SPECIFICATION

Security of EnOcean Radio Networks

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REVISION HISTORY

The following major modifications and improvements have been made to the first version of this document:

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1.4	Editorial on CMAC computing	22.11.2012	MH
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1.6	Abstraction from telegram to message	03.07.2013	MF
1.7	Teach-in unidirectional/bidirectional procedure described	10.07.2013	MF
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1 Security of EnOcean Radio Networks

1.1Terms & Abbreviations

Term / Abbr.	Description
µC	Microcontroller (external)
API	Application Programming Interface
APP	Application
Data	Payload of EHW telegram
EEP	EnOcean Equipment Profile
EHW	Energy Harvested Wireless protocol
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

Table 1. Abbreviations used in this document.

2 Introduction

This document specifies the security concept proposal for the Energy Harvested Wireless protocol (EHW). This concept was specially designed for devices powered by energy harvesters and is based on the EHW lower protocol lower layers. The objective of the design was to keep the energy requirements and µC resources for the implementation of the security as low as possible.

3 Scenarios

The EHW protocol 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.

3.1 Attacker scenarios

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

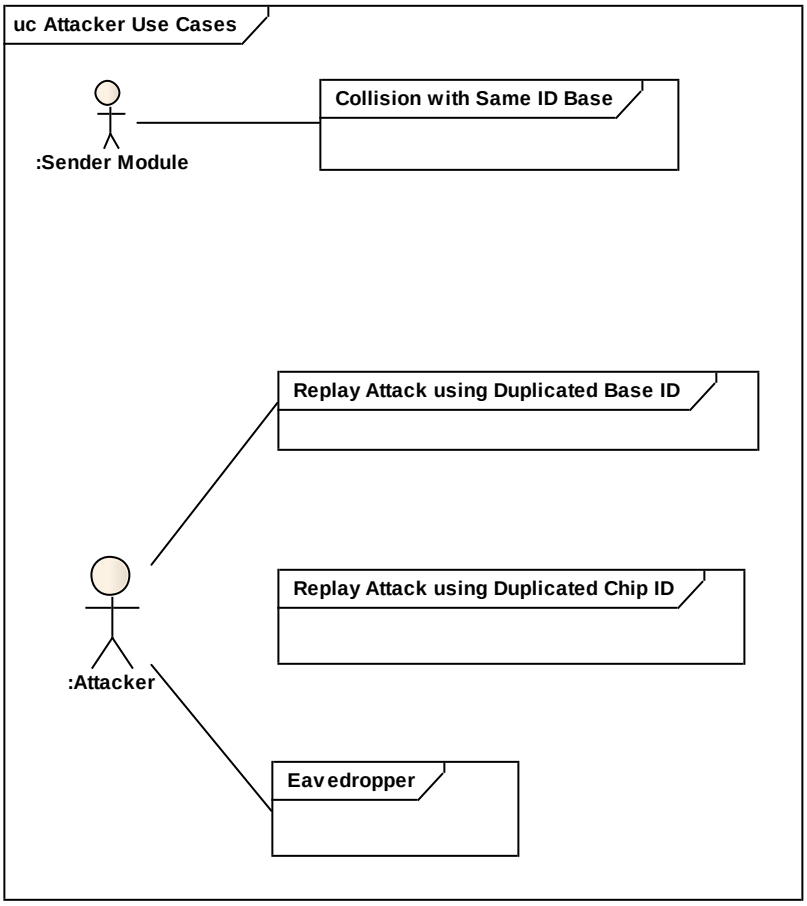


Figure 1. The picture shows the possible interferences and attacks in the actual EO radio communication. Attacks other than the ones shown in this figure will not be considered in this documentation and in the implementation of a secure radio protocol. Attacks not considered include, for instance, the 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*.

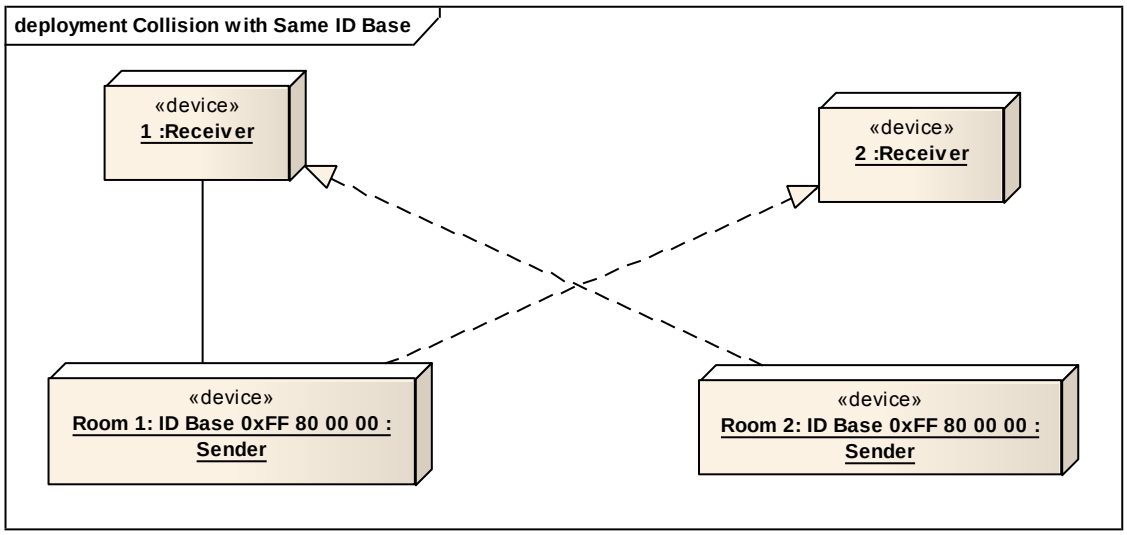


Figure 2. This scenario is not a proper attack. It's simply an ID duplication within the range of the base ID (see what is EnOcean Base ID). The duplication happens because two different users programmed their sender modules with identical ID within the base ID range. When the user in room 1 sends a 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.

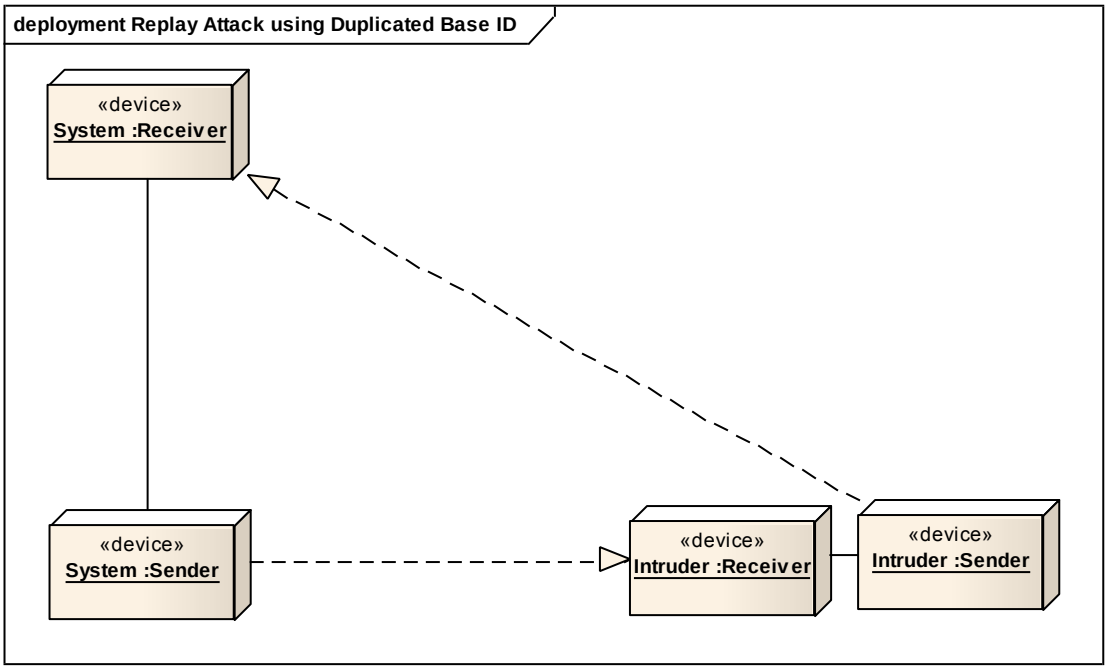


Figure 3. In this scenario an attacker programs the ID base taking intentional control of the system receiver. To do this, the intruder simply listens to the sender ID. It programs then this same Base ID in his sender module, and controls the system receiver. All this is possible using EO tools without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

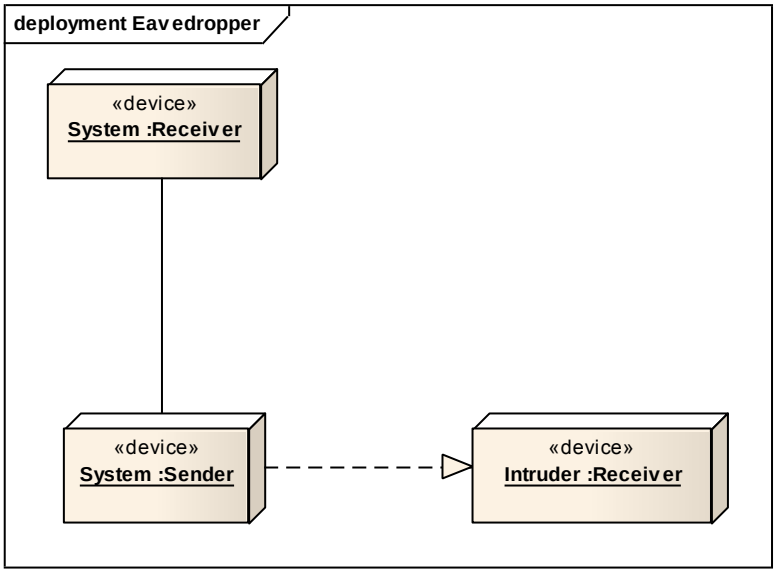


Figure 4. With the only help of an EO receiver it is possible to hear the communication between an EO sender and a receiver. This is undesired if the information being transmitted is private. This is the case of metering reading systems.

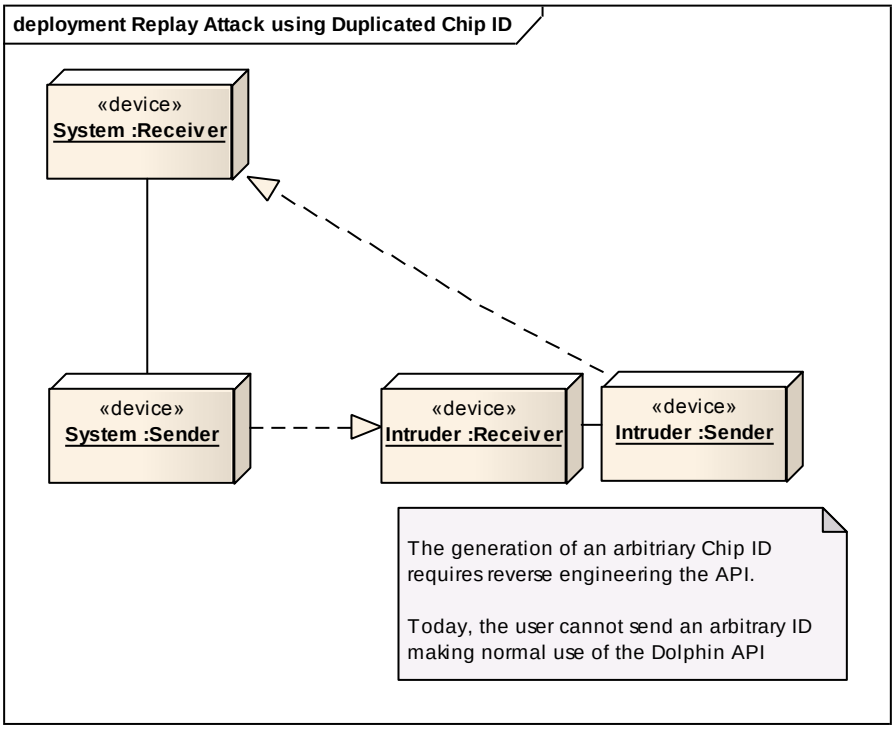


Figure 5. In a more sophisticated attack version the attacker listens to the telegrams in the air. The attacker sends a telegram with the same chip ID (replay) as the one in the system sender. This can be done by using a HW tool that reproduces listened telegrams,

or by applying reverse engineering to the Dolphin API and modifying the sendTelegram functions which contain the chip ID.

3.2 System Architecture

Typical system architecture using EHW protocol is showed on the figure below:

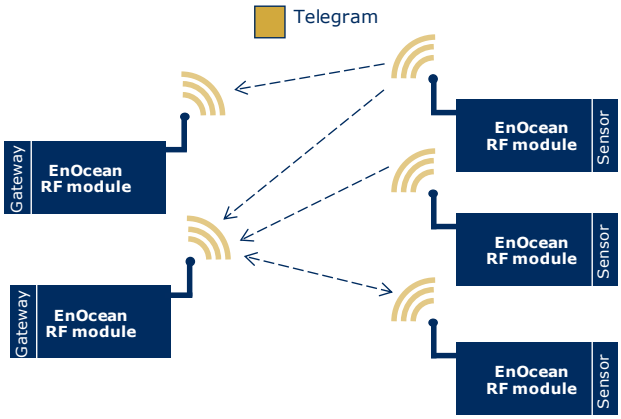


Figure 6 EHW system architecture

In an EHW 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.

4 Specification

To handle security of EnOcean Radio networks 4 new ORGs will be created according the following table:

R-ORG	Description
0x30	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	Secure message that transport the original R-ORG non secure code.
0x32	Non-secure message type that results from the decryption of a secure message with R-ORG 0x30.
0x35	Secure Teach-In telegrams transmit private key and rolling to the communication partner

Table 2 New ORGs for security handling

4.1 Security for operation mode

The EHW security is implemented on the OSI presentation layer of the EHW 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. Through the combination of all security strategies a higher degree of security can be reached at the expense of a high amount of energy spent due to higher processing and transmission time.

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 may 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 and the qualitative energy factor they represent.

MESSAGE	Scenario	Replay Attacks	Eaves-dropping	Energy & resource demand
R-ORG DATA	Unsecured	Yes	Yes	Energy Harvester
R-ORG S DATA	Thermostat & Vacation Mode	Yes	No	
R-ORG S DATA RLC CMAC	Window Control	No	Yes	
R-ORG S DATA RLC CMAC	Automated Meter Reader	No	No	Line Powered

Table 3 The table shows the different secure messages structures for typical applications EnOcean secure messages can be built up with a higher or lower degree of security,

which allows to find a balance between security and energy consumption. 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. Message members in green indicate the usage of encryption.. **Any combination of DATA encrypted/not encrypted, RLC present/not present, and CMAC present/not present is possible.** In the table only some typical combinations were depicted.

The structure of the secure telegram is negotiated between the devices within the teach-in procedure. See 4.2.

4.1.1 Message structure

Figure 7. Relevant message members. In what follows the DATA member includes the DATA and OPTIONAL DATA.

4.1.1.1 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 or 0x35, denoted generally *R-ORG S* in the Table 3.

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

4.1.1.2 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 4.3.

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.

4.1.1.3 RLC (ROLLING CODE)

This field contains a code that changes according to a predefined algorithm (see 4.3.7). Sender and receiver must keep this code synchronize. The code changes 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.

RLC is MSB first.

The teach-in procedure synchronizes the RLC in the receiver with the one in the receiver.

The RLC field is actually optional. Although the RLC may not be sent by the transmitter it can be used internally in the transmitter and receiver modules to perform the calculation of the CMAC code and DATA field encryption. See 4.3.8. 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.

Details of the RLC algorithm are explained in section 4.3.7

4.1.1.3.1 Synchronizing RLC when synchronization window is lost

In the event that the RLC in the receiver losses the RLC window no communication between sender and receiver will be possible.

In order to synchronize the RLC in the receiver the sender must send a teach-in telegram. See chapter 4.2. The receiver does not have to be put into teach-in mode. The current RLC in the teach-in telegram can be used now by the receiver to synchronize with the sender.

4.1.1.4 CMAC

The CMAC is the cipher-based message authentication code field –with MSB first. Its mission is to guarantee that the message is genuine, meaning that no other party that the expected one transmitted the message.

The CMAC is dependent on the private key (see 4.2.1.5), a public vector, the message bytes and, if it exists, the rolling code (see 4.1.1.3).

For maximal security the RLC should be present but not transmitted. The MAC field code changes for every sent message. The way the CMAC changes is unpredictable unless the key and the RLC state are known.

The algorithm to calculate CMAC is explained in the chapter 4.3.8

4.1.2 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.

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

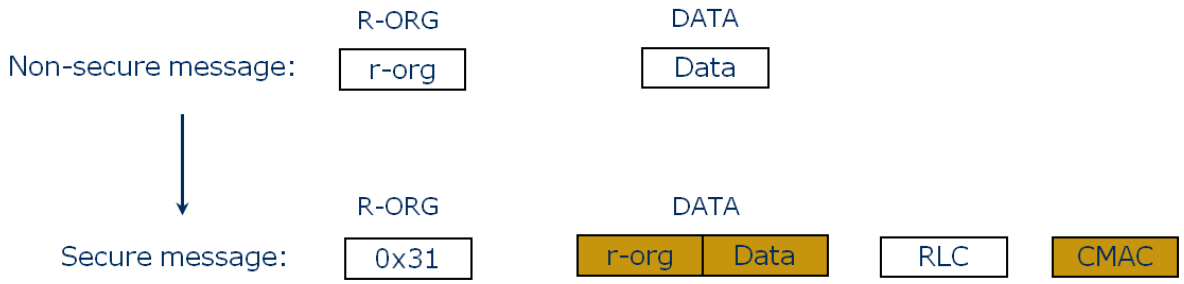


Figure 8. An unsecure message is transformed into a secure message that includes the original R-ORG by 1- transforming the message R-ORG code to 0x31. 2- The unsecure R-ORG field code and the unsecure DATA fields are concatenated and then encrypted. 3- The result of the encryption is stored in the most significant bytes of the secure message DATA field. 4- A rolling code, RLC, might be calculated (section 4.3.7). 5- Finally, it is possible to add a CMAC code (chapter 4.3.8). Other message fields like sender ID, receiver ID or repeater counter are not modified.

4.1.2.2 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.

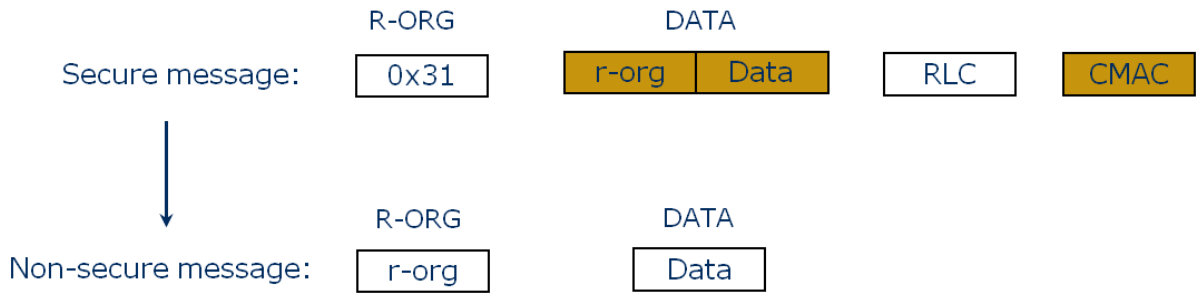


Figure 9. A secure message with R-ORG 0x31 contains the unsecured R-ORG encrypted in the DATA field. The DATA field of the message must be decrypted, maybe with the help of the RLC. The first decrypted byte represents the message R-ORG of the unsecure message. The rest of the decrypted DATA field bytes 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

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

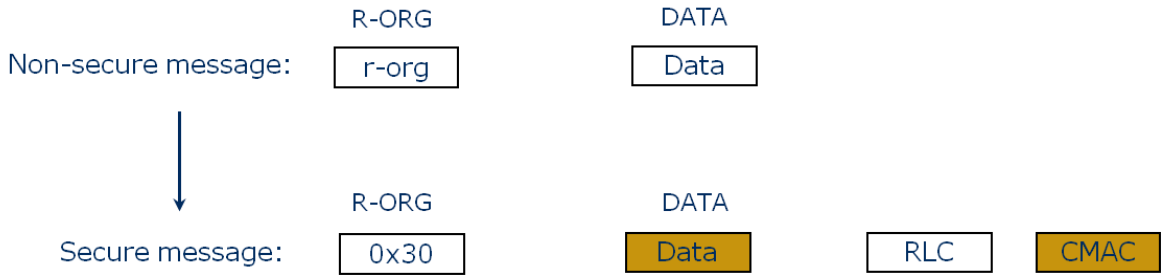


Figure 10. An unsecure message is transformed into a secure message that does not include the original R-ORG by 1- rewriting the message R-ORG code to 0x30. 2- The unsecure DATA field is encrypted. 3- The result of the encryption is stored in the secure message DATA field. 4- A rolling code might be 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.

4.1.2.4 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.

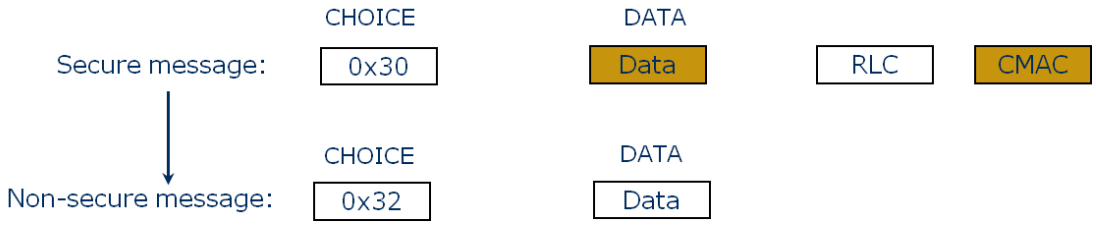


Figure 11. The secure message with R-ORG 0x30 does not include the non-secure R-ORG information in any form. In the conversion from secure to non-secure message the latter becomes the R-ORG = 0x32.The DATA field is decrypted, maybe using the RLC field. The CMAC does not play a role in the decryption.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

4.2 Security for teach-in mode

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 an unidirectional or bidirectional process. See 4.2.1.2 to learn how to configure this option.

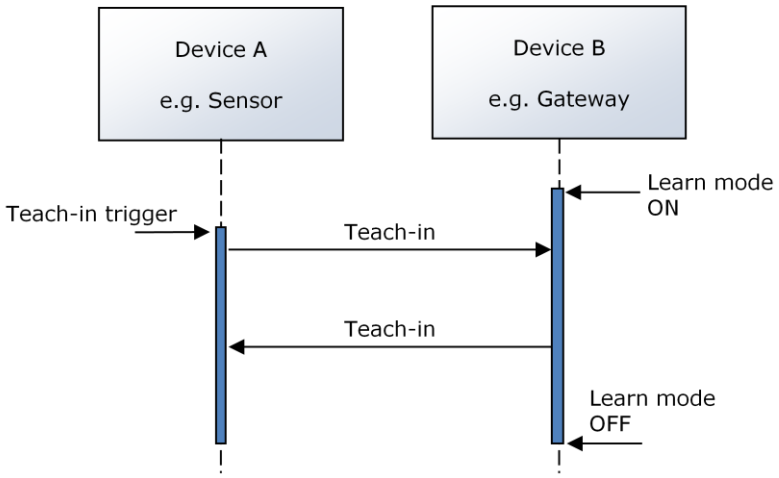


Figure 12. Schematic representation of the most general bidirectional teach-in procedure. In the case of unidirectional security teach-in Device B does not send a teach-in message.

Firstly, the Device B must be set in its learn mode to accept the teach-in messages from Device A. The Device A sends the security teach-in message (are described in chapter 4.2.1) 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_s, current RLC, RLC_s, RLC_s size and $CMAC_s$ size and way of encrypting information. The KEY_s and RLC_s can be sent encrypted by the sender using the so called pre-shared key, PSK_s. More details under 4.2.1.2.3 and 4.2.2 chapters.

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_s 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_g and RLC_g and $CMAC_g$. 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.
- 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 means that any listener can eavesdrop the information.
- 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 4.2.2.

4.2.1 Message structure

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

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 encryped 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.

4.2.1.1 R-ORG TS

Secure teach-in R-ORG is 1-byte long with code 0x35.

4.2.1.2 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 4.2.1.2.5

Table 4. Teach-in info byte fields

4.2.1.2.1 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 then IDX= 0 also. More about chaining in 4.4.1.2 chapter

4.2.1.2.2 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

4.2.1.2.3 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 4.2.2

If IDX not 0

This field is reserved

4.2.1.2.4 Field TYPE

If IDX = 0

Indicates if the application is a PTM or not

0- Non-specific type

1- PTM

If IDX not 0

This field is reserved

4.2.1.2.5 Field INFO

The interpretation of this field depends on the code in Field (4.2.1.2.1)

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 case

This field is reserved

4.2.1.3 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.

7	6	5	4	3	2	1	0
RLC_ALGO		**RLC_TX**	**MAC_ALGO**		**DATA_ENC**		
0 – No RLC algorithm 1 – 16-bit x = (x+1) 2 – 24-bit x= x+1 3 – N/A		0 - No 1 - Yes	0 – No MAC 1 – AES128 3 byte 2 – AES128 4 byte 3 – N/A		0 – No data encryption 1 – N/A 2 – N/A 3 – VAES – AES128 4 – AES-CBC – AES128		

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.

4.2.1.3.1 Field RLC_ALGO

Defines the type of the rolling code algorithm used during secure communication.

0 No RLC used in telegram or internally in memory.

1 RLC= 2-byte long. RLC algorithm consists on incrementing in +1 the previous RLC value.

2 RLC= 3-byte long. RLC algorithm consists on incrementing in +1 the previous RLC value.

3 Not defined algorithm.

4.2.1.3.2 Field RLC_TX

Indicates if the rolling code is transmitted or not in the secure operation mode

0 Secure operation mode telegrams do not contain RLC. A RLC could still be used internally for CMAC and DATA encryption as indicated by 4.2.1.3.1. In this case the initial RLC will be sent by the teach-in message (see 4.2.1.4).

1 Secure operation mode messages contain RLC.

4.2.1.3.3 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 4.3.8 chapter

2 MAC is a 4-byte-long code. MAC is calculated using AES128 as described in the 4.3.8 chapter

3 N/A

4.2.1.3.4 Field DATA_ENC

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

0 DATA not encrypted.

1 Reserved. Not defined.

2 Reserved. Not defined.

3 DATA will be encrypted/decrypted XORing with a string obtained from a AES128. See 4.3.3.

4 DATA will be encrypted/decrypted using the AES128 algorithm. See 4.3.1. and 4.3.2 sections

4.2.1.4 RLC

Contains the rolling code needed for the transmitter-receiver RLC synchronization. Only available if SLF defines it (RLC_ALGO not 0) . See chapter 4.2.1.3.

4.2.1.5 KEY

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

4.2.2 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 4.3.3 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

4.2.2.1 PSK checksum

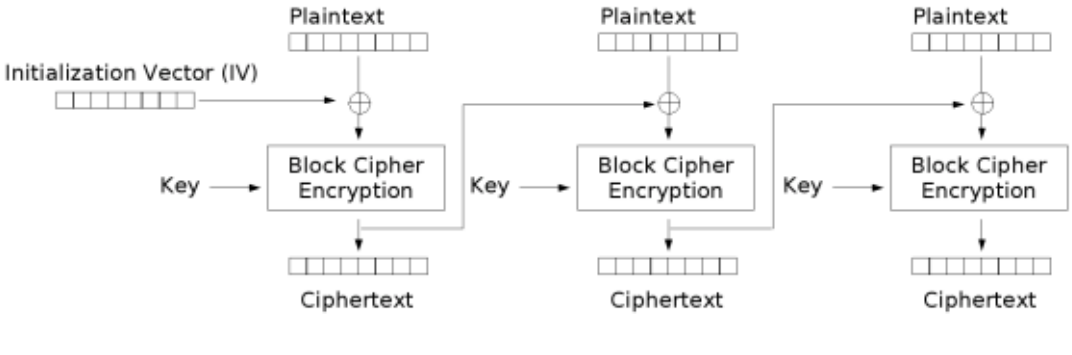
The PSK code (16 bytes) comes together with an extra byte, CRC checksum, which is used to verify that the installer/user writes correctly the 16-byte PSK code into the Device B (see Figure 12). The checksum uses a CRC8 algorithm that is explained in chapter 4.4.3.

4.3 Security algorithms

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

4.3.1 AES128 encryption

DATA can be encrypted using the standard high-security AES128[(1),(2)] algorithm with cipher-block chaining (CBC)[((5)]. Constant data will result in constant encrypted information.



Cipher Block Chaining (CBC) mode encryption

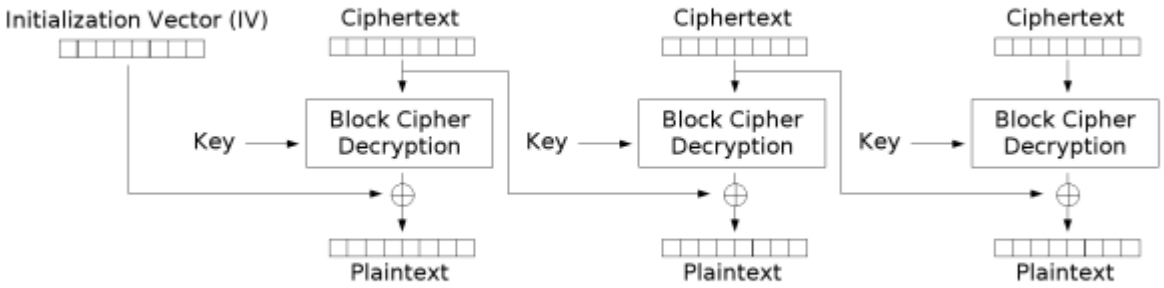
Figure 14. AES128 schematic diagram flux. DATA to be encrypted is called "plaintext" in the figure. The plaintext bytes are divided in chunks of 16 bytes. The first 16-byte array is the plaintext array to the left. If the last piece of plaintext is not 16-byte long the bit sequence 10..0 will be added to complete 16 bytes. The initialization vector has all bytes set to 0. The Block Cipher Encryption block uses the standard AES128 algorithm (1). The 16-byte long key is the same for all AES operation blocks.

AES128 algorithm with cipher-block chaining is only used with chained EnOcean telegrams, because all data blocks transmitted have to be divided in 16-Byte blocks.

Each message sent, consisting of chained telegrams, will start from the initialization vector.

4.3.2 AES128 decryption

DATA encrypted using the method described in section AES128 encryption can be decrypted using the standard high-security AES128[(1)] algorithm for decryption with CBC[((5)].



Cipher Block Chaining (CBC) mode decryption

Figure 15. AES128 schematic diagram flux. DATA to be decrypted (ciphertext) is divided in 16-byte long arrays. PRIVATE KEY is 16-byte long. The algorithm returns a 16-byte DATA encrypted (plaintext) operating as indicated in the figure.

The application must eliminate the padding bytes in case these were inserted in the plaintext when encryption took place.

Usually CBC will be used over more messages. In Security of EnOcean networks, the initialization vector will be applied at each new message (which could consist of more EnOcean telegrams).

4.3.3 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.

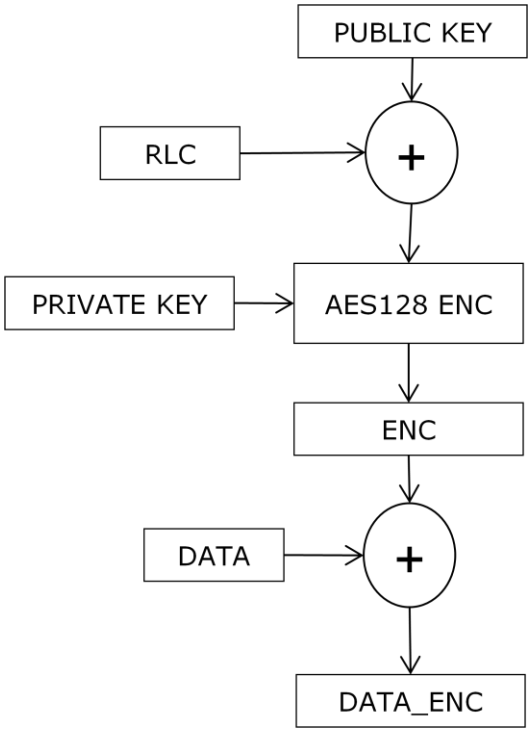


Figure 16. Encryption of telegram DATA using variable XOR AES128 for DATA equal or less than 16 bytes. The AES128 is used to perform a pseudo random generator. The plus symbol within a circle represents a bitwise XOR operation. One DATA chunk can have a maximum of 16 bytes. The length of DATA_ENC is equal to the length of DATA. PUBLIC KEY is a constant 16-byte hexadecimal string array. The RLC, is XORed with the PUBLIC key before entering the AES128 algorithm. The PUBLIC KEY byte array first element, PUBLIC_KEY[0], is XORed with the RLC most significant byte. PUBLIC_KEY[1] is XORed with the RLC 2nd most significant byte and so on. The RLC is filled with 00..0 until 16 bytes. In the same way DATA and ENC arrays are XORed to produce the output code

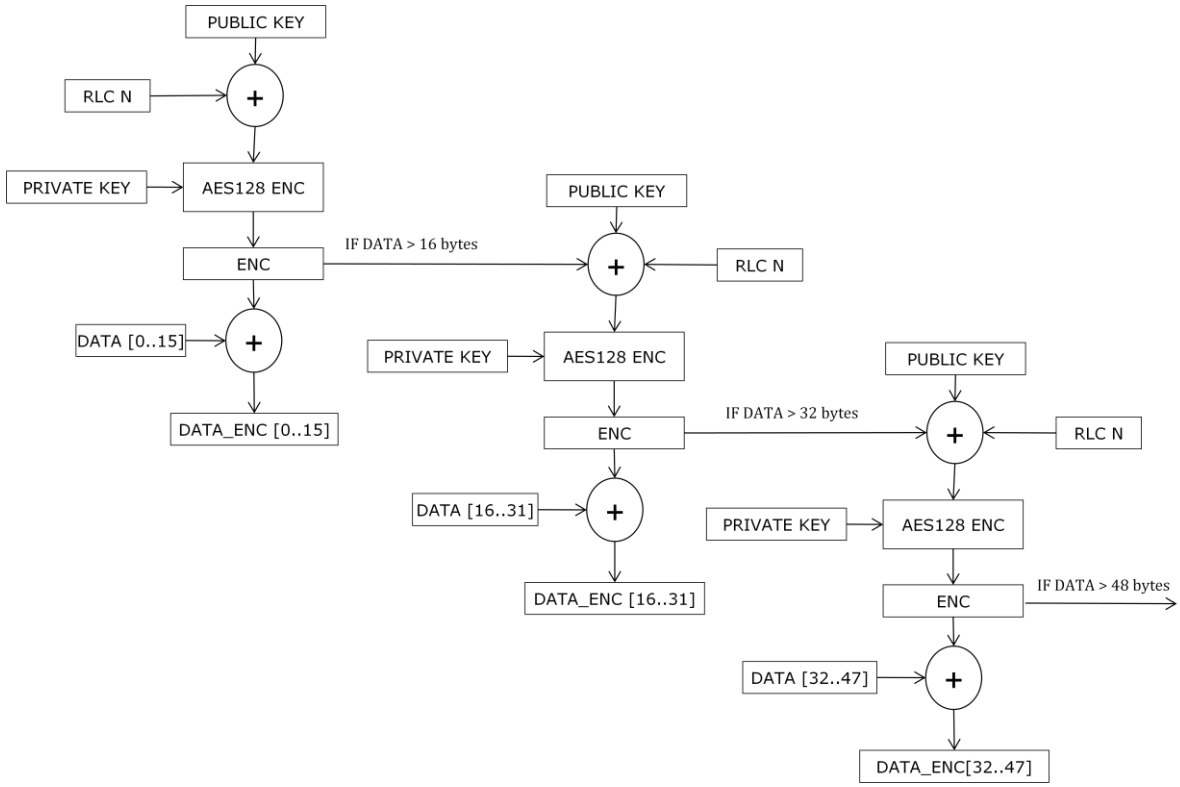


Figure 17. Encryption of telegram DATA using variable XOR AES128 for DATA longer than 16 bytes. Encryption is repeated but in all following cycles the ENC field from previous cycle is XORed with the encryption input for the actual cycle. The Rolling Code is the same for all cycles. By using the ENC field 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.

4.3.4 VAES (variable AES) decryption

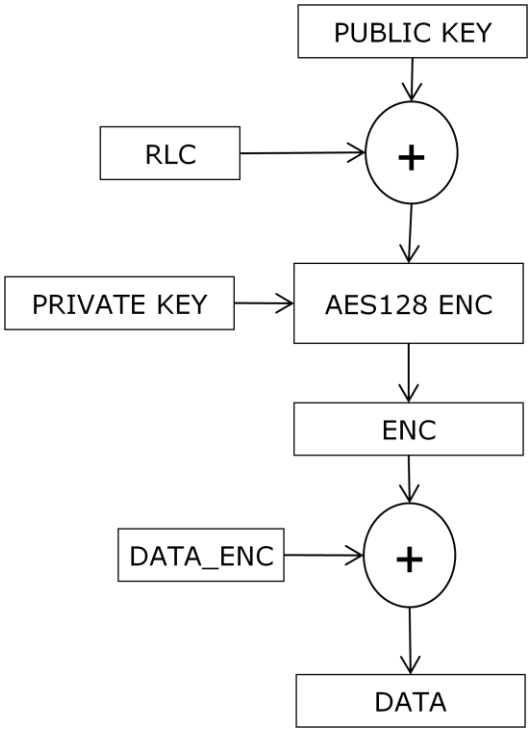


Figure 18. Decryption algorithm of the received telegram. DATA_ENC is the received encrypted DATA. DATA is less than 16 bytes. Note: The AES algorithm required is the same as in the encryption algorithm. The RLC value in the receiver must be the same as in the transmitter module. Otherwise the decrypted 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 16

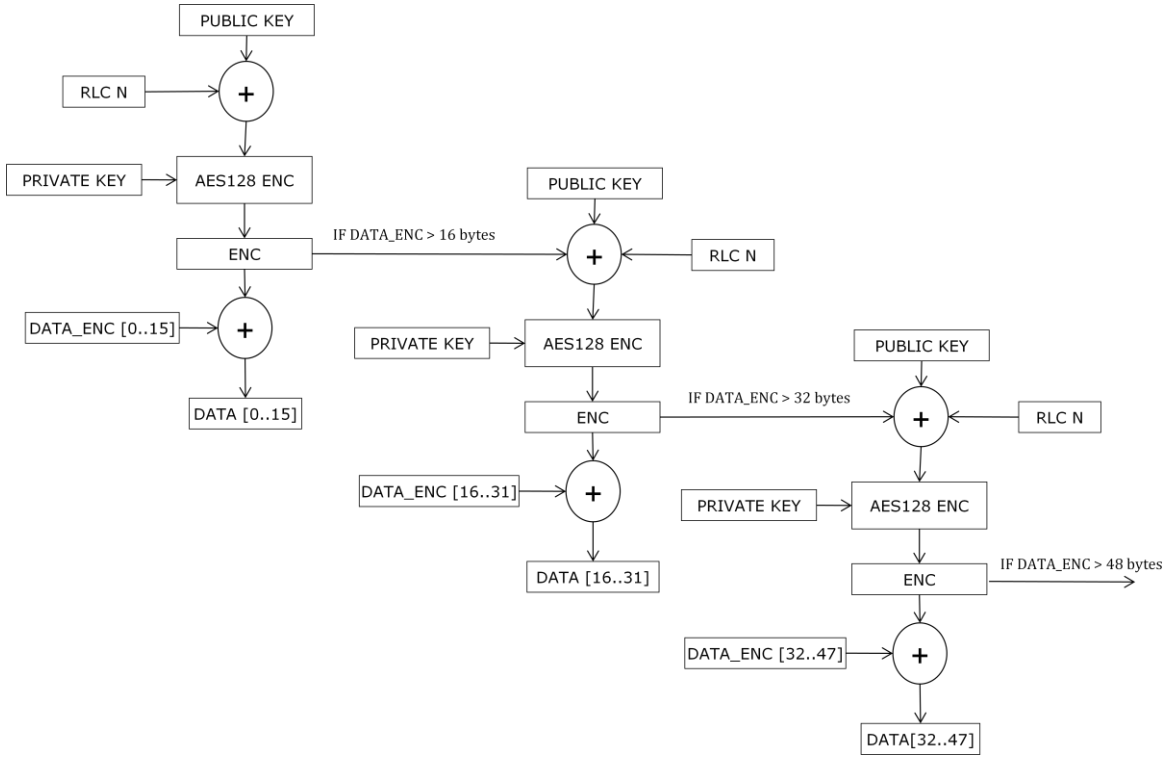


Figure 19. Decryption algorithm of the received telegram. DATA_ENC is the received encrypted DATA from the transmitter. DATA is more than 16 bytes.

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 4.3.8).

4.3.5 Public key

The public key 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 PUBLIC_KEY first element, PUBLIC_KEY[0] = 0x34
The array last element is PUBLIC_KEY[15] = 0xbd

4.3.6 Private key

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

4.3.7 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 (4.3.8) and VAES encryption values(4.3.3) although telegram DATA remains constant.

Explicit RLC strategy - The RLC may be transmitted as part of the telegram information (4.1) to speed-up the MAC calculation in the receiver, at expense of increasing the energy spent in radio transmission and decreasing the degree of security.

Implicit RLC strategy - It is possible for the transmitter module not to send RLC in the telegram. This strategy increases the system security at the expense of increasing the processing time for CMAC verifications (see 4.3.8).

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. When the code rolls-over it starts at 0 again.

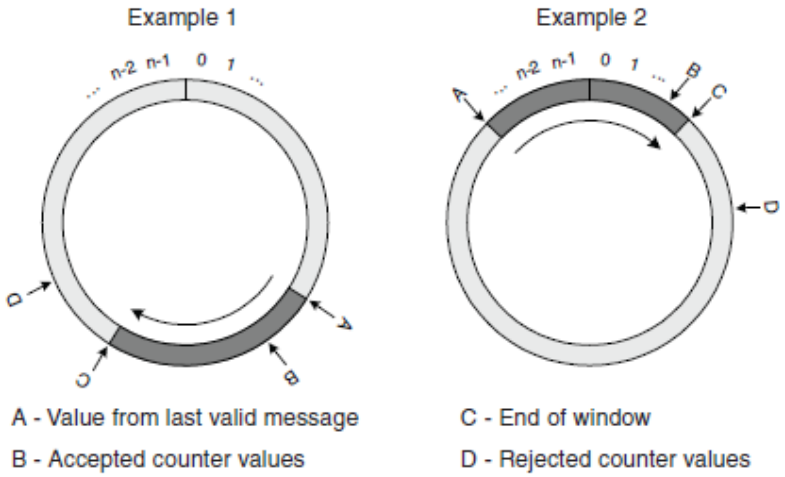


Figure 20 Rolling Window of Acceptance for Counter Values *(AVR411: Secure Rolling Code Algorithm)*

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 where 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.

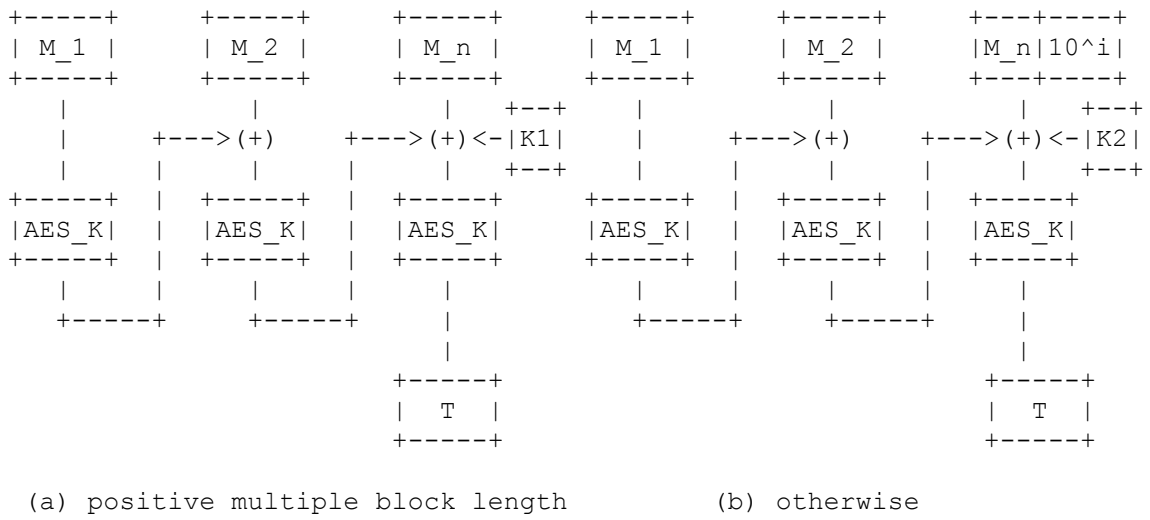
Once the receiver cannot match the transmitter roling code in the range of the window size it may block the TXID of the transmitter.

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 4.2).

The window size for incorrect RLC has a value of 128.

4.3.8 CMAC algorithm

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



(a) positive multiple block length (b) otherwise

Figure 21. The case (a) applies for messages that are multiple of 16 bytes. Subkey K1 is used in this case. See 4.3.8.3 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).

4.3.8.1 CMAC calculation for operation mode telegrams

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

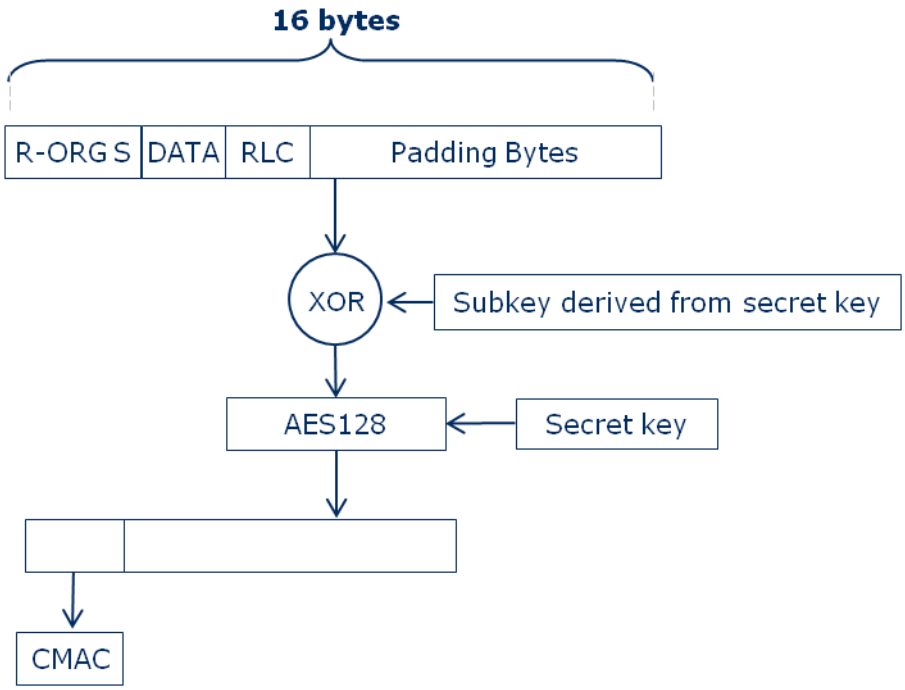


Figure 22 CMAC generation algorithm for a message <= 16 bytes. The R-ORG-S is the secure radio message R-ORG code. DATA is the secure message DATA field. When R-ORG S= 0x31, DATA includes the encrypted non-secure R-ORG as most significant byte. When R-ORG S= 0x30, DATA does not include the encrypted 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 private key*. R-ORG S XORs Subkey_der[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 Figure 21. 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.

4.3.8.2 CMAC calculation for teach-in telegrams

The input stream bytes to the calculation of the CMAC algorithm, as described in chapter 4.3.8, is

Figure 23. Padding bytes are necessary when the amount of bytes from R-ORG TS to the last KEY byte is not a multiple of 16. In this case the stream is completed with padding bytes as explained in chapter 4.3.8. The RLC and KEY fields are encrypted as explain in chapter 4.2.2

4.3.8.3 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.

4.4 Appendix

4.4.1 ERP1 secure telegrams

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

4.4.1.1 Operation mode with EPR1

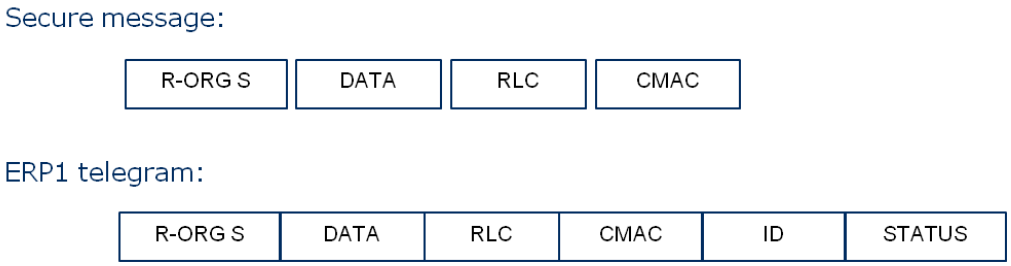


Figure 24. In the most general version of the secure message the RLC and CMAC fields are present. DATA can be encrypted. The fields R-ORG S, DATA, RLC and CMAC are integrated without modification in the ERP1 telegram. If DATA is encrypted in the message it is also encrypted in the ERP1 telegram. The ID and STATUS are specific to the telegram.

4.4.1.2 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).

Figure 25. The general teach-in message security members

Dividing the message into two telegrams results in the following:

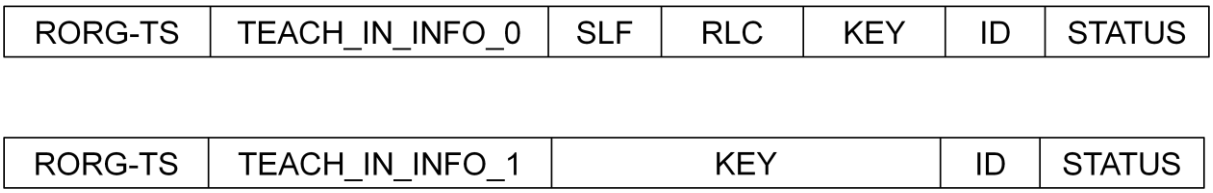


Figure 26. Teach-in message information divided in two ERP1 telegrams. The telegram with TEACH_IN_INFO_0 byte is sent first. This telegram contains the teach-in RLC, SLC and the first part of the KEY of the teach-in message. The second telegram transports the second part of the KEY.

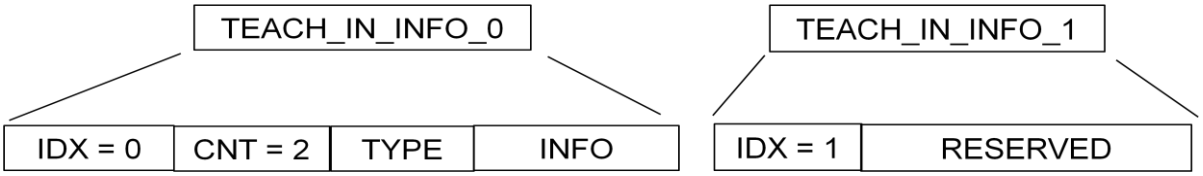


Figure 27. The IDX bit field of TEACH_IN_INFO_0 = 0 indicates that this is the first telegram. The CNT=2 indicates that the message is divided in 2 telegrams. TEACH_IN_INFO_1 IDX field = 1 says that this telegram is the second one. See chapter 4.2.1.2 to learn more about the TEACH-IN INFO bit fields.

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.

4.4.2 ERP2 secure telegrams

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

4.4.2.1 Operation mode with EPR2

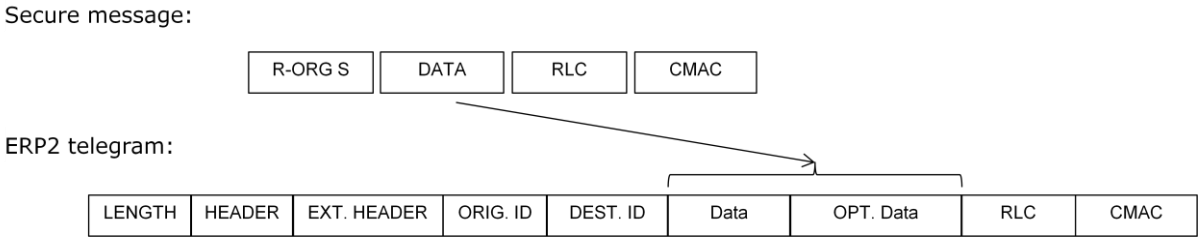


Figure 28. The secure message DATA field used throughout this documentation contains the information of the concatenated ERP2 telegram Data and Optional Data fields. If the message DATA field is encrypted is also encrypted in the telegram. The RLC and CMAC are placed after the Optional Data. The information of the R-ORG S is contained within the HEADER field. The EXTENDED HEADER depends on the telegram. See ERP2 Specification

4.4.2.2 Secure teach-in with ERP2

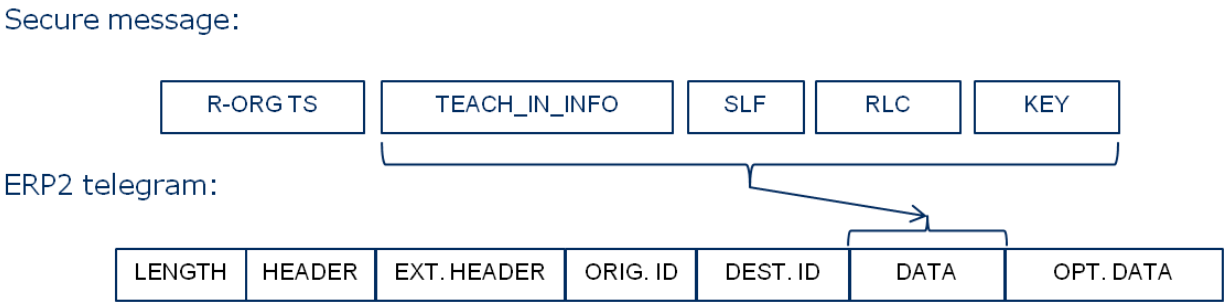


Figure 29. The message fields TEACH_IN_INFO, SLF, RLC and KEY are concatenated in the order indicated and placed in the DATA field of the ERP2 telegram. The information of R-ORG TS is contained within the HEADER. The EXTENDED HEADER depends on the telegram.

4.4.2.2.1 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 4.2) in several telegrams.

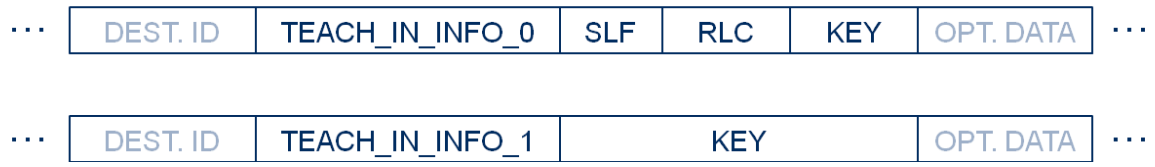


Figure 30. The secure teach-in message is transmitted here by two ERP2 telegrams. The information within the field DATA, between the telegram's Destination ID and Optional Data, is shown. SLF, RLC and the first part of the KEY are transmitted in the first telegram. The second telegram contains the second part of the KEY. The TEACH_IN_INFO_X bytes are interpreted like in the Figure 27

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.

4.4.3 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

5 Referenced documents

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

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