RND B can be executed, because RLC is not present and replay attacks could be executed. To transmit bigger data quantities at once use message chaining.

Please see process description in the sequence diagram below.

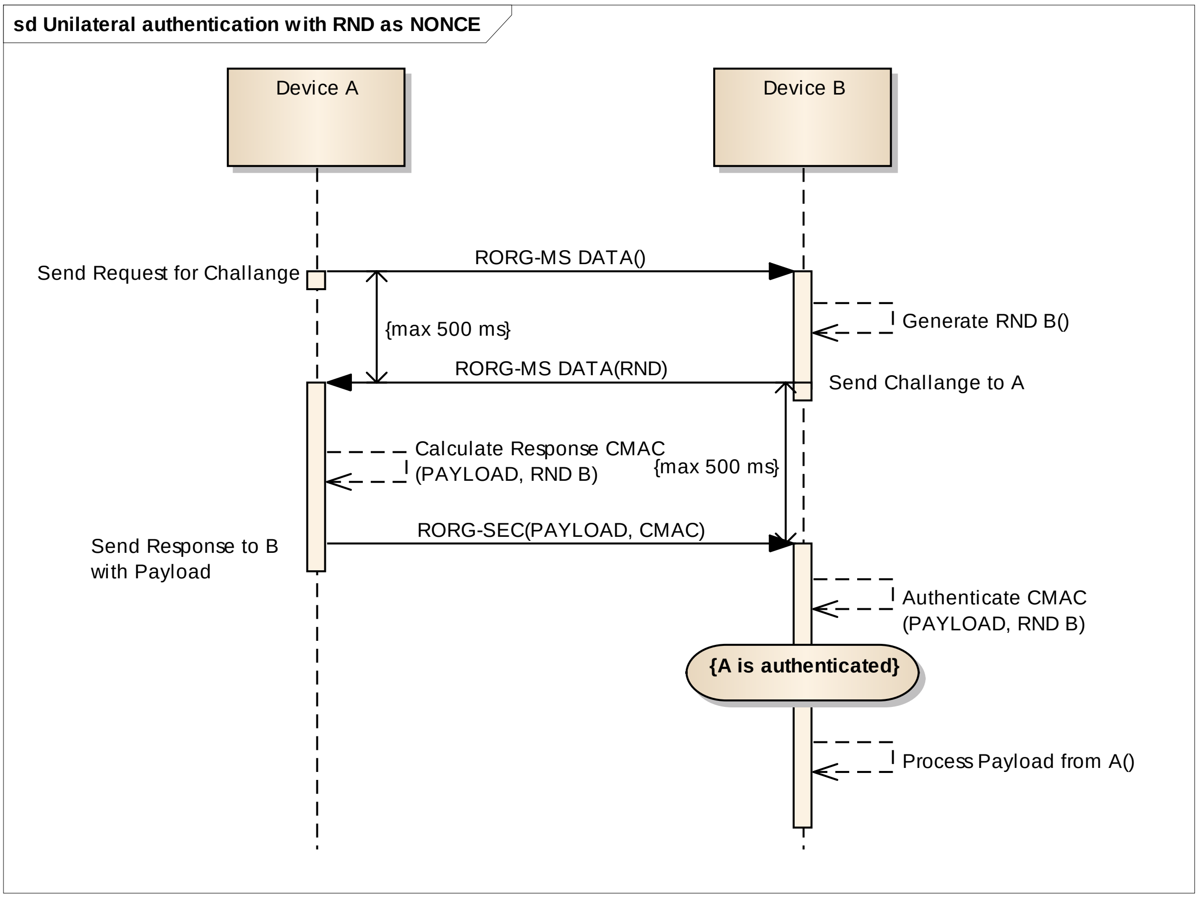


Figure Unilateral authentication with RND as NONCE.

6.2.2.3 Error scenarios

If the message gets lost the process is considered as failed.

Repeated transmissions of request for challenge or challenge messages between identical communication partners shall restart the authentication process and cancel any previous ongoing validation.

6.3 High Security inclusion into existing concept

6.3.1 Security Level Format extension

Which High Security communication concept is used during data communications needs to be communicated at teach in time. For this purpose the defined SLF is extended. Following extension has been made:

7	6	5	4	3	2	1	0
RLC_ALGO		**RLC_TX**	**MAC_ALGO**		**DATA_ENC**		
					1 – VEAS – AES128 - RND		

Table 6. Security Level Format extension fields and its interpretation.

DATA_ENC – Value: 0x1

VAES – AES128 – RND is used as initialization vector instead of RLC i.e. Mutual authentication with RND as NONCE, Unilateral authentication with RND as NONCE.

If secure teach in is bidirectional or not is already defined in INFO field – see chapter 4.1.2.

6.3.2 Meta Security Telegram

The Meta Security Telegram is required to support additional task required in high security. Following message structure is defined.

RORG-MS	HEADER	RND	CMAC

Figure 21 Meta security Telegram structure

RORG-MS

Meta Security telegrams are identified by the code 0x36.

Header

The RORG-MS telegram has a header which expresses what content of the meta-security information is carried. This header is always present at the first place.

7	6	5	4	3	2	1	0
NA	**NA**	**NA**	**NA**	**NA**	**NA**	**RND Included**	**CMAC Included**
						0: RND not included 1: RND is included	0: CMAC not included 1: CMAC is included

Table 6 Meta Security Telegram header fields and its interpretation.

RND - Random number used as challenge – if included.

CMAC - CMAC is included, used as response for authentication – if included.

6.3.3 Algorithm extension

6.3.3.1 CMAC

The CMAC is altered for data communication and for meta security telegram.

Following fields are added:

- SOURCE ID - Also the LSB 32-bit of the communication ID of the originating device
- RND 1 – 32 bit, first included random number
- RND 2 – 32 bit, second included random number (optional, depending on scenario i.e. Mutual or unilateral)

RND 1, RND 2 – can be represented by RND A, or RND B. The order is specified and is important to consider. Please see communication scenarios chapter 6.2.2 for details on order and content.

All fields are included only if required. Please find meta security header definition chapter 6.3.2 and communication scenarios chapter 6.2.2 for details and contend of the telegrams.

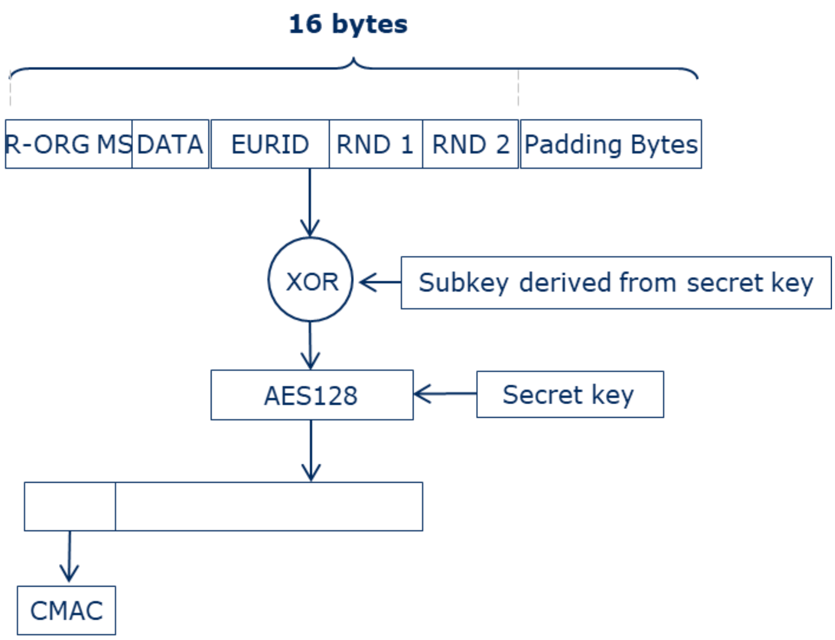


Figure 22 Graphical representation of altered CMAC for Meta Security Telegram

6.3.3.2 VAES

The VAES process has to be extended to use RND during processing of VEAS INIT Vector. The communication scenarios in chapter 6.2.2 are defined to RND as initialisation vector.

The RND is 32 bit long so the XOR operation needs to be extended to uses all 32 bits.

The VAES INIT VECTOR byte array first element, VEAS_INIT_VECTOR[0], is XORed with the RND most significant byte. VEAS_INIT_VECTOR[1] is XORed with the RND 2nd most significant byte and so on.

Please see graphical representation bellow.

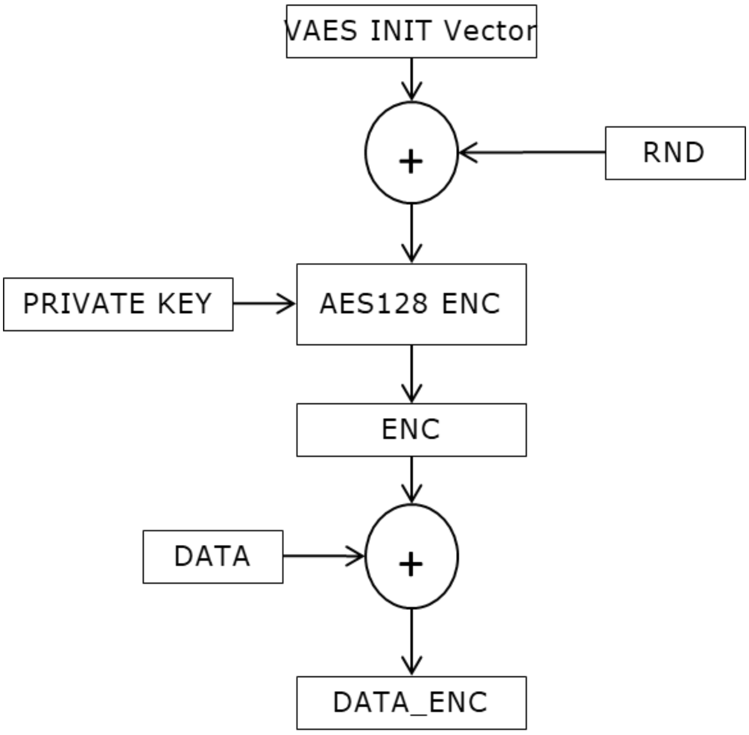
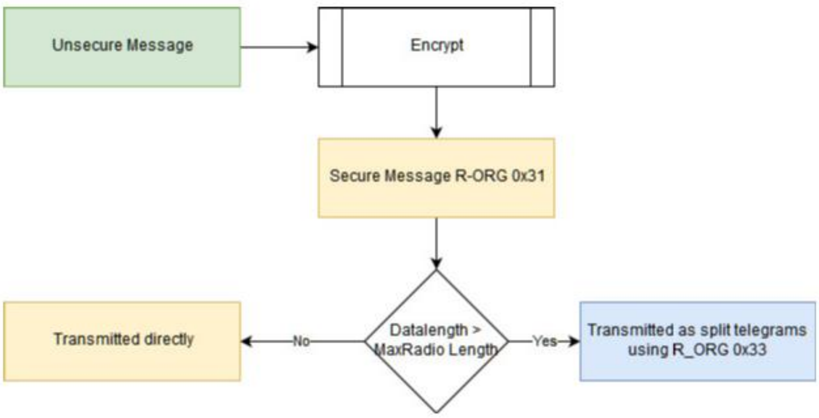


Figure 23 Graphical representation of VAES extended process.

7 SEC_CDM – 0x33 chained secure messages

Secure chaining is an add-on for the ERP chaining mechanism. The core functionality is the same as for Chained messages and the operation key and SLF will be used for transmitting secure chained messages. The message will be first encrypted like a normal telegram with encapsulated R-ORG and the SLF of the device. The encryption function uses the 0x31 R-ORG internally for the CMAC calculation. After the encryption using the 0x31 R-RORG was successful and the data length is longer than the maximum transmittable length. The message will be chained using the SEC_CDM.
This has the advanced that only once the overhead of transmitting the CMAC and RLC is added to the transmission of the split telegrams and only one RORG encapsulation is happening.



As most devices are embedded devices with limited memory capacity, it is highly recommended that only one chained message is send at a time. (To or from a device).

SEC_CDM	SEQ	IDX	data field	EURID	status	checksum
1 byte	2 bit	6 bit	N bytes. Depend if addressed or not And protocol	4 bytes	1 byte	1 byte
	1 byte					

Table 8: Radio telegram structure of SECURE chained telegram – NOT ADDRESSED.

Reminder from CDM:

A message consists of a number of chained telegrams. Each telegram in a chain has a sequence number and an index. The sequence number is the same for each message in the same chain and indicates that the messages belong to the same chain. It is increased with every new CDM and cannot be equal to 0.

The index starts from 0 and is incremented with each message in a chain. The purpose of the index is to indicate the correct order of the messages. The first message of a chain contains the total length of the payload of the message.

A full working example can be found in the appendix Annex A.

Example for the IDX 0 and ERP1: the following data is in the data field:

SEC_ CDM	SEQ	IDX	data length	RORG_EN	Payload	EURID	status	checksum
1 byte	2 bit	6 bit	2 Bytes	1 byte	10 bytes	4 bytes	1 byte	1 byte
	1 byte							
0x33	IDX= 0		Unencrypted, clear text. Data length = RORG+ Payload + RLC+CMAC length	Encapsulated RORG	Payload			

For the following index which are not the last telegram

SEC_ CDM	SEQ	IDX	Payload	EURID	status	checksum
1 byte	2 bit	6 bit	<= 13bytes	4 bytes	1 byte	1 byte
	1 byte					
0x33	IDX= x					

For the last telegram:

SEC_ CDM	SEQ	IDX	data field	RLC	CMAC	EURID	status	checksum
1 byte	2 bit	6 bit	Last part of the payload data	0,2 or 3 bytes	0, 3,4 bytes	4 bytes	1 byte	1 byte
	1 byte							
0x33	IDX=last			Depend on SLF	Depend on SLF			

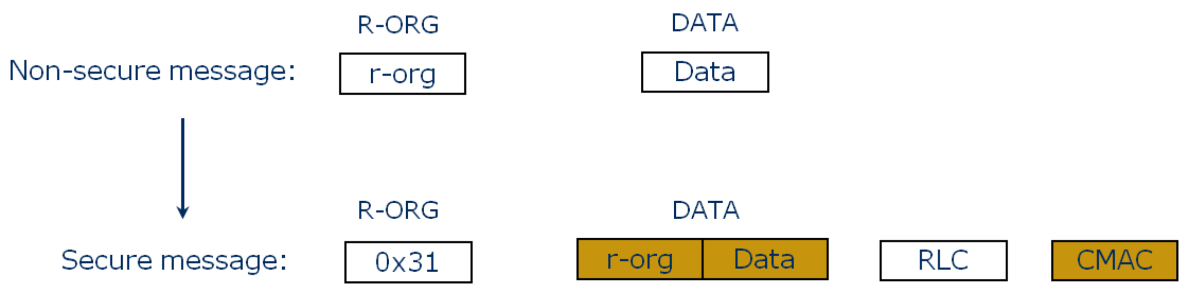


Figure 24 Reminding of "Transforming an unsecure message into a secure message with R-ORG encapsulation" Section 3.2.1. The secured message "0x31" is than transformed while sending into the 0x33 message

8 Implementations Aspects

This chapter explains which device should use which sort of SLF explained 4.1.3. All these points should be used when starting new devices. Only devices using these SLF shall get a "secured certification" **01.03.2020.** These devices can still be certified using lower levels, but a secure interoperable communication cannot be guaranteed. Other possible combinations of the SLF are deprecated and should no longer be used, except the challenge response (High security).

8.1 Rolling code

Rolling code is the key element in data protection and validation. The following definitions shall be adopted:

The RLC as plain information (not encrypted) should be transmitted explicitly inside the telegram without corrupting the data encryption / authentication or increasing the risk of potential intruder attacks. If the device does not have any energy storage and is extremely limited (See 8.2.3) this may be omitted.

The RLC shall be a 32-bit sequence number where possible. The 24-bit length should be used only in applications with limited energy. (See 8.2.2 and below)

The initial value of the RLC in every produced device should be 0.

When the rolling code is explicitly included inside the telegram, the RLC window limit concept shall not be applied. This results in the acceptance of any incoming RLC from the communication partner, as long as it has a higher value as the previously stored RLC. Roll over shall not be allowed in this case.

The RLC shall only be increased. An exception to this is when a new AES KEY is used; the RLC counter shall be set to 0 again.

This removes the need of RLC resynchronization, and simplifies the use case scenario by not compromising any security protection.

For devices using 8.2.3 it could be that RLC synchronization is needed after e.g. a power down reset. The recommendation for this is to one time increase the RLC window after a power down, to allow a guaranteed resync. Alternatively the RLC could be set directly in the receiver after reading it out.

8.2 Standard security level format

8.2.1 For line powered, -and devices with sufficient energy budget

The standard security level format shall be used for all

- Line powered Devices.

It should be used for

- Battery powered
- Energy Harvesting devices

7	6	5	4	3	2	1	0
RLC_ALGO			**MAC_ALGO**		**DATA_ENC**		
7 – 32 bit RLC / 32bit transmitted			2 – AES128 4 byte		3 – VAES – AES128 - RLC		

8.2.2 Reduced SLF - exceptions for energy limited applications

If a device does not have enough energy to transmit the additional 2 bytes it can use the "Reduced SLF"

This reduced SLF can only be used with

- Battery powered
- Energy Harvesting

And should only be used if 8.2.1 Standard SLF uses too much energy.

7	6	5	4	3	2	1	0
RLC_ALGO			**MAC_ALGO**		**DATA_ENC**		
5- 24bit RLC – 24 bit Transmitted 6 – 32 bit RLC / 24bit transmitted			1 - AES128 3 byte		3 – VAES – AES128 - RLC		

8.2.3 Push Button Transmitter SLF - Exceptions for kinetic devices with no energy storage

This SLF shall only be used if a device does not contain any sort of energy storage and has an extremely tight energy budget. Therefore, it has to use the generated energy directly after harvesting it. For example, a kinetic transmitter which immediately sends after activation secure data (Push button transmitter)

7	6	5	4	3	2	1	0
RLC_ALGO			**MAC_ALGO**		**DATA_ENC**		
4– 24bit RLC – not transmitted 5- 24bit RLC – 24 bit Transmitted			1 - AES128 3 byte		3 – VAES – AES128 - RLC		

8.3 Secure Teach-in

Plain text AES transmission over the AIR is deprecated and shall not be used for new implementations. The security teach-in shall be handled by, entering the security container

(SLF + Key (+optional RLC)) using a second pathway (e.g. Security Link tables with Secure ReMan, Serial Communication or via IP backbone).

Alternatively, the Security container can be transmitted using a PSK.

8.3.1 Secure Teach-in using QR Labels (or NFC)

The security container (SLF + key) of a device can be entered into another device using a “scan & copy” method.

1. Scan the 128bit AES key + SLF from
   a. The label of the communicating device.
   b. Or using an NFC tag
2. Enter the 128bit AES code into the receiving device.
   a. Via ReCom
   b. User Input method
   c. IP Backbone
   d. Serial Communication
3. The receiving device will use the RLC from the first data telegram for initialization.

NOTE: Since the RLC is part of the CMAC computing, the RLC in every data telegram is signed. Therefore there is no additional risk in taking the RLC from the first radio telegram. It is recommended that the first data telegram must be triggered by the user at a defined moment, similar to teach-in telegrams.

8.3.2 Secure Teach-in over the AIR with PSK

The PSK scenario includes scanning the device PSK and entering it into the receiver. By keeping these steps, the following scenario is possible:

1. Scan the 128bit AES PSK code from the label of the communicating device.
2. Enter the 128bit AES code into the receiving device.
3. Afterwards, the receiver will use the PSK to decrypt incoming teach in telegrams.

8.4 AES Key Selection and update mechanism

8.4.1 Key Selection

For the AES key, the following implementation aspects shall be used:

1. Each device shall have a unique, randomly generated AES key when it’s delivered
2. This key shall be the one printed on the QR – Label

3. Each device shall have a possibility to change the AES key:
    a. Via external interface to a certain value
    b. Randomly via user interaction

After changing the AES key, the RLC code shall be set to 0.

If keys can be changed, each key shall be selected uniquely and not duplicated.

8.5 Bidirectional communication

For bidirectional communication and changeable keys the following rules apply.

1. Each direction shall use a unique key with its own RLC.
2. For each communication partner, another unique key shall be used.
    a. Broadcast shall be seen for this use case as “one communication” partner

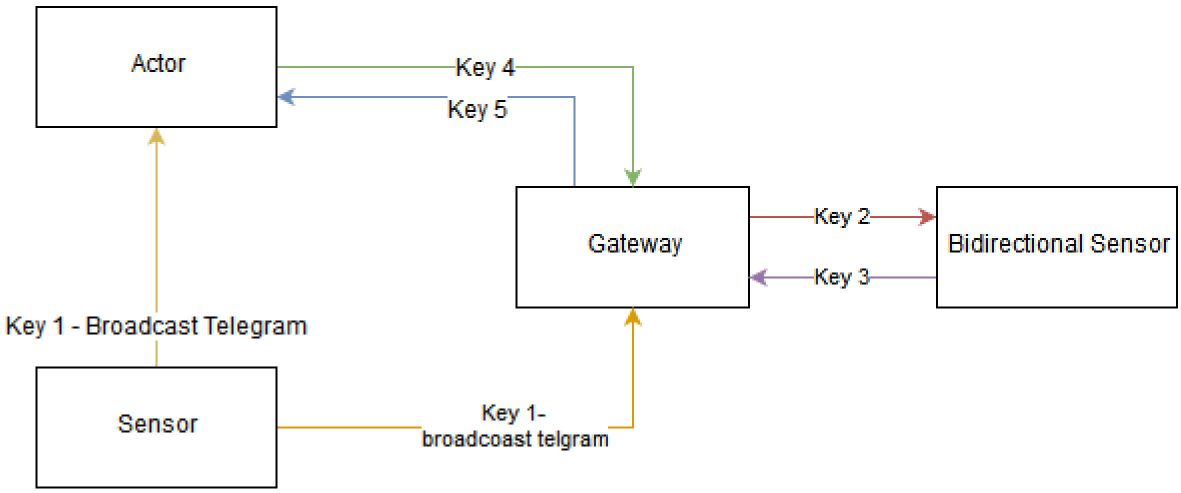


Figure 25 Example for multiple devices and used keys

9 Referenced documents

(1) NIST,FIPS 197, *Advanced encryption standard (AES)*, 2001

http://csrc.nist.gov/publications/fips/fips197/fips-197.pdf

(2) - Zabala, *Rijndael Cipher, 128-bit version (data block and key)*

http://www.cs.bc.edu/~straubin/cs381-05/blockciphers/rijndael_ingles2004.swf

(3) - JH. Song, R. Poovendran, J. Lee, T. Iwata, 2006, *The AES-CMAC Algorithm*

http://www.rfc-editor.org/rfc/rfc4493.txt

(4) - *AVR411: Secure Rolling Code Algorithm*.

http://www.atmel.com/Images/doc2600.pdf

(5) – Wikipedia, *Block cipher modes of operation*.

http://en.wikipedia.org/wiki/Block_cipher_modes_of_operation

Annex A Appendix

A.1 ERP1 secure telegrams

The following figure indicates the concretization of the secure message into ERP1 protocol.

A.1.1 Operation mode with EPR1

Secure message:

R-ORG S	DATA	RLC	CMAC

ERP1 telegram:

R-ORG S	DATA	RLC	CMAC	ID	STATUS

Figure 26. In the most general version of the secure message the RLC and CMAC fields are present. DATA can be encrypted. The fields R-ORG S, DATA, RLC and CMAC are integrated without modification in the ERP1 telegram. If DATA is encrypted in the message it is also encrypted in the ERP1 telegram. The ID and STATUS are specific to the telegram.

A.1.2 Secure teach-in chaining with ERP1

The ERP1 limits the amount of bytes transmitted to 21 per telegram. Therefore, the secure teach-in message must be partitioned in at least two telegrams (chaining).

R-ORG TS	TEACH_IN_INFO	SLF	RLC	KEY

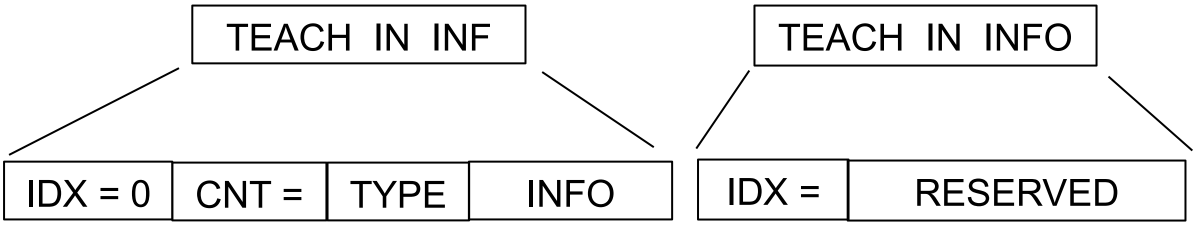
Figure 27 The general teach-in message security members

Dividing the message into two telegrams results in the following:

RORG-TS	TEACH IN INFO	SLF	RLC	KEY	ID	STAT

RORG-TS	TEACH IN INFO	KEY	ID	STAT

Teach-in message information divided in two ERP1 telegrams. The telegram with TEACH_IN_INFO_0 byte is sent first. This telegram contains the teach-in RLC, SLC and the first part of the KEY of the teach-in message. The second telegram transports the second part of the KEY.



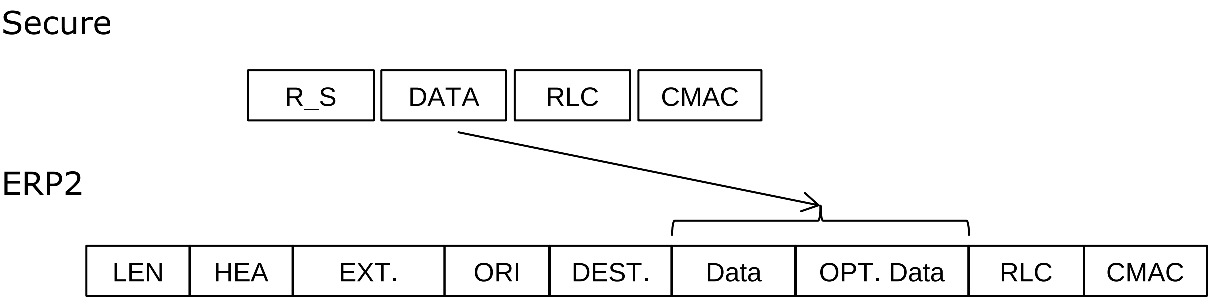
The IDX bit field of TEACH_IN_INFO_0 = 0 indicates that this is the first telegram. The CNT=2 indicates that the message is divided in 2 telegrams. TEACH_IN_INFO_1 IDX field = 1 says that this telegram is the second one. See chapter 4.1.2 to learn more about the TEACH-IN INFO bit fields.

It is specified, that there is no direct timeout between the chained telegrams of the teach-in-message. Each newer received telegram overwrites older received telegrams. At the end of the learn mode, all partly received messages will be deleted.

A.2 ERP2 secure telegrams

The following figure indicates the concretization of the secure message into ERP2 protocol.

A.2.1 Operation mode with EPR2



The secure message DATA field used throughout this documentation contains the information of the concatenated ERP2 telegram Data and Optional Data fields. If the message DATA field is encrypted is also encrypted in the telegram. The RLC and CMAC are placed after the Optional Data. The information of the R-ORG S is contained within the HEADER field. The EXTENDED HEADER depends on the telegram. See ERP2 Specification

A.2.2 Secure teach-in with ERP2

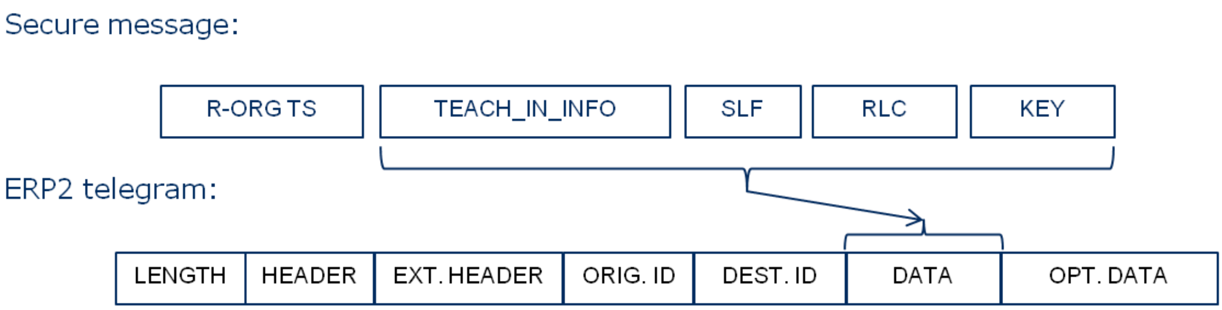


Figure 28. The message fields TEACH_IN_INFO, SLF, RLC and KEY are concatenated in the order indicated and placed in the DATA field of the ERP2 telegram. The information of R-ORG TS is contained within the HEADER. The EXTENDED HEADER depends on the telegram.

A.2.2.1 Secure teach-in chaining with ERP2

Many EnOcean applications have a very limited amount of energy available. For this reason, if needed, is possible to fragment the teach-in message (described in 4) in several telegrams.

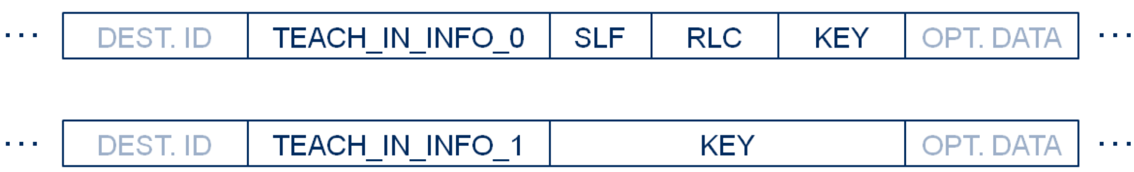


Figure 29. The secure teach-in message is transmitted here by two ERP2 telegrams. The information within the field DATA, between the telegram's Destination ID and Optional Data, is shown. SLF, RLC and the first part of the KEY are transmitted in the first telegram. The second telegram contains the second part of the KEY. The TEACH_IN_INFO_X bytes are interpreted like in the Chapter 4.

It is specified, that there is no direct timeout between the chained telegrams of the teach-in-message. Each newer received telegram overwrites older received telegrams. At the end of the learn mode, all partly received messages will be deleted.

A.3 PSK CRC8 checksum algorithm

The polynomial is P(x) = $x^8 + x^2 + x^1 + x^0$

```
code uint8 u8CRC8Table[256] = {
    0x00, 0x07, 0x0e, 0x09, 0x1c, 0x1b, 0x12, 0x15,
    0x38, 0x3f, 0x36, 0x31, 0x24, 0x23, 0x2a, 0x2d,
    0x70, 0x77, 0x7e, 0x79, 0x6c, 0x6b, 0x62, 0x65,
    0x48, 0x4f, 0x46, 0x41, 0x54, 0x53, 0x5a, 0x5d,
    0xe0, 0xe7, 0xee, 0xe9, 0xfc, 0xfb, 0xf2, 0xf5,
    0xd8, 0xdf, 0xd6, 0xd1, 0xc4, 0xc3, 0xca, 0xcd,
    0x90, 0x97, 0x9e, 0x99, 0x8c, 0x8b, 0x82, 0x85,
    0xa8, 0xaf, 0xa6, 0xa1, 0xb4, 0xb3, 0xba, 0xbd,
    0xc7, 0xc0, 0xc9, 0xce, 0xdb, 0xdc, 0xd5, 0xd2,
    0xff, 0xf8, 0xf1, 0xf6, 0xe3, 0xe4, 0xed, 0xea,
    0xb7, 0xb0, 0xb9, 0xbe, 0xab, 0xac, 0xa5, 0xa2,
    0x8f, 0x88, 0x81, 0x86, 0x93, 0x94, 0x9d, 0x9a,
    0x27, 0x20, 0x29, 0x2e, 0x3b, 0x3c, 0x35, 0x32,
    0x1f, 0x18, 0x11, 0x16, 0x03, 0x04, 0x0d, 0x0a,
    0x57, 0x50, 0x59, 0x5e, 0x4b, 0x4c, 0x45, 0x42,
    0x6f, 0x68, 0x61, 0x66, 0x73, 0x74, 0x7d, 0x7a,
    0x89, 0x8e, 0x87, 0x80, 0x95, 0x92, 0x9b, 0x9c,
    0xb1, 0xb6, 0xbf, 0xb8, 0xad, 0xaa, 0xa3, 0xa4,
    0xf9, 0xfe, 0xf7, 0xf0, 0xe5, 0xe2, 0xeb, 0xec,
    0xc1, 0xc6, 0xcf, 0xc8, 0xdd, 0xda, 0xd3, 0xd4,
    0x69, 0x6e, 0x67, 0x60, 0x75, 0x72, 0x7b, 0x7c,
    0x51, 0x56, 0x5f, 0x58, 0x4d, 0x4a, 0x43, 0x44,
    0x19, 0x1e, 0x17, 0x10, 0x05, 0x02, 0x0b, 0x0c,
    0x21, 0x26, 0x2f, 0x28, 0x3d, 0x3a, 0x33, 0x34,
    0x4e, 0x49, 0x40, 0x47, 0x52, 0x55, 0x5c, 0x5b,
    0x76, 0x71, 0x78, 0x7f, 0x6A, 0x6d, 0x64, 0x63,
    0x3e, 0x39, 0x30, 0x37, 0x22, 0x25, 0x2c, 0x2b,
    0x06, 0x01, 0x08, 0x0f, 0x1a, 0x1d, 0x14, 0x13,
    0xae, 0xa9, 0xa0, 0xa7, 0xb2, 0xb5, 0xbc, 0xbb,
```

0x96, 0x91, 0x98, 0x9f, 0x8a, 0x8D, 0x84, 0x83,
0xde, 0xd9, 0xd0, 0xd7, 0xc2, 0xc5, 0xcc, 0xcb,
0xe6, 0xe1, 0xe8, 0xef, 0xfa, 0xfd, 0xf4, 0xf3

```
crc=0;
for (i=0; i<sizeof(key); i++)
{
   crc  = u8CRC8Table[crc ^ key[i]];
}
```

Example

key = 0x3410de8f1aba3eff9f5a117172eacabd

crc8 = 0x07

A.4 Security Test vectors

The following test vectors are useful to check the user implementation for secure applications.

A.4.1 Secure STM with ID (01 9E B6 3B)

The first example uses variable AES128 as encryption algorithm, 4 byte CMAC and 3 byte rolling code as security parameters.

- Teach-In Messages: Transmitted packets over the air:
  1. 35 20 93 C0 FF EE 45 6E 4F 63 65 61 6E 01 9E B6 3B 00
  2. 35 40 20 47 6D 62 48 2E 31 33 00 01 9E B6 3B 00
- Teach-Info : 0x00
- Security Layer format: 0x93
- “SLF_DATA_ENC_VAES128 | SLF_MAC_4BYTE | SLF_RLC_ALGO_24BIT”
- Security Key: 0x45, 0x6E, 0x4F, 0x63, 0x65, 0x61, 0x6E, 0x20, 0x47, 0x6D, 0x62, 0x48, 0x2E, 0x31, 0x33, 0x00
- Rolling code: 0xC0FFEE

Unsecure Data message:

- Transmitted Packet over the Air: A5 08 27 FF 80 01 9E B6 3B 00
- RORG: 0xA5
- DATA: 0x08, 0x27, 0xFF, 0x80

Secure Data Message:

Data encryption:

```
VAES init vector    0x3410de8f1aba3eff9f5a117172eacabd
XOR
RLC padded          0xc0ffee00000000000000000000000000
---------------------------------------------------
Input               0xf4ef308f1aba3eff9f5a117172eacabd
AES
Key                 0x456E4F6365616E20476D62482E313300
---------------------------------------------------
                    0x9be2e35d5fe7858645200587dd3b515c
XOR
Data padded         0xa50827ff800000000000000000000000
---------------------------------------------------
Data encrypted      0x3eeac4a2dfe7858645200587dd3b515c
```

Subkey generation for CMAC calculation

```
Key             0x456E4F6365616E20476D62482E313300
AES128
Input           0x00000000000000000000000000000000
--------------------------------------------------
                         0xdd21aa892ddf3cb967c314369a272338
<<

--------------------------------------------------
             0xba4355125bbe7972cf86286d344e4670
XOR
             0x00000000000000000000000000000087
--------------------------------------------------
K1=                 0xba4355125bbe7972cf86286d344e46f7
<<

--------------------------------------------------
             0x7486aa24b77cf2e59f0c50da689c8dee
XOR
             0x00000000000000000000000000000087
--------------------------------------------------
K2=          0x7486aa24b77cf2e59f0c50da689c8d69


Message padded 0x313eeac4a2dfc0ffee80000000000000
XOR
K2             0x7486aa24b77cf2e59f0c50da689c8d69
----------------------------------------------------
Input          0x45b840e015a3321a718c50da689c8d69
AES128
Key            0x456E4F6365616E20476D62482E313300
---------------------------------------------------
CMAC(128bits)  0xeaf20eed28679f641c15b10b9308d0d4
```

- Transmitted Packet over the Air:
  31 3E EA C4 A2 DF EA F2 0E ED 01 9E B6 3B 00
- RORG: 0x31 (secure ROG with encrypted original ROG)
- DATA: 0x3E, 0xEA, 0xC4, 0xA2, 0xDF
- CMAC: 0xEA, 0xF2, 0x0E, 0xED
- RLC (not transmitted): 0xC0FFEE

The second example uses variable AES128 as encryption algorithm, 3 byte Rolling code and no CMAC as security parameters.

Teach-In Message

- Transmitted packets over the air
  1. 35 20 83 C0 FF EE 45 6E 4F 63 65 61 6E 01 9E B6 3B 00
  2. 35 40 20 47 6D 62 48 2E 31 33 00 01 9E B6 3B 00
- Teach-Info : 0x00
- Security Layer format: 0x83
- “SLF_DATA_ENC_VAES128 | SLF_MAC_NO | SLF_RLC_ALGO_24BIT”
- Security Key: 0x45, 0x6E, 0x4F, 0x63, 0x65, 0x61, 0x6E, 0x20, 0x47, 0x6D, 0x62, 0x48, 0x2E, 0x31, 0x33, 0x00
- Rolling code: 0xC0FFEE

Unsecure Data Message:

- Transmitted Packet over the Air: A5 08 27 FF 80 01 9E B6 3B 00
- RORG: 0xA5
- DATA: 0x08 0x27 0xFF 0x80

Secure Data Message:

- Transmitted packet over the air: 31 3E EA C4 A2 DF 01 9E B6 3B 00
- RORG: 0x31
- DATA: 0x3E 0xEA 0xC4 0xA2 0xDF Same byte sequence as in example 1..
- RLC: 0xC0FFEE

A.4.2 Secure PTM (with ID 01 85 E1 77)

This example uses variable AES128 encryption algorithm, 3 byte CMAC and 2 byte rolling code.

Teach-In Message:

- Transmitted packets over the air:
  1. 35 24 4B 3E 2D 45 6E 4F 63 65 61 6E 01 85 E1 77 00
  2. 35 40 20 47 6D 62 48 2E 31 33 00 01 85 E1 77 00
- Teach-In info: 0x04 // TEACH_INFO_PTM | TEACH_INFO_PTM_ROCKERA
- Security Layer format = 0x4B
  SLF_DATA_ENC_VAES128 | SLF_MAC_3BYTE | SLF_RLC_ALGO_16BIT
- Security Key:
  0x45, 0x6E, 0x4F, 0x63, 0x65, 0x61, 0x6E, 0x20, 0x47, 0x6D, 0x62, 0x48, 0x2E, 0x31, 0x33, 0x00
- Rolling code: 0x3E2D

Unsecure Data message:

- Transmitted Data over the air:
  D2 09 01 85 E1 77 00
- RORG: 0xD2
- DATA: 0x09

Secure Data message:

Data encryption:

```
VAES init vector    0x3410de8f1aba3eff9f5a117172eacabd
XOR
RLC padded          0x3E2D0000000000000000000000000000
---------------------------------------------------
Input               0x0a3dde8f1aba3eff9f5a117172eacabd
AES
Key                 0x456E4F6365616E20476D62482E313300
---------------------------------------------------
                    0xc77f3257ca9f626ad8f6ed44db04d26c
XOR
Data padded         0x09
---------------------------------------------------
                    0xce
```

```
AND
Mask(*)            0x0f
----------------------------------------------------
Data encrypted      0x0e
```

(*) For PTM secure telegrams the secured data most significant byte is chopped.

```
CMAC generation (like in example 1)
Key            0x456E4F6365616E20476D62482E313300
Subkey K2      0x7486aa24b77cf2e59f0c50da689c8d69

Message padded 0x300E3E2D800000000000000000000000
XOR
K2             0x7486aa24b77cf2e59f0c50da689c8d69
----------------------------------------------------
Input          0x44889409377cf2e59f0c50da689c8d69
AES128
Key            0x456E4F6365616E20476D62482E313300
---------------------------------------------------
CMAC(128bits)  0xebdcc47285ab750a21c06a4ed2627ad0
```

Generated Encrypted Message:

Payload with encrypted RORG + Payload + CMAC

- Transmitted Data over the air: 30 0E EB DC C4 01 85 E1 77 00
- RORG: 0x30
- DATA: 0x0E
- CMAC: 0xEB, 0xDC, 0xC4

Decrypted Data Message by the receiver:

- Transmitted Data over the air: 32 09 01 85 E1 77 00
- RORG: 0x32
- DATA: 0x09

A.4.3 Secure Chained Data

This example uses variable AES128 as encryption algorithm, 4 byte CMAC and 4 byte rolling code as security parameters.

- Security Layer format: 0xF3
- "SLF_DATA_ENC_VAES128 | SLF_MAC_4BYTE | SLF_RLC_ALGO_32BIT | SLF_RLC_TX_ON"
- Security Key: 0xE5, 0x08, 0x80, 0xCF, 0x67, 0x79, 0x0D, 0x5D, 0x66, 0xAA, 0x7F, 0x3B, 0x7A, 0xD7, 0x7A, 0x3F
- Rolling code: 0x01020304

Unsecure Data message:

- RORG: 0xD1
- DATA: 00 01 02 03 04 05 06 07 08 09 0A 0B 0C 0D 0E 0F 10 11 12 13 14 15 16 17 18 19 1A 1B 1C 1D

Secure Data Message:

Data encryption: 1st part

```
VAES init vector    0x3410de8f1aba3eff9f5a117172eacabd
XOR
RLC padded          0x01020304000000000000000000000000
---------------------------------------------------
Input               0x3512dd8b1aba3eff9f5a117172eacabd
AES
Key                 0xE50880CF67790D5D66AA7F3B7AD77A3F
---------------------------------------------------
                    0x6a17c07806cef0515aea013a24b97fae
XOR
Data padded         0xD1000102030405060708090A0B0C0D0E
---------------------------------------------------
                    0xbb17c17a05caf5575de208302fb572a0
```

Data encryption: 2nd part

```
VAES init vector    0x3410de8f1aba3eff9f5a117172eacabd
XOR
RLC padded          0x01020304000000000000000000000000
AES-Result 1st part 0x6a17c07806cef0515aea013a24b97fae
---------------------------------------------------
Input               0x5f051df31c74ceaec5b0104b5653b513
```

```
AES
Key                  0xE50880CF67790D5D66AA7F3B7AD77A3F
---------------------------------------------------
                     0xf22a5526b70483e715fe14d8166b673f
XOR
Data padded          0x0F1011121314151617181911A1B1C1D
---------------------------------------------------
                     0xfd3a4434a41096f102e60dc20d777a
```

Generated Encrypted Message:

Payload with encrypted RORG + Payload + RLC + CMAC

RORG: 31

Data: BB 17 C1 7A 05 CA F5 57 5D E2 08 30 2F B5 72 A0 FD 3A 44 34 A4 10 96 F1 02 E6 0D C2 0D 77 7A 01 02 03 04 3B 4C 38 0F

Transmitted Telegrams over air:

RORG	SEQ	IDX	Date length	Payload
SEC_CDM	2 bit	6 bit	2 byte	11 byte
33	2	0	00 27	BB 17 C1 7A 05 CA 05 F5 57 5D E2

Table Chained Secure telegram IDX = 0

RORG	SEQ	IDX	Payload
SEC_CDM	2 bit	6 bit	12 byte
33	2	1	08 30 2F B5 72 A0 FD 3A 44 34 A4 10

Table Chained Secure telegram IDX = 1

RORG	SEQ	IDX	Payload
SEC_CDM	2 bit	6 bit	12 byte
33	2	2	96 F1 02 E6 0D C2 0D 77 7A 01 02 03

Table Chained Secure telegram IDX = 2

RORG	SEQ	IDX	Payload
SEC_CDM	2 bit	6 bit	7 byte
33	2	3	04 3B 4C 38 0F

Table Chained Secure telegram IDX = 3