

# Generation of IEEE 802.15.4 Signals

## Application Note

### Products:

R&S® SMW200A	R&S® SMU200A
R&S® SMBV100A	R&S® SMJ100A
R&S® SGT100A	R&S® SMATE200A

This application note describes how to create and generate standard-conform IEEE 802.15.4 test signals with the R&S Vector Signal Generators (VSG).

It provides a brief introduction in the IEEE 802.15.4 PHY and MAC layer, explains in detail how a user-defined frame can be created by using the R&S IEEE 802.15.4 *Frame Builder* Excel spreadsheet and provides the information required to generate a *Frame Builder* based test signal with the R&S vector signal generators.

Finally an overview of standardized IEEE 802.15.4 PHY receiver tests is given.

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# Table of Contents

<b>1</b>	<b>Introduction .....</b>	<b>5</b>
1.1	IEEE 802.15.4 Overview .....	5
1.1.1	PHY Layer Specification .....	5
1.1.1.1	Frequency Bands .....	6
1.1.1.2	O-QPSK PHY .....	6
1.1.2	MAC Layer Specification .....	10
1.1.2.1	General MAC Frame Format .....	10
1.1.2.2	Individual MAC Frame Formats .....	12
1.1.2.3	Inter Frame Spacing (IFS) .....	13
1.1.3	Higher Layers .....	14
<b>2</b>	<b>IEEE 802.15.4 Frame Creation .....</b>	<b>15</b>
2.1	IEEE 802.15.4 Frame Builder .....	15
2.1.1.1	First Steps .....	15
2.1.1.2	Overview .....	16
2.1.1.3	Frame Creation Steps .....	17
2.1.1.4	Symbol to Chip Mapping .....	20
2.1.1.5	Inter Frame Spacing .....	20
2.1.1.6	R&D Data- and Control-List Creation .....	21
<b>3</b>	<b>IEEE 802.15.4 Signal Generation .....</b>	<b>22</b>
3.1	Custom Digital Modulation (CDM) .....	22
3.1.1	CDM Configuration .....	23
3.1.1.1	General Settings .....	23
3.1.1.2	Filter Settings .....	24
3.1.1.3	Modulation Settings .....	24
3.1.1.4	Data Source Settings .....	25
3.1.1.5	Marker Settings .....	25
3.1.2	Signal Evaluation .....	26
3.1.3	Remote CDM Configuration – CDM-Toolbox .....	27
3.2	Arbitrary Waveform Generator (ARB) .....	28
3.2.1	ARB Waveform creation with WinIQSIM2 .....	28
3.2.2	ARB Configuration .....	30
3.3	Signal Performance .....	31

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3.3.1	Vector Signal Analyzer .....	31
3.3.1.1	Time Domain (Zero Span).....	31
3.3.1.2	RF Domain (Spectrum) .....	32
3.3.1.3	Demodulation.....	32
3.3.1	IEEE 802.15.4 Wireless Protocol Analyzer.....	38
<b>4</b>	<b>IEEE 802.15.4 Receiver Tests.....</b>	<b>39</b>
4.1	IEEE 802.15.4 O-QPSK PHY Receiver Requirements .....	39
4.1.1	Receiver Sensitivity .....	39
4.1.1.1	General Definition .....	39
4.1.1.2	Requirement.....	39
4.1.1.3	Measurement .....	39
4.1.2	Receiver Interference Rejection.....	40
4.1.2.1	Requirement.....	40
4.1.2.2	Measurement .....	40
4.1.3	Receiver maximum Input Level.....	40
4.1.3.1	Requirement.....	40
4.1.3.2	Measurement .....	40
4.2	ETSI EN 300 440-1/2 Receiver Requirements .....	41
4.2.1	Adjacent Channel Selectivity .....	41
4.2.1.1	Requirement.....	41
4.2.1.2	Measurement .....	41
4.2.2	Blocking or Desensitization .....	42
4.2.2.1	Requirement.....	42
4.2.2.2	Measurement .....	42
<b>5</b>	<b>Abbreviations .....</b>	<b>43</b>
<b>6</b>	<b>References.....</b>	<b>44</b>
<b>7</b>	<b>Appendix.....</b>	<b>46</b>
7.1	O-QPSK – Modulation Mapping File .....	46
7.2	Half-Sine – Pulse Shaping Filter File.....	47
7.3	IEEE 802.15.4 Data Frame – Data/Control List File .....	48
<b>8</b>	<b>Ordering Information .....</b>	<b>49</b>

The following abbreviations are used in this application note for Rohde & Schwarz products:

- The R&S<sup>®</sup> SMW200A vector signal generator is referred to as SMW
- The R&S<sup>®</sup> SMBV100A vector signal generator is referred to as SMBV
- The R&S<sup>®</sup> SGT100A vector RF source is referred to as SGT
- The R&S<sup>®</sup> SMU200A vector signal generator is referred to as SMU
- The R&S<sup>®</sup> SMATE200A vector signal generator is referred to as SMATE
- The R&S<sup>®</sup> SMJ100A vector signal generator is referred to as SMJ

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# 1 Introduction

This application note describes how to create and generate **standard-conform IEEE 802.15.4 [12] test signals** with the R&S Vector Signal Generators (VSG).

It provides a brief introduction in the IEEE 802.15.4 PHY and MAC layer, explains in detail how a user-defined frame can be created by using the **R&S IEEE 802.15.4 Frame Builder Excel spreadsheet** and provides the information required to generate a *Frame Builder* based test signal with the R&S vector signal generators. Finally an overview of standardized IEEE 802.15.4 PHY receiver tests is given.

## 1.1 IEEE 802.15.4 Overview

The standard **IEEE 802.15.4 [12]** defines the physical layer (PHY) and medium access control (MAC) sub-layer for low-data-rate wireless connectivity with fixed, portable, and moving devices with no battery or very limited battery consumption requirements. It is therefore in the true sense of the word the fundament of several well-known protocols like **ZigBee™**, **RF4CE**, **6LoWPAN**, **Wireless HART**, **SmartLink**, **THREAD** and others.

### 1.1.1 PHY Layer Specification

In general, the PHY data service enables the transmission and reception of data packets called PHY protocol data units (PPDUs) across the physical radio channel. IEEE 802.15.4 defines multiple PHYs for a variety of **frequency bands** and with various **modulation types** and **data rates**.

802.15.4 PHY – Frequency Bands, Spreading- and Data Parameters [12]						
PHY [MHz]	Frequ. Band [MHz]	Spreading-Parameters		Data-Parameters		
		Chip rate [kChip/s]	Modulation	Bit rate [kbit/s]	Sym. rate [kSym/s]	Symbols
780	779-787	1000	O-QPSK	250	62.5	16ary orth.
780	779-787	1000	MPSK	250	62.5	16ary orth.
868/915 <sup>1</sup>	868-868.6	300	BPSK	20	20	Binary
	902-928	600	BPSK	40	40	Binary
950	950-956	-	GFSK	100	100	Binary
950	950-956	300	BPSK	20	20	Binary
<b>2450</b>	<b>2400-2483.5</b>	<b>2000</b>	<b>O-QPSK</b>	<b>250</b>	<b>62.5</b>	<b>16ary orth.</b>

1) If a transceiver supports the 868 MHz band it must support the 915 MHz band as well, and vice versa  
Note: Optional PHY variants are not shown

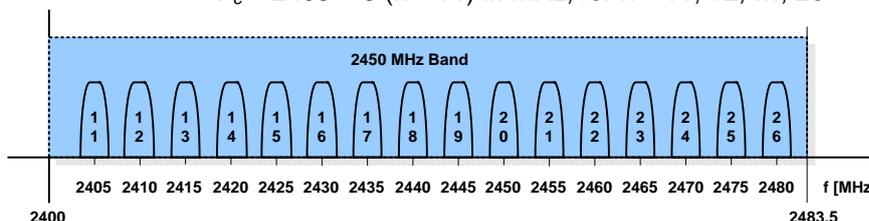
**Table 1: 802.15.4 PHY – Frequency Bands, Spreading- and Data-Parameters**

### 1.1.1.1 Frequency Bands

The 868 MHz band is used in Europe for short range wireless networking. The 915 MHz band and also the 2450 MHz band are part of the industrial, scientific and medical (ISM) frequency bands. The 915 MHz band is mainly used in the USA and the 2450 MHz band is used worldwide. The 780 MHz band was specified for transceivers intended to be used in China and the 950 MHz band is of special interest in Japan.

In general, the **most common PHY variant is running on the 2450 MHz band** since it offers the maximum data rate of 250 kbit/s and provides a maximum number of 16 RF channels, numbered 11 through 26. The center frequency of these channels is defined as follows:

$$F_c = 2405 + 5 (k - 11) \text{ in MHz, for } k = 11, 12, \dots, 26$$



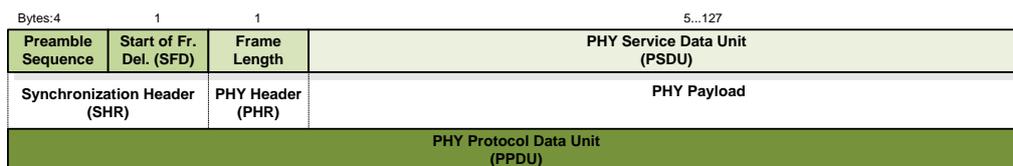
**Figure 1: IEEE 802.15.4 PHY – 2450 MHz Band RF Channels**

The following paragraphs provide a closer insight into the functionality and the PHY and MAC parameters of the popular PHY variant in the 2450 MHz band, which is called **O-QPSK PHY**.

### 1.1.1.2 O-QPSK PHY

#### PPDU Format

The following figure shows a schematic and general view of the O-QPSK PHY PPDU format and the included fields.



**Figure 2: O-QPSK PHY – PPDU Format**

Each successive protocol layer adds to this structure with layer-specific headers and footers. The MAC frames, for example, are passed to the PHY as the PHY service data unit (PSDU), which becomes the PHY payload. The different fields of the PPDU appear in a fixed order and have to be part of every packet. The format of the SHR and PHR depends on the PHY type (see *Table 1*) used. In the following, the definition for the **O-QPSK PHY** is provided:

#### **Synchronization Header (SHR):**

The synchronization header (SHR) consists of the preamble sequence followed by the start of frame delimiter (SFD). The preamble sequence is defined to be 4 bytes (i.e. 8 symbols) of 0x00. The SFD is one byte set to 0xA7.

A synchronization header is always transmitted first in all transmission modes since it enables the receiver to synchronize and to lock into a bit stream.

#### PHY Header (PHR):

The frame length field defines the number of bytes in the PSDU. Note that the length field does not include the length field itself. It does however include the frame check sequence (FCS) of the MPDU.

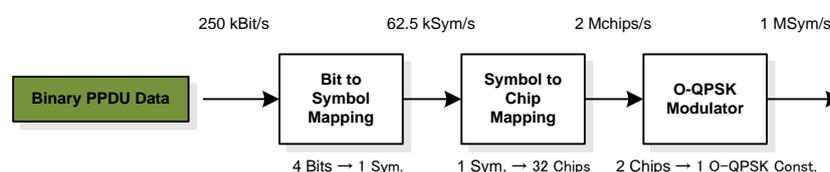
The length field is 7 bits in length and has a maximum value of 127. The most significant bit in the length field is reserved and has to be set to zero.

#### PHY Service Data Unit (PSDU):

The MAC frames (MPDU) are passed to the PHY as the PHY service data unit (PSDU), which becomes the PHY payload.

### Spreading and Modulation

This paragraph provides an introduction to the spreading and modulation format specified for the **O-QPSK PHY** in the **2450 MHz band**.



**Figure 3: O-QPSK PHY – Spreading and Modulation**

The O-QPSK PHY employs a 16-ary quasi-orthogonal modulation technique. Each data symbol consisting of four PPDU bits is mapped to one out of 16 nearly orthogonal pseudo-random noise (PN) sequences (32 chips each).

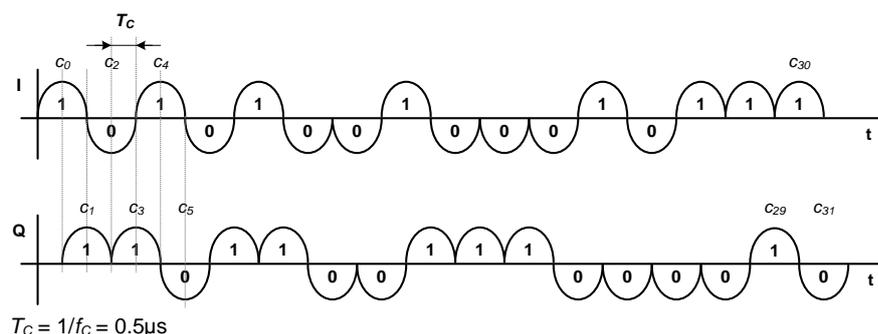
O-QPSK PHY – Symbol to Chip Mapping (2450 MHz Band) [12]	
Data Symbols	Chip values ( $c_0..c_{31}$ )
0	11 01 10 01 11 00 00 11 01 01 00 10 00 10 11 10 <sub>bin</sub> 3 1 2 1 3 0 0 3 1 1 0 2 0 2 3 2 <sub>hex</sub>
1	11 10 11 01 10 01 11 00 00 11 01 01 00 10 00 10
2	00 10 11 10 11 01 10 01 11 00 00 11 01 01 00 10
3	00 10 00 10 11 10 11 01 10 01 11 00 00 11 01 01
4	01 01 00 10 00 10 11 10 11 01 10 01 11 00 00 11
5	00 11 01 01 00 10 00 10 11 10 11 01 10 01 11 00
6	11 00 00 11 01 01 00 10 00 10 11 10 11 01 10 01
7	10 01 11 00 00 11 01 01 00 10 00 10 11 10 11 01
8	10 00 11 00 10 01 01 10 00 00 01 11 01 11 10 11
9	10 11 10 00 11 00 10 01 01 10 00 00 01 11 01 11
10	01 11 10 11 10 00 11 00 10 01 01 10 00 00 01 11
11	01 11 01 11 10 11 10 00 11 00 10 01 01 10 00 00
12	00 00 01 11 01 11 10 11 10 00 11 00 10 01 01 10
13	01 10 00 00 01 11 01 11 10 11 10 00 11 00 10 01
14	10 01 01 10 00 00 01 11 01 11 10 11 10 00 11 00
15	11 00 10 01 01 10 00 00 01 11 01 11 10 11 10 00

**Table 2: O-QPSK PHY – Symbol to Chip Mapping (2450 MHz Band)**

In detail the 4 LSBs ( $b_0, b_1, b_2, b_3$ ) of each PPDU octet are mapped into one data symbol, and the 4 MSBs ( $b_4, b_5, b_6, b_7$ ) of the same octet are mapped into the next data symbol. The resulting chip sequences for successive data symbols are concatenated.

Since each data symbol is represented by a 32-chip sequence, the chip rate  $f_C$  is 32 times the symbol rate  $f_S$ .

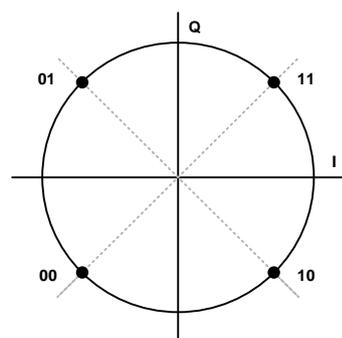
Each chip is **shaped as a half-sine**, transmitted alternately in the I and Q channels with a chip period offset. Even-indexed chips are modulated onto the in-phase (I) carrier, and odd-indexed chips are modulated onto the quadrature-phase (Q) carrier. To realize the offset between I-phase and Q-phase, the Q-phase chips are delayed by  $T_C$  in respect of the I-phase chips, as shown in the following figure, where  $T_C$  is the inverse of the chip rate  $f_C$ .



**Figure 4: O-QPSK PHY – I and Q Phases – Zero Symbol Chip Sequence**

During each symbol period  $T_S$  ( $2 \times T_C$ ), the least significant chip,  $c_0$ , is transmitted first and the most significant chip,  $c_{31}$ , is transmitted last.

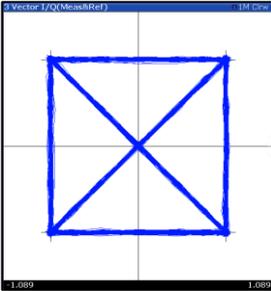
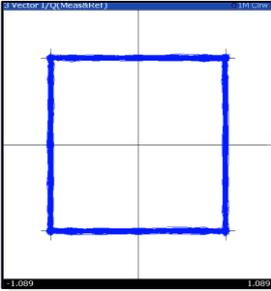
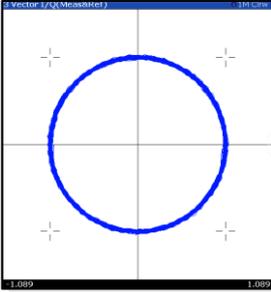
The four phases/constellation points in O-QPSK correspond to the binary numbers 00, 01, 10 and 11. The following figure highlights the chip to constellation point mapping of the O-QPSK modulator.



**Figure 5: O-QPSK PHY – I and Q Constellation Mapping**

O-QPSK is thus similar to QPSK except for the timing of the I and Q transitions. In QPSK, I and Q transitions to the next symbol occur at the same time. This leads to constellation trajectories passing through the origin of the vector diagram ( $180^\circ$  phase changes), which introduces amplitude modulation and requires linear amplifiers. Since the transitions of I and Q are offset by half of the symbol time with O-QPSK, the maximum phase changes are limited to  $90^\circ$  which reduces the envelope variations significantly and allows a more efficient RF amplification.

The additional half-sine pulse shaping filter changes the vector diagram of the O-QPSK from a square to a circle. Thus it eliminates any amplitude variations and turns the O-QPSK into a constant envelope modulation.

QPSK/O-QPSK-Constellation	
Modulation/Shaping	Constellation (Vector Diagram)
QPSK/Rectangular:	
O-QPSK/Rectangular:	
O-QPSK/Half-Sine:	

**Figure 6: QPSK/O-QPSK-Constellation**

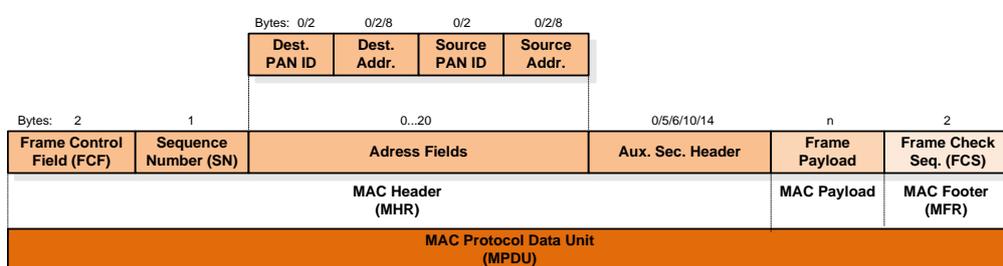
## 1.1.2 MAC Layer Specification

The MAC layer forms the interface between the PHY layer and the higher application specific layers, like the ZigBee™ network layer.

### 1.1.2.1 General MAC Frame Format

The MAC data service enables the transmission and reception of frames called MAC protocol data units (MPDUs) across the PHY data service. IEEE 802.15.4 defines four different **MAC frame formats/types** (data-, beacon-, acknowledgment- and MAC command-frames). The following section provides a brief introduction into the general IEEE 802.15.4 MAC frame format which is the basis for all individual frame formats/types.

The general IEEE 802.15.4 MAC frame format is shown by the following figure:



**Figure 7: IEEE 802.15.4 – General MAC Frame Format**

The MAC frame consists of three main sections: the MAC header (MHR), the MAC payload and the MAC footer (MFR). All of these sections contain at least one parameter field.

The frame control field (FCF), the sequence number (SN) and the frame check sequence (FCS) have to be part of every frame whereas the addressing fields, the auxiliary security header and the MAC payload might not be included in a frame (type). Fields consisting of more than a single octet (e.g. FCF) are sent to the PHY starting with the octet containing the least significant bits through to the octet containing the most significant bits.

#### Frame Control Field (FCF):

The FCF contains information defining the frame type, addressing fields, and other control flags. The FCF shall be formatted as follows:

Frame Control Field (FCF) Format [12]		
Bits		Information
0-2	$b_2..b_0$	<b>Frame Type</b>
	000	Beacon
	001	Data
	010	Acknowledgement
	011	MAC command

Frame Control Field (FCF) Format [12]		
Bits		Information
3	$b_0$	<b>Security Enabled</b>
	0	No frame protection
	1	Frame is protected by the MAC sublayer. The Auxiliary Security Header field of the MHR shall be present only if the Security Enabled field is set to one.
4	$b_0$	<b>Frame Pending</b>
	0	No additional frames are pending
	1	The device sending the frame has more data for the recipient
5	$b_0$	<b>Acknowledge Request</b>
	0	No acknowledgment is required from the recipient
	1	An acknowledgment is required from the recipient
6	$b_0$	<b>Personal Area Network (PAN) ID Compression</b>
	0	The PAN Identifier field shall be present only if the corresponding address is present
	1	Only one of the PAN identifier fields has to be present. If source and destination addresses are present, the frame shall contain only the destination PAN identifier field
7-9	$b_2..b_0$	<b>Reserved</b>
	000	
10-11	$b_1..b_0$	<b>Destination Addressing Mode</b>
	00	PAN identifier and address fields are not present
	10	Address field contains a short address (16 bit)
	11	Address field contains an extended address (64 bit)
12-13	$b_1..b_0$	<b>Frame Version</b>
	00	Frame is compatible with IEEE Std. 802.15.4-2003
	01	IEEE 802.15.4 frame
14-15	$b_1..b_0$	<b>Source Addressing Mode</b>
	00	See 'Destination Addressing Mode'
	10	
	11	

**Table 3: IEEE 802.15.4 – Frame Control Field (FCF) Format**

**Sequence Number:**

The sequence number specifies the sequence identifier (e.g. beacon sequence number, BSN; data sequence number, DSN) for the frame.

**Destination PAN Identifier:**

The destination Personal Area Network (PAN) identifier field, when present, specifies the unique PAN identifier of the intended recipient of the frame. A value of  $FFFF_h$  in this field shall represent the broadcast PAN identifier, which shall be accepted as a valid PAN identifier by all devices currently listening to the channel.

**Destination Address:**

The destination address field, when present, specifies the address of the intended recipient of the frame. A value of  $FFFF_h$  in this field shall represent the broadcast short address, which shall be accepted as a valid address by all devices currently listening to the channel.

This field shall be included in the MAC frame only if the FCF source addressing mode field is nonzero.

**Source PAN Identifier:**

The source PAN Identifier field, when present, specifies the unique PAN identifier of the originator of the frame. This field shall be included in the MAC frame only if the FCF Source Addressing Mode field is nonzero and the FCF PAN ID compression field is equal to zero.

**Source Address:**

The source address field, when present, specifies the address of the originator of the frame. This field shall be included in the MAC frame only if the FCF source addressing mode field is nonzero.

**Auxiliary Security Header:**

The auxiliary security header field specifies information required for security processing. This field shall be present only if the FCF security enabled field is set to one.

**Frame Payload:**

The frame payload field contains information specific to individual frame types. If the FCF security enabled field is set to one, the frame payload of the frame may be cryptographically protected

**Frame Check Sequence:**

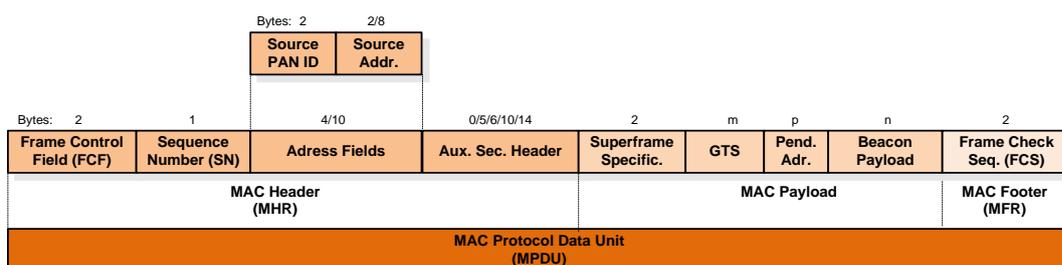
The 2 byte frame check sequence (FCS) follows the last MAC payload byte. The FCS is calculated over the MPDU. The FCS calculation is based on the International Telecommunications Union (ITU) Cyclic Redundancy Check (CRC) and uses the following polynomial:  $x^{16} + x^{12} + x^5 + 1$

### 1.1.2.2 Individual MAC Frame Formats

IEEE 802.15.4 specifies four individual MAC frame formats. All of them are based on the general MAC frame structure (see chapter 1.1.2.1).

**Beacon Frame:**

The beacon frame is used by the network coordinator to synchronize the clock of all entities within a certain network.

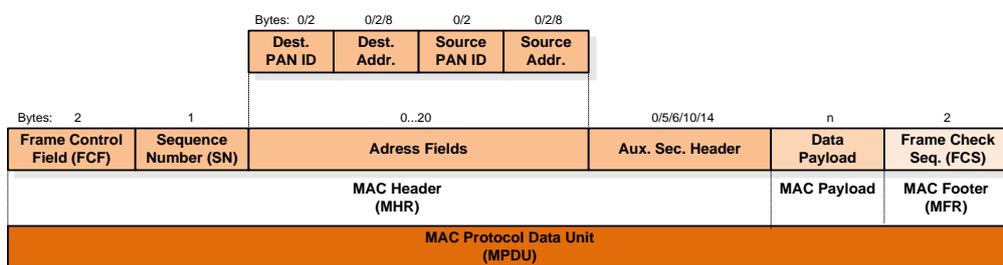


Note: The number of GTS, pending address and beacon payload bytes is variable

**Figure 8: IEEE 802.15.4 – MAC Beacon Frame Format**

**Data Frame:**

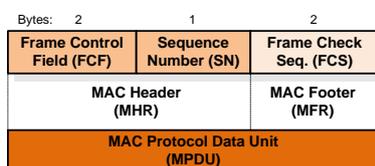
The data frames are used to transmit data.



**Figure 9: IEEE 802.15.4 – MAC Data Frame Format**

**Acknowledgment Frame:**

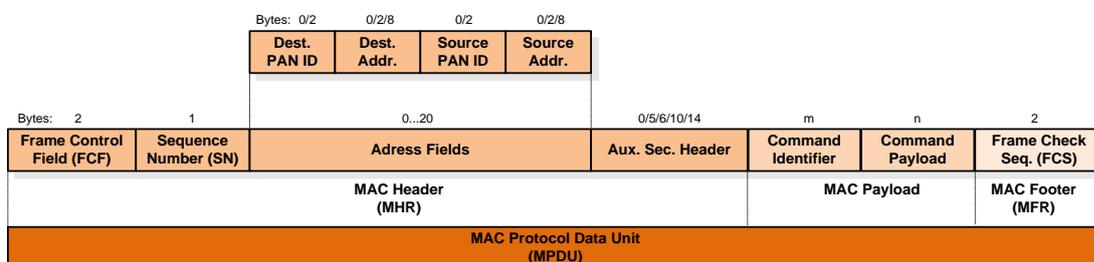
Acknowledgement frames are used to acknowledge the successful reception of a certain data frame.



**Figure 10: IEEE 802.15.4 – MAC Acknowledgment Frame Format**

**MAC Command Frame:**

MAC commands are transmitted by using MAC command frames.



**Figure 11: IEEE 802.15.4 – MAC Command Frame Format**

For further details, especially about the fields of the different MAC payload frame types, refer to [12].

### 1.1.2.3 Inter Frame Spacing (IFS)

Each device which is transmitting data to another one has to take care that the recipient PHY has enough time to process the data received before the next frame is sent. Therefore two successive frames transmitted from a device shall be separated by an adequate Inter Frame Spacing (IFS) period.

The length of the IFS period depends on the frame size. Frames (i.e., MPDUs) of up to 18 octets shall be followed by a short IFS (SIFS) period of at least 12 symbols. Frames with greater length shall be followed by a long IFS (LIFS) period of at least 40 symbols.

### 1.1.3 Higher Layers

Since IEEE 802.15.4 is focusing on the specification of the PHY and MAC layer only, the higher network layers have to be based on:

- Proprietary manufacturer specific designs for custom applications which do not require interoperability with devices of other vendors.
- Specifications or standards to enable multi-vendor interoperable solutions. The ZigBee™ Alliance, for example, develops and evolves the ZigBee™ specification [18] which enhances the IEEE 802.15.4 standard by adding network and security layers and an application framework.

On that basis, standards [19] (e.g. targeted towards markets as diverse as home automation, consumer electronics, medical, smart energy, and industrial), developed by the ZigBee™ Alliance can be used to create multi-vendor interoperable devices.

## 2 IEEE 802.15.4 Frame Creation

The following paragraph describes in detail how an IEEE 802.15.4 based data frame can be defined/created by using the **R&S 802.15.4 Frame Builder** Excel spreadsheet.

### 2.1 IEEE 802.15.4 Frame Builder

The Microsoft® Excel 2010 based **R&S 802.15.4 Frame Builder** allows a flexible specification of all IEEE 802.15.4 PHY and MAC layer parameters of the **O-QPSK PHY** operating in the **2450 MHz band**.

It is thus most suitable to create standard-conform and/or user-specific IEEE 802.15.4 frames, especially for component and receiver tests.

It enables product designers and test engineers of IEEE 802.15.4 based devices to speed up the test phase significantly and thus to save time and money.

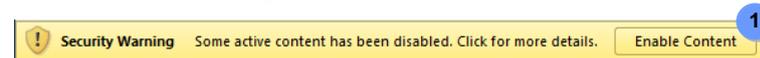
The following functionalities are covered by the *Frame Builder*:

- MAC header definition with extended assistance for standard-conform FCF configuration
- Import of MAC payload data files
- Input data validation
- FCS calculation
- Synchronization header definition
- Symbol to Chip mapping
- Chip export functionality (binary and/or hex)
- Definition of inter frame spacing (IFS)
- Creation of R&S data list files based on the defined frame and IFS
- Creation of R&S control list files based on the defined frame and IFS
- Graphical overview of the frame (content)
- Administration of frame libraries

#### 2.1.1.1 First Steps

Copy the provided R&S 802.15.4 *Frame Builder* Excel spreadsheet to the selected destination on your PC. If you want to define frames of a certain type, for a specific device or test campaign feel free to rename the spreadsheet as desired (e.g. `TA-Test Frames.xlsx`).

Open the spreadsheet by double clicking the file and thus start the Excel application. Since the *Frame Builder* includes VBA code to allow simplified user interaction, an Excel security warning ① pops up immediately after the *Frame Builder* startup.



**Figure 12: Frame Builder – Enable Content**

In order to activate the VBA code and thus the overall frame creation functionality, the 'Enable Content' key has to be pressed. After that the *Frame Builder* is ready for usage.

### 2.1.1.2 Overview

The *Frame Builder* spreadsheet is organized as follows:

The screenshot displays the 'O-QPSK PHY Frame Builder' spreadsheet. It is organized into several columns: 'B' for frame parameters, 'C' for control buttons, 'D' for parameter values, and 'T' for control buttons. A 'Schematic view of the 802.15.4 PHY/MAC Frame [1]' is shown on the right, illustrating the frame structure with fields like Frame Control Field (FCF), Sequence Number (SN), Address Fields, Aux. Sec. Header, Data Payload, and Frame Check Seq. (FCS). The spreadsheet includes fields for Source and Destination addresses, PAN ID, and various control flags. It also features a 'Data/Control List' at the bottom with buttons for 'Data List' and 'Ctrl List', and a 'Symbol to Chip' section showing the conversion of bits to chips and symbols.

**Figure 13: Frame Builder – Overview**

① On the top right position of the 'O-QPSK' tab, a **schematic of the IEEE 802.15.4 PHY/MAC frame** is provided to simplify the overall orientation.

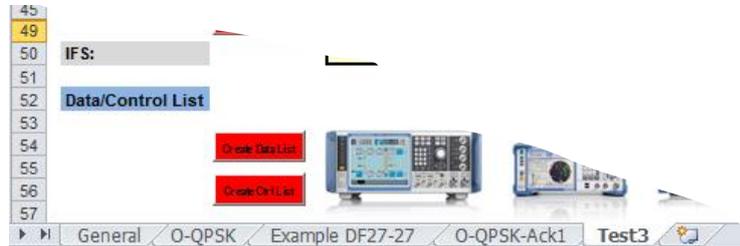
② All **control buttons** of the *Frame Builder* which allow the performance of certain actions (e.g. 'Reset') are located in column 'C'. For the normal mode of frame creation, the buttons are pressed sequentially from top to bottom with the required frame parameter alteration in between.

③ In column 'B' all **frame parameters** are itemized which have to be configured deliberately. At first, the MAC frame parameters have to be provided, starting with the frame control field and its sub-parameters. Later on the PHY parameters could be modified if values other than those specified by IEEE 802.15.4 have to be used. When the PPDU and thus the frame symbols are available the related chips can be shown. In the end, the inter frame spacing can be specified if applicable.

④ The **frame parameter values** have to be provided starting in column 'D'. In general, it is recommended to manually modify only yellow highlighted values in order to prevent the frame to become invalid/corrupt. For this reason also most of the cells are write protected and/or have a cell specific input value range check.

⑤ The 'General' tab provides some **background information about IEEE 802.15.4** and some parameter values which are used by the *Frame Builder* VBA code. Therefore this tab must not be deleted!

© Each defined frame can be held on a separate tab. If several frames of a certain project have to be administered by a single *Frame Builder* spreadsheet the initial 'O-QPSK' tab can easily be duplicated and/or renamed (frame type specific).

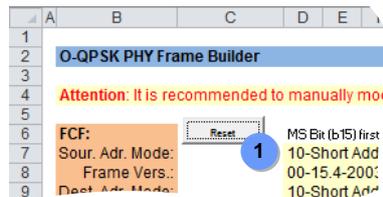


**Figure 14: Frame Builder – Frame Administration/Library**

### 2.1.1.3 Frame Creation Steps

In the following, all the steps are described which are required to create an **IEEE 802.15.4 compliant frame** from scratch. If the frame creation is based on an already existing *Frame Builder* project, some of the described steps may be skipped.

① In general, the frame creation should be started by resetting all frame parameter fields to their default values. This action can be achieved by pressing the 'Reset' button:



**Figure 15: Frame Builder – Reset**

After resetting the *Frame Builder* all PPDU, MPDU and MHR fields, the Data Payload and the FCS fields are cleared.

The FCF parameters are set to arbitrary default values:

Frame Control Field (FCF) – Default Values		
Bits		Information
0-2	001	<b>Frame Type:</b> Data
3	0	<b>Security Enabled:</b> No frame protection
4	0	<b>Frame Pending:</b> No additional frames are pending
5	1	<b>Acknowledge Request:</b> An ack. is required from the recipient
6	0	<b>PAN ID Compression:</b> The PAN Identifier field shall be present if the corresponding address is present
7-9	000	<b>Reserved</b>
10-11	10	<b>Destination Addressing Mode:</b> Short address (16 bit)
12-13	00	<b>Frame Version:</b> Compatible with IEEE Std. 802.15.4-2003
14-15	10	<b>Source Addressing Mode:</b> Short address (16 bit)

**Table 4: IEEE 802.15.4 – Frame Control Field (FCF) – Default Values**

The SHR fields are set, to the values specified by IEEE 802.15.4.

② After this initial step the FCF field should be adapted based on the frame type which has to be created:

6	FCF:	Reset	MS Bit (b15) first
7	Sour. Adr. Mode:		11-Ext. Addr.
8	Frame Vers.:		00-15.4-2003
9	Dest. Adr. Mode:		10-Short Addr.
10	Reserved:		000
11	PAN ID Comp.:	2	1-Yes
12	Ack. Requ.:		1-Yes
13	Frame Pend.:		0-No
14	Sec. Enabled:		0-No
15	Frame Type:		001-Data
16			.. C8 61 2 byte

**Figure 16: Frame Builder – FCF Configuration**

The *Frame Builder* prevents the user from providing erroneous inputs since only standard-conform input values are supported.

③ Based on these fundamental settings, all further MHR parameters like the SN, the address fields and, if required, the auxiliary security header, have to be specified:

18	SN:	01	1 byte
19	Dest. PAN:	22 22	0 or 2 byte
20	Dest. Address:	12 34	0,2 or 8 byte
21	Src. PAN:	44 44	0 or 2 byte
22	Src. Adr.:	AB CD	0,2 or 8 byte
23	Aux. Sec Head:		0,5,6,10 or 14 byte

**Figure 17: Frame Builder – MHR Configuration**

Depending on the current FCF configuration, certain parameter fields are shown in grey to indicate that no input is expected for these fields in case of a standard-conform frame. If any input is provided in gray fields the numbers are shown in red.

In *Figure 17* or example, a source PAN is provided although only the destination PAN has to be specified with the PAN ID compression activated (shown in *Figure 16*).

④ After having specified all MHR parameter fields as required, the MHR part of the MAC frame can be set up by pressing the MHR button:

16			.. C8 61 2 byte
17			
18	SN:	01	1 byte
19	Dest. PAN:	22 22	0 or 2 byte
20	Dest. Address:	12 34	0,2 or 8 byte
21	Src. PAN:		0 or 2 byte
22	Src. Adr.:	AB CD	0,2 or 8 byte
23	Aux. Sec Head:		0,5,6,10 or 14 byte
24			
25	MHR:	Up date MHR	61 C8 01 22 22 34 12 CD AB
26			

**Figure 18: Frame Builder – MHR Update**

During the MHR update all parameter fields/bytes are aligned (byte swap) according to IEEE 802.15.4.

⑤ As a next step the MAC payload has to be specified. This can be done manually or by importing the hex payload from an ASCII text file:

26			
27	Data Payload:	5	01 23 45 67 89 AB C0 08
28			

**Figure 19: Frame Builder – MAC Payload Import**

The MAC payload import functionality performs a validation of the provided MAC payload data:

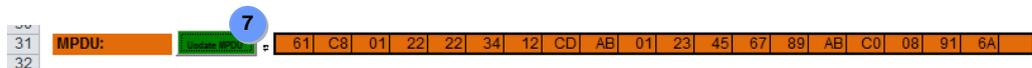
- Only hex characters (0, 1, 2,..9, A,..F) must be used
- Only an integer number of bytes must be provided
- The overall number of payload bytes provided must not result in an excess of the specified maximum MAC frame byte count.

⑥ In order to complete the MAC frame parameters/fields, the calculation of the FCS has to be initiated by pressing the 'Calc. FCS' button:



**Figure 20: Frame Builder – FCS Calculation**

⑦ All MAC frame parts are concatenated to build the MPDU by pressing the 'Update MPDU' button:



**Figure 21: Frame Builder – MPDU Update**

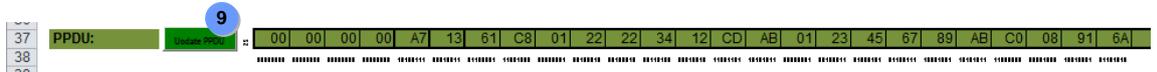
⑧ When the MPDU which forms the PHY payload is available, the PHY header (PHR) and the synchronization header (SHR) have to be specified in a final step:



**Figure 22: Frame Builder – PHY Parameter**

The PHR which contains the MPDU frame length information only, is setup automatically by the *Frame Builder*. The preamble sequence and the start of frame delimiter which form the SHR are preset to the values specified by IEEE 802.15.4 and must therefore not be modified if a standard-compliant frame has to be created.

⑨ In order to set up the entire PPDU and thus to concatenate the different PHY parts, the 'Update PPDU' button has to be pressed:



**Figure 23: Frame Builder – PPDU Update**

### 2.1.1.4 Symbol to Chip Mapping

① The *Frame Builder* automatically performs the required symbol to chip mapping of the PDU according to IEEE 802.15.4:



**Figure 24: Frame Builder – Symbol to Chip Mapping**

The resulting chip sequence can be exported to an ASCII text file either as a ② binary or a ③ hex data string if required.

### 2.1.1.5 Inter Frame Spacing

The *Frame Builder* also includes the functionality to define an Inter Frame Spacing (IFS). This is required since IEEE 802.15.4 signals are bursted with an inter frame gap which must not fall below a specified (frame length dependent) minimum value (see chapter 1.1.2.3 for further details).

In the following example, an IFS of 6 data bytes was specified which results in 12 symbols (x2), 384 chips (x32) and thus 192µs (x0.5µs):



**Figure 25: Frame Builder – Inter Frame Spacing**

The specified inter frame spacing is considered during the data- and control list creation process, described in the following paragraph.

### 2.1.1.6 R&D Data- and Control-List Creation

① To further simplify the import of an IEEE 802.15.4 chip sequence into an R&S VSG, the *Frame Builder* includes the functionality to **convert and export a calculated chip sequence as an R&S data list file**.



**Figure 26: Frame Builder – Data- and Control List Creation**

When the 'Create Data List' button was pressed, the chip sequence and the specified number of IFS chips (all 0) will be converted into a data list file. The resulting file can be saved at any location reachable from the PC running the *Frame Builder* spreadsheet.

For certain test applications, it is sometimes required to perform a so-called power ramping of the frame burst. Other setups require a marker signal to allow the synchronization of auxiliary test equipment with the VSG transmitting the test signal.

② To fully support these needs the *Frame Builder* allows the **creation of R&S control list files** which enable the VSG used in conjunction with the related data list to ramp the frame burst with a certain shape and to provide a marker signal, which is high during the frame interval and low during the IFS phase.

Refer to [8] for details about data and control-lists and their usage.

## 3 IEEE 802.15.4 Signal Generation

BPSK modulated test signals with RRC-filtering as required for IEEE 802.15.4 devices operating in the 861 MHz band can be generated with most standard vector signal generators (VSG).

In contrast, **O-QPSK modulated signals** with half-sine pulse shaping as required for receiver tests of **IEEE 802.15.4 devices operating in the 2450 MHz** band are not supported by every VSG due to the unusual shaping filter and the required specific O-QPSK constellation mapping.

The following paragraphs describe how this task can be accomplished straightforward by all R&S VSGs either by using their realtime Custom Digital Modulation (CDM) or the ARbitrary waveform generator (ARB) functionality.

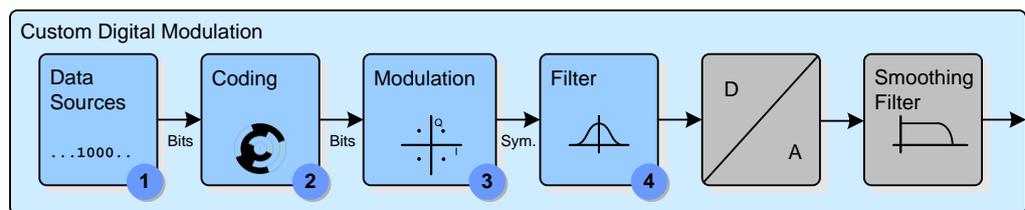
It is also described how R&S data lists containing IEEE 802.15.4 chip sequences are used to provide standard-conform modulation data to the VSG and how R&S control lists may be used to influence the shape of the frame burst and/or to allow the synchronization of the VSG to auxiliary test equipment.

### 3.1 Custom Digital Modulation (CDM)

All R&S VSGs equipped with a realtime baseband generator (see [1], [2], [3], [4] and [5] for details) are able to generate digitally modulated baseband signals in realtime. The characteristic of these signals is either determined by a certain standard (e.g. LTE) or is completely user-definable. The latter signal type is called Custom Digital Modulation (CDM).

In CDM operation mode nearly all baseband parameters and settings with an impact on the signal characteristics are under user control. For further details about CDM, refer to [8].

The following figure provides an overview of the baseband functional blocks and processing steps to be run through when generating a CDM signal:



**Figure 27: Custom Digital Modulation – Overview**

For enabling the VSG to create an IEEE 802.15.4 compliant RF signal by using its CDM functionality, the different functional blocks have to be configured in principle as follows:

- ① The data list files created and exported by using the **Frame Builder spreadsheet** have to be used to provide **standard-conform chip sequences** as data source.
- ② Since IEEE 802.15.4 does not specify any kind of chip coding, this functional block has to remain deactivated.
- ③ The **O-QPSK modulation mapping** specified for the O-QPSK PHY (see *Figure 5*) is not supported by default by the R&S VSGs and thus has to be made available via a user-specific modulation mapping file. This mapping file '15\_4-OQPSK.vam' created with the R&S MATLAB application MapWiz [10] is provided with this application note.

④ The required **half-sine pulse shaping** has to be realized by using a user-specific pulse shaping file. This shaping file '15.4-HalfSine.vaf' created with the R&S MATLAB application FiltWiz [11] is provided with this application note.

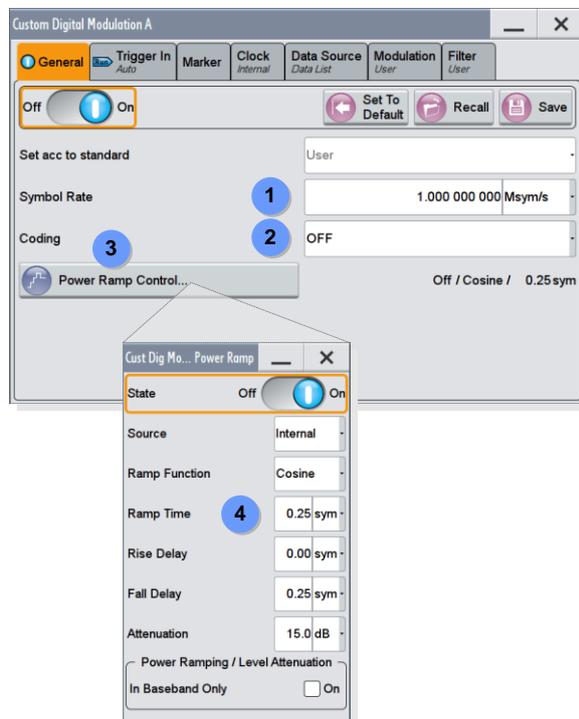
The following paragraphs exemplarily illustrate how these settings have to be made manually using an SMW or by means of the CDM-Toolbox application software [8].

### 3.1.1 CDM Configuration

The CDM parameters of the SMW which are organized in a tab based dialog have to be set as follows:

#### 3.1.1.1 General Settings

① The **symbol rate** has to be set to 1 MSym/s.



**Figure 28: Custom Digital Modulation – General**

② Chip coding is not required, therefore **coding has to be deactivated**.

③ In order to have a transmission only during the frame and not during the IFS period, the frame burst interval has to be specified by a so-called **burst marker** defined within an R&S control list (see chapter 3.1.1.4 for further details).

④ Some burst specific parameters like the expected rise and fall time and the shape of the burst slopes have to be specified by the 'Power Ramp Control' dialog.

To optimize the EVM of a bursted IEEE 802.15.4 signal, it is recommended to properly adjust especially the 'Ramp Time' and the 'Fall Delay' since these parameters have a direct impact on the first and last symbol of a certain frame (see also chapter 3.3.1.3).

### 3.1.1.2 Filter Settings

① To comply with IEEE 802.15.4 a **half-sine pulse shaping filter** has to be used. Since this filter type is not supported by default, a 'User' defined filter has to be specified.

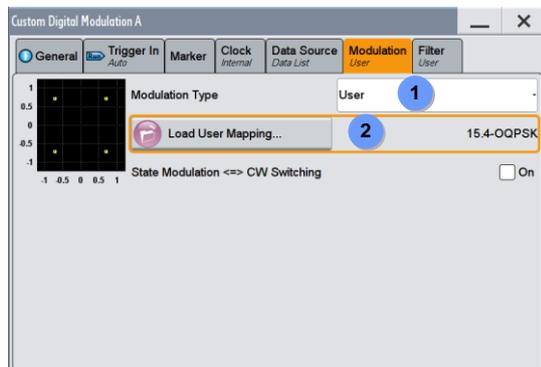


**Figure 29: Custom Digital Modulation – Filter**

② Select the shaping filter file '15.4-HalfSine.vaf', which is provided with this application note. To simplify the access to the different kinds of file types supported by the R&S VSGs, it is recommended to use dedicated file type specific folders, e.g.: /var/user/Filters for user-specific shaping filter files.

### 3.1.1.3 Modulation Settings

① The IEEE 802.15.4 specific **O-QPSK constellation mapping** is also not supported by default but can be activated by using a 'User' defined mapping file.



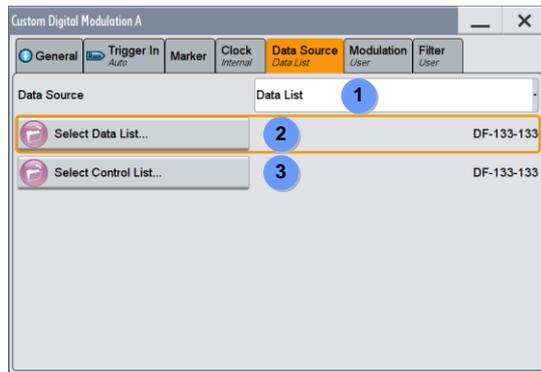
**Figure 30: Custom Digital Modulation – Modulation**

② Select the mapping file '15.4-OQPSK.vam', which is provided with this application note. To simplify the access to the different kinds of file types supported by the R&S VSGs, it is recommended to use dedicated file type specific folders, e.g.: /var/user/Mappings for user-specific mapping files.

### 3.1.1.4 Data Source Settings

It is essential to use chip sequences which were created according to IEEE 802.15.4 if the modulated RF signal has to be properly demodulated by any IEEE 802.15.4 based device.

① This kind of data has to be provided by **R&S data list files** which may be created by using the *Frame Builder* Excel spreadsheet (see chapter 2.1 for details).



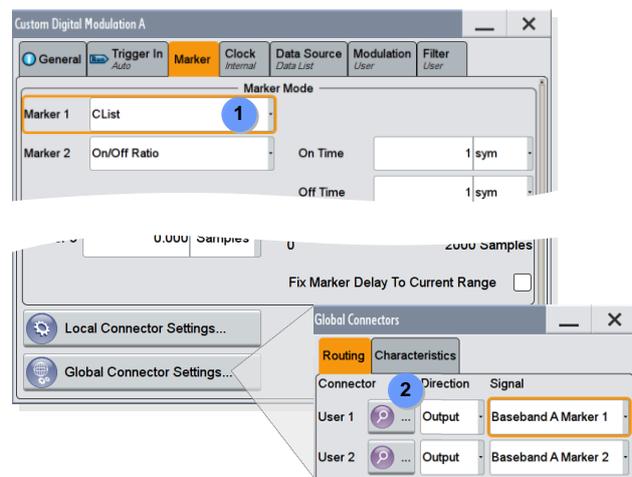
**Figure 31: Custom Digital Modulation – Data Source**

② Select any data list file containing a valid IEEE 802.15.4 chip sequence. To simplify the access to the different kinds of file types supported by the R&S VSGs, it is recommended to use dedicated file type specific folders, e.g.: `/var/user/DataLists` for data list files.

③ In addition, an appropriate **R&S control list file** has to be selected if it is intended to generate a bursted (framed) signal and/or a marker signal has to be generated by the used VSG.

### 3.1.1.5 Marker Settings

① To enable the output of a certain marker signal which was specified by a selected control list, the related marker mode has to be set to 'CList':



**Figure 32: Custom Digital Modulation – Marker**

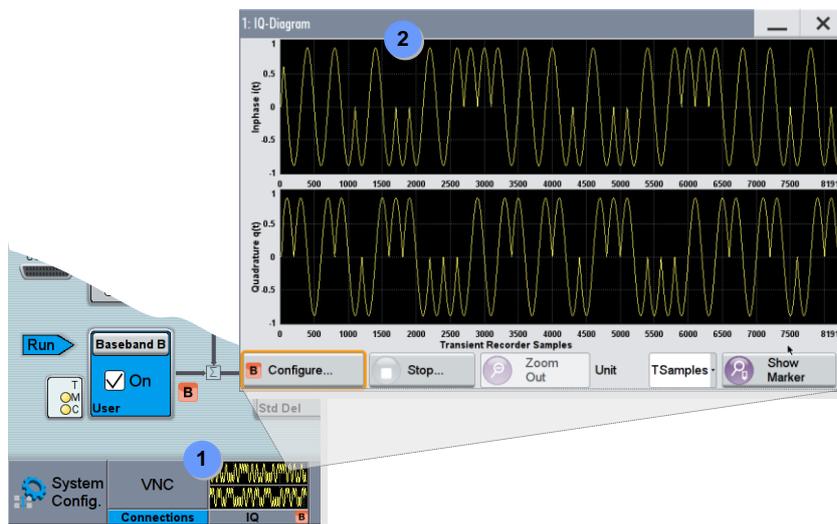
② Since the SMW allows a very flexible assignment of all available control signals (In/Out) to local or global connectors, the marker signal of interest has to be mapped to the selected connector (e.g. User 1)

### 3.1.2 Signal Evaluation

To evaluate the performed custom digital modulation configuration without the need of any additional test equipment the **'Graphics' functionality** offered by most of the R&S VSGs may be used.

For example the graphics functionality of the SMW has to be configured as follows:

① Specify the data source which has to be evaluated (e.g. Baseband B) and simply choose among a wide variety of graphics modes the desired one (e.g. I/Q). After the activation of a certain signal graphics it is immediately shown as a minimized graphics in the task bar.



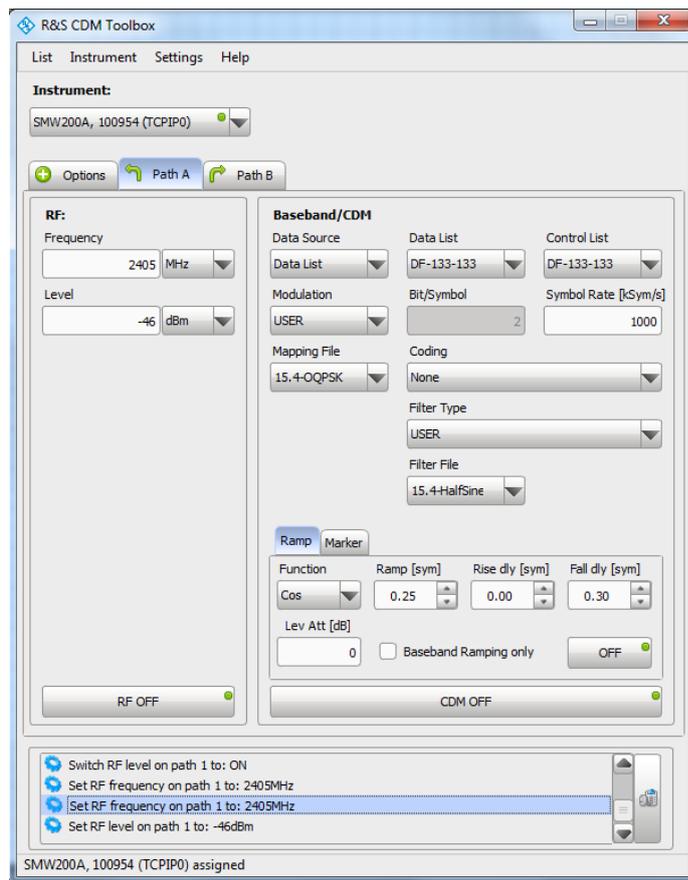
**Figure 33: Signal Performance – SMW Signal Graphics**

② For a more detailed analysis of the signal the minimized graphics may be enlarged.

### 3.1.3 Remote CDM Configuration – CDM-Toolbox

The manual configuration of the custom digital modulation functionality by using the VSG GUI described in the previous chapter is straight forward and is normally done in no time.

Nevertheless, it may be helpful to use the 'CDM-Toolbox' remote control application for any kind of custom digital modulation based tests, especially in case of excessive data and control list usage:

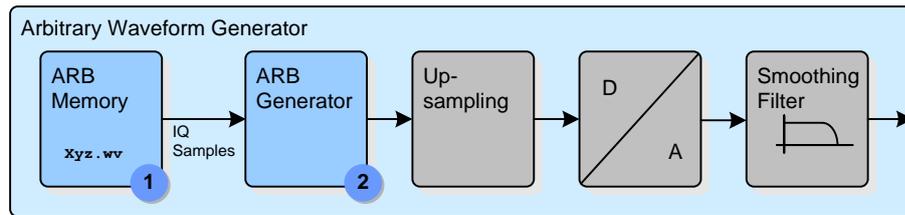


**Figure 34: Custom Digital Modulation – CDM Toolbox**

For further details refer to [8].

## 3.2 Arbitrary Waveform Generator (ARB)

This chapter describes how IEEE 802.15.4 compliant signals can be generated also by R&S VSGs not equipped with the realtime CDM functionality but with an arbitrary waveform generator (ARB) only (e.g. the R&S SGT [6]). In the ARB mode of operation, nearly all baseband parameters and settings with an impact on the signal characteristics have to be considered during the waveform creation process. Only the sampling rate used to replay the waveform may be altered by the VSG used. The following figure provides an overview of the baseband functional blocks and processing steps to be run through when generating an ARB based signal:



**Figure 35: Arbitrary Waveform Generator – Overview**

To enable the VSG to create an IEEE 802.15.4 compliant RF signal by using its ARB functionality, the different functional blocks have to be configured in principle as follows:

- ① A so-called waveform file containing the IQ samples of an IEEE 802.15.4 compliant signal has to be selected and loaded to the VSG ARB memory.
- ② Then, the ARB waveform generator just has to be started.

The following paragraphs exemplarily illustrate how IEEE 802.15.4 waveform files are created and how they are selected, loaded and activated using an SGT.

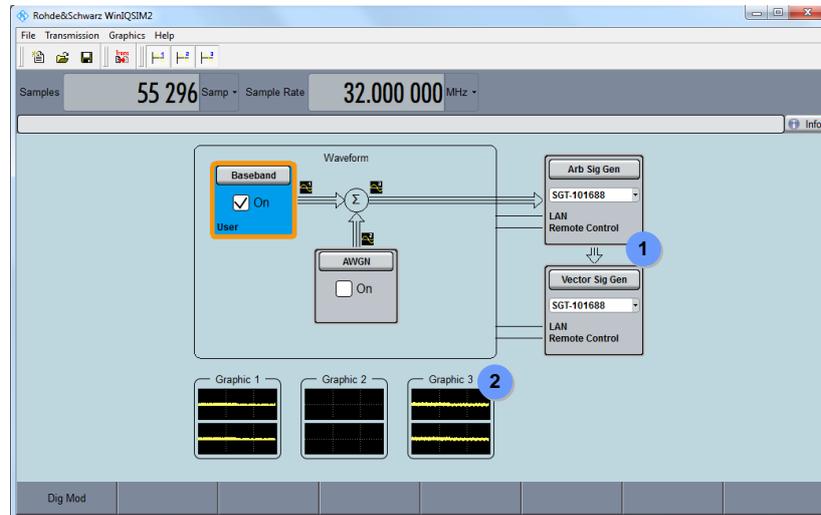
### 3.2.1 ARB Waveform creation with WinIQSIM2

The R&S WinIQSIM2 [7] software, which is available free of charge, permits the calculation of digitally modulated baseband signals and the creation of the related R&S waveform files on a Windows PC system.

The signal calculation is either based on certain standards (e.g. WLAN/WiFi) or is completely user definable (CDM).

The overall functional range of WinIQSIM2 is therefore comparable with the realtime options offered by R&S VSGs with one major difference – the signal includes only a user-defined limited number of symbols and is therefore a snapshot of a realtime signal.

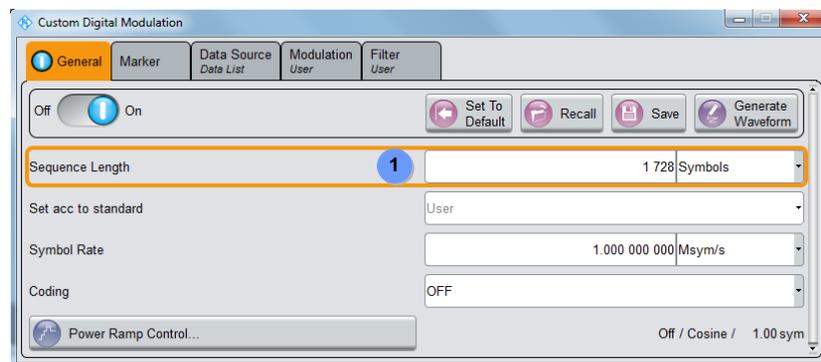
The look-and-feel of WinIQSIM2, especially the block diagram, is based on the R&S VSG GUI. Therefore users of any R&S vector signal generator can easily get used to the handling and behavior of this powerful software.



**Figure 36: WinIQSIM2 – Overview**

For further WinIQSIM2 details, amongst others the ① remote interaction with R&S VSGs (e.g. for waveform file download) or the available features to ② visualize the waveform data in different formats, refer to [7].

The required IEEE 802.15.4 waveform files can easily be created by using the CDM functionality offered by WinIQSIM2.



**Figure 37: WinIQSIM2 – Custom Digital Modulation – General**

To simplify the waveform creation process, nearly all CDM configuration steps are identically to the realtime CDM setup described in chapter 3.1.

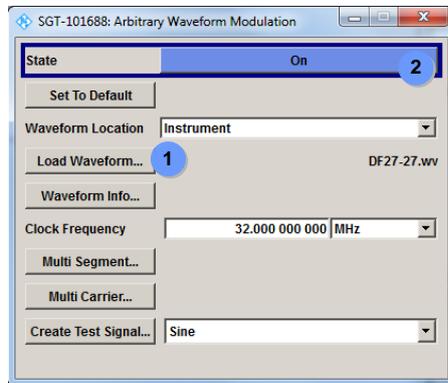
① Only one additional parameter, the 'Sequence Length' has to be set.

To prevent any kind of time domain truncation effect, it is essential to set the 'Sequence Length' to the number of O-QPSK symbols provided by the data list file.

### 3.2.2 ARB Configuration

The ARB parameters of the SGT have to be set as follows:

- ① Select/Load the desired waveform file which may be located on the hard disc of the SGT or any file system reachable by the controller PC running the (SGMA GUI).



**Figure 38: Arbitrary Waveform Generator – Settings**

- ② Activate the arbitrary waveform generator. For further details about the SGT operation refer to [6].

### 3.3 Signal Performance

The following paragraphs provide an overview about the **excellent performance of bursted IEEE 802.15.4 signals** generated with R&S VSGs.

The test signal used for the performance analysis was generated by an SMW based on the data list file (DF-27-27.dm-iq.d) provided with this application note (see chapter 7.3).

#### 3.3.1 Vector Signal Analyzer

In general, a vector signal analyzer (VSA) is required to allow in depth analysis of the PHY layer signal performance in the frequency, time and IQ domain.

The following results of several PHY layer signal performance measurements were done by using an R&S FSW vector signal analyzer.

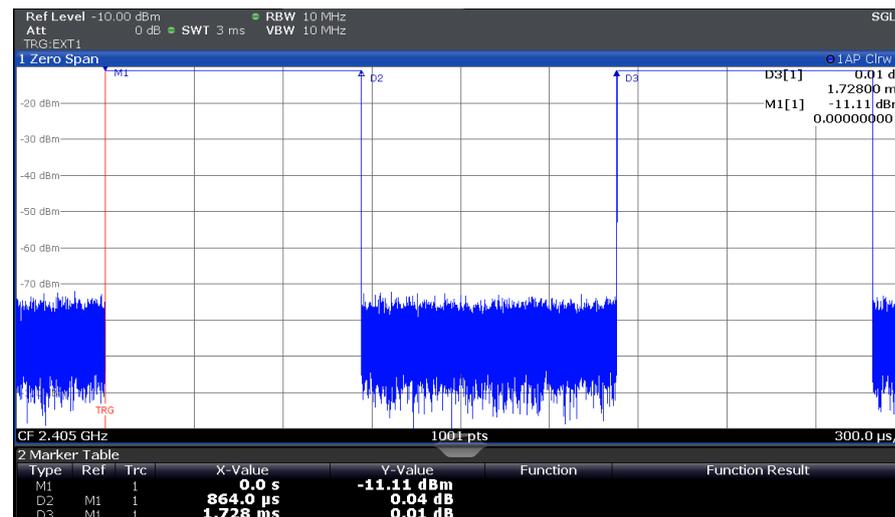
All measurements have been performed with the following basic settings:

Signal Performance – VSA/VSG Basic Settings	
Parameter	Setting
RF Frequency:	2.405 GHz (Channel 11)
RF Level:	-10 dBm
Synchronization:	FSW 10 MHz REF Out to SMW REF In
Triggering (optional):	SMW Marker 1 (Control List) Out to FSW Trigger 1 In

**Table 5: Signal Performance – Basic VSA/VSG Settings**

##### 3.3.1.1 Time Domain (Zero Span)

As a first step, the signal was analyzed in the zero span mode to evaluate the overall burst timing and to obtain information on the nature of the burst and the IFS period.



**Figure 39: Signal Performance – Time Domain (Zero Span)**

### 3.3.1.2 RF Domain (Spectrum)

A gated frequency sweep highlights the IEEE 802.15.4 O-QPSK (Half-sine) spectrum.



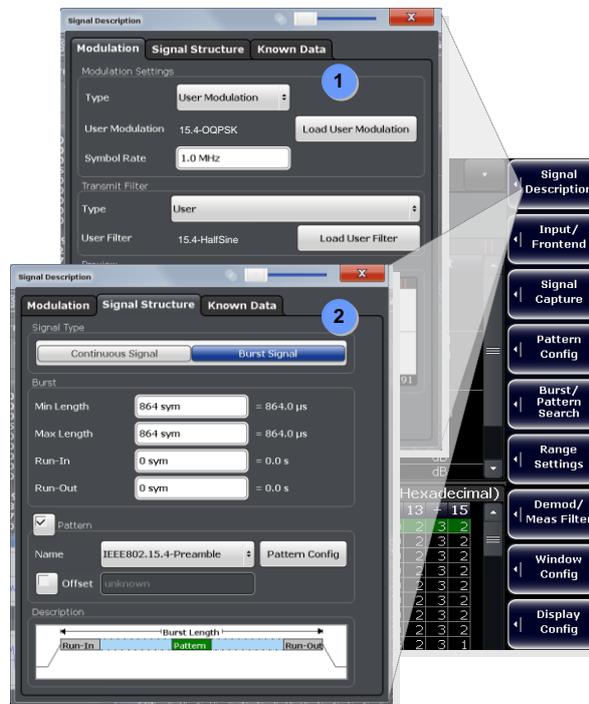
Blue: Repeated DF-27-27 data frame, Green: Repeated PRBS9 chips

**Figure 40: Signal Performance – RF Domain (Spectrum)**

### 3.3.1.3 Demodulation

The demodulation of the IEEE 802.15.4 signal and the subsequent evaluation of the resulting IQ baseband signal was done by using the VSA personality of the FSF.

The required/used FSF VSA settings are shown at a glance in the following figures:



**Figure 41: FSF, VSA Settings – Signal Description**

The **'Signal Description'** dialog allows the configuration of modulation and shaping filter type specific parameters and has to be used to define the expected time domain signal structure.

① It is recommended to apply the same user specific modulation mapping and shaping filter files on the FSW as activated on the SMW (see chapter 3.1.1.2 and 3.1.1.3).

Only this approach guarantees a perfect match of the performed modulation and demodulation processes and thus achieves the best performance results.

② The signal type has to be set to 'Bursted Signal'. The related burst 'Min/Max Length' parameter has to be specified based on the transmitted number of O-QPSK symbols per burst.

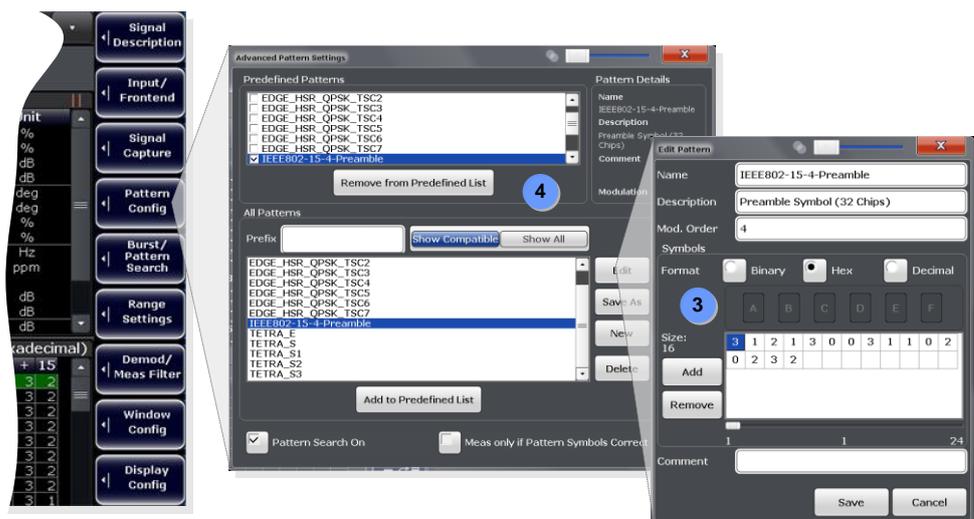
In order to allow a reproducible and stable demodulation result, it is required to synchronize the FSW to a well-known IQ pattern. Therefore, the related 'Pattern' checkbox has to be activated and a burst specific search pattern has to be selected.

The pattern also allows the VSA personality to compensate for rotations in the IQ plane, i.e. phase shifts.

The required pattern configuration/definition steps are highlighted in the following.

The **'Pattern Config'** dialog must be used to specify and to activate a certain search pattern. Here, in the present example, the FSW is synchronized by the chip sequence of the first PPDU preamble symbol (0) (see *Table 2*).

③ If none of the available 'Predefined Patterns' fits to the needs, a new pattern can be created. Specify the pattern symbols in a preferred format and save the new pattern with a meaningful name.

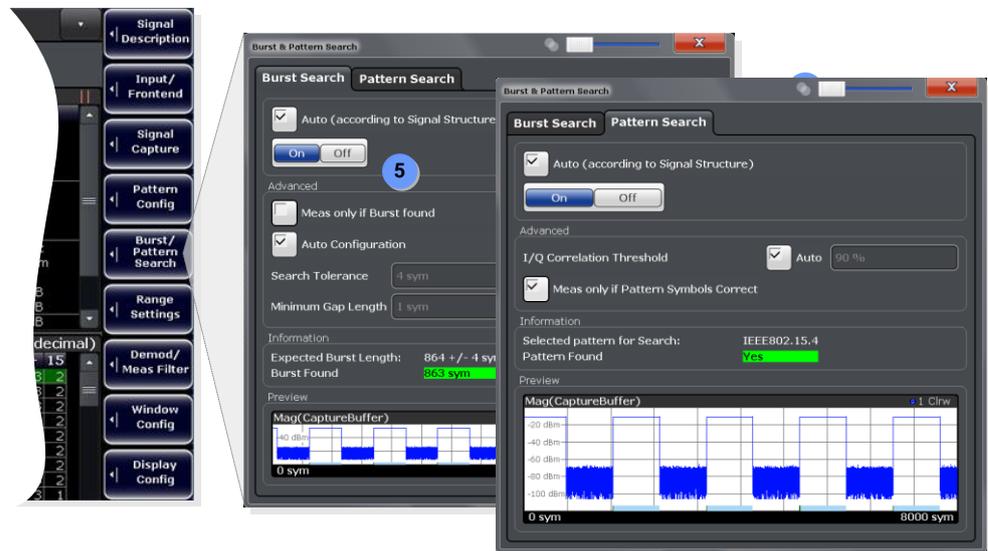


**Figure 42: FSW, VSA Settings – Pattern Config**

④ The pattern has then to be added to the 'Predefined Patterns' and finally selected via the related checkbox.

⑤ The **'Burst/Pattern Search'** dialog is used to configure the burst and pattern search process applied by the FSW, and to provide information about the current burst/pattern search status.

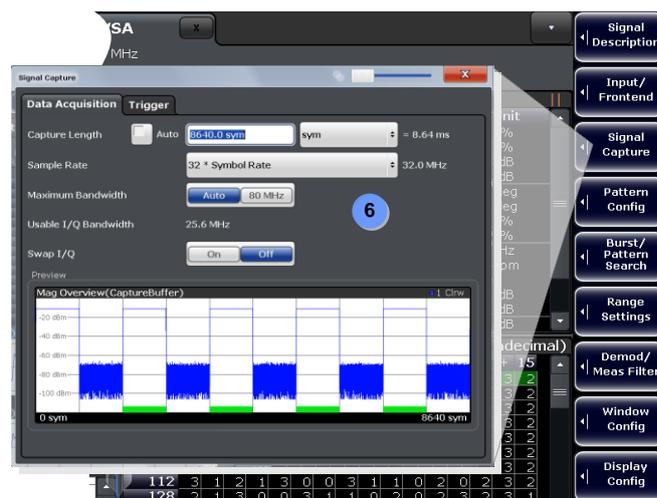
Based on the previous pattern configuration steps, the related burst/pattern search dialog shows as follows:



**Figure 43: FSW, VSA Settings – Burst/Pattern Search**

Both tabs, the 'Burst Search' as well as the 'Pattern Search' have an indicator field showing the result of the burst and pattern search over the current capture buffer. Green fields indicate a successful search process.

⑥ The **'Signal Capture'** dialog provides all settings for the IQ data acquisition. In order to optimize the demodulation performance the 'Capture Length', should be set to an integer multiple of the transmitted O-QPSK symbols per frame. The 'Sample Rate' should be set to an oversampling rate of 32.

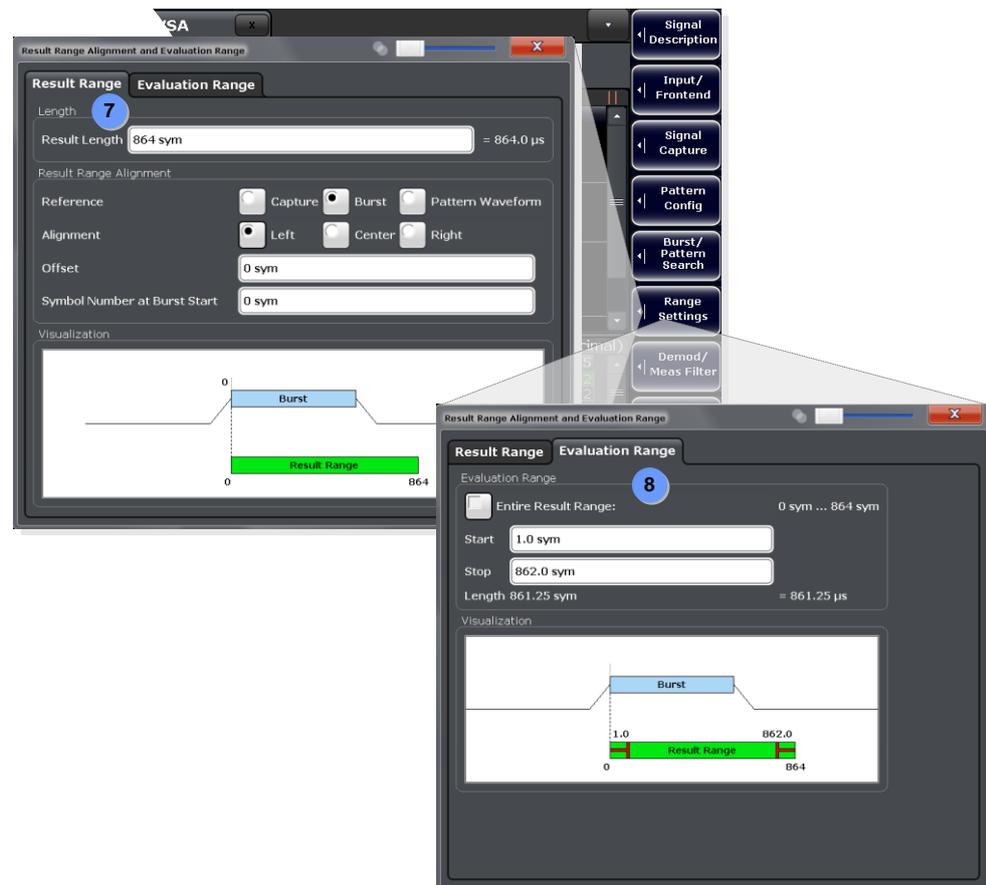


**Figure 44: FSW, VSA Settings – Signal Capture**

Finally, the 'Range Settings' dialog must be used to define the so-called 'Result Range' and the 'Evaluation Range'.

⑦ The 'Result Range' tab on the one hand allows the specification of the 'Result Length' and the number of shown O-QPSK symbols of a certain burst, and on the other hand takes care of the proper alignment of the result range.

In the following figure, the result length was specified to be exactly the same as the burst length (see *Figure 41*). The result range was left aligned with no additional symbol offset, to show all (and only) symbols of the burst period.



**Figure 45: FSW, VSA Settings – Range Settings**

⑧ The 'Evaluation Range' is essential to properly determine the area of result range symbols considered for any IQ performance parameter calculation (e.g. EVM). Unless the effect of power ramping is of special interest, it is recommended to exclude the first and the last samples of the result range, e.g. start the evaluation at symbol 2 and stop the evaluation 2 symbols prior to the result range end. Thus, the power ramping is not taken into account for the EVM calculation.

Based on the FSW (VSA) settings above, the following demodulation results have been obtained:

### Modulation Accuracy/EVM:

① The 'Result Summary' demonstrates an excellent EVM of < 0.3 % (-50 dB) of the generated IEEE 802.15.4 signal.

The shown EVM is the residual EVM and thus includes contributions from both the signal generator and the signal analyzer.

A very low residual EVM is important for R&D and production environments where smaller error margins mean a better knowledge of the DUT and, ultimately, a better yield.



Figure 46: Signal Performance – EVM

The scope of the EVM evaluation was limited to the data burst by adjusting the evaluation range of the signal analyzer (see Figure 45). Note that the evaluation range is highlighted by red vertical lines in the IQ diagram and the symbol table.

See also [9] for further background information on EVM measurements of ZigBee™ signals.

### IQ-Signals:

② It is helpful to display the IQ data stream in the time domain in order to get an impression of the demodulated IQ signals and thus to allow a direct comparison with the generated IQ signals (see chapter 3.1.2).

### Symbols:

③ The 'Symbols' table visualizes the demodulated O-QPSK symbol sequence and thus allows the determination of the received IEEE 802.15.4 data symbols.

For example, the symbols shown in the figure above can be mapped to the following data symbols by applying the IEEE 802.15.4 O-QPSK symbol to chip mapping rules (see Table 2):

00 00 00 00 A7 15 21 8

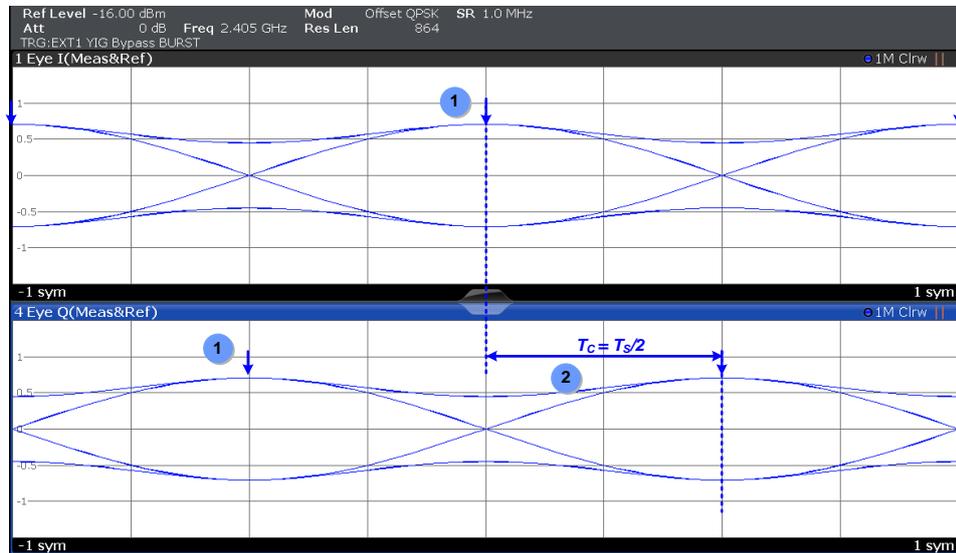
Figure 47: Signal Performance – Demodulated PPDU Data

A comparison with the transmitted PPDU data (see Figure 52) shows that the transmitted and the received/demodulated sequence are really identical.

**IQ Signals (Eye-Diagram):**

The following figure shows the IQ eye-diagram.

- ① The wide eyes and the precise definition of the signals during the sample phase confirm the very good modulation quality.
- ② The comparison eye diagrams of the I- and Q-components clearly shows how the I and Q data is shifted from each other in time by half the symbol period  $T_S$ .

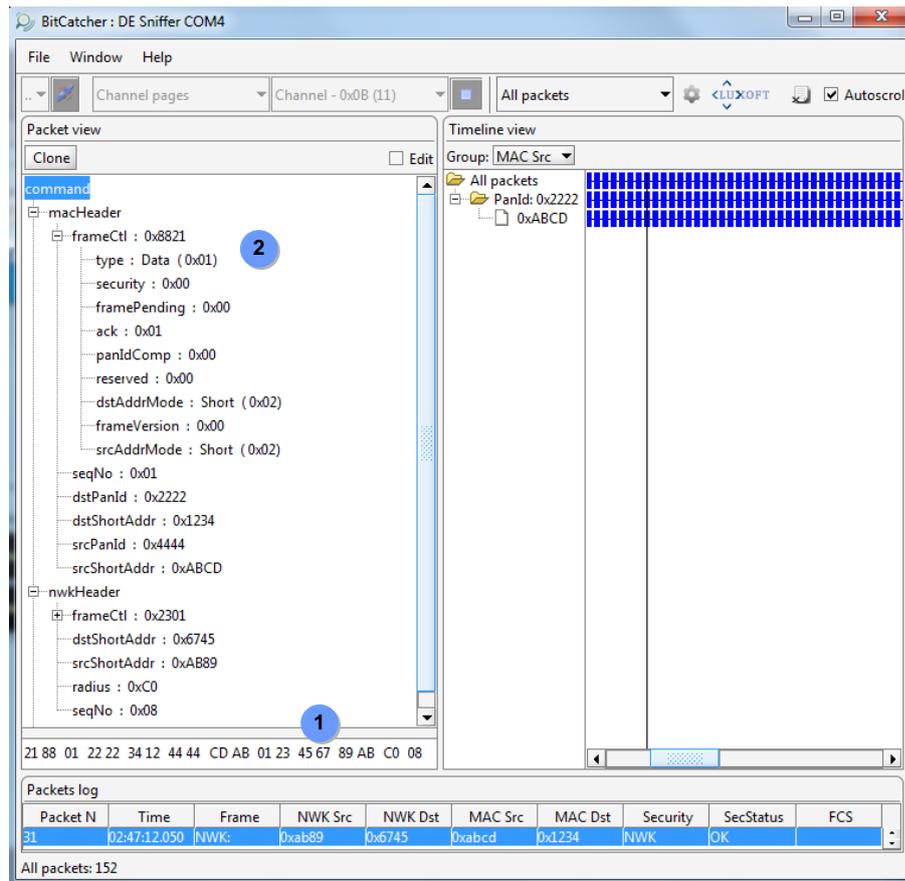


**Figure 48: Signal Performance – IQ Signals (Eye-Diagram)**

### 3.3.1 IEEE 802.15.4 Wireless Protocol Analyzer

A wireless protocol analyzer has to be used to enable a more advanced analysis of the generated IEEE 802.15.4 packets/frames. Such equipment allows the observation of data flows and runtime performance. They provide a graphical user interface which enables the user to observe real time packet transfers and to create and view log files with detailed information about the packet/frame structure of a received signal.

A protocol analysis performed with the 'BitCatcher' analyzer stick [22][23] shows the following result:



**Figure 49: IEEE 802.15.4 BitCatcher – Packet/Frame Analysis**

① The frame which was transmitted repeatedly was properly received and demodulated by the analyzer and ② all MAC frame parameter fields are identical with those specified during the frame creation using the *Frame Builder* spreadsheet (see chapter 7.3).

## 4 IEEE 802.15.4 Receiver Tests

IEEE 802.15.4 devices have to proof compliance with the general PHY requirements and worldwide radio frequency regulations like:

- World Wide: IEEE 802.15.4 [12]
- Europe: ETSI EN 300 328 and EN 300 440 class 2 [20][21]
- US: FCC CFR47 Part 15
- Japan: ARIB STD-T66

Some of these standards specify receiver tests which require the generation of standard conform IEEE 802.15.4 test signals.

The following paragraphs provide an overview about these receiver tests and the related definitions, requirements and the specified test signal (parameters).

### 4.1 IEEE 802.15.4 O-QPSK PHY Receiver Requirements

IEEE 802.15.4 [12] specifies following receiver requirement for the O-QPSK PHY operation in the 2450 MHz band.

#### 4.1.1 Receiver Sensitivity

##### 4.1.1.1 General Definition

IEEE 802.15.4 [12] defines the receiver sensitivity and the related packet error rate (PER) parameter as follows:

IEEE 802.15.4 – Receiver Sensitivity Definition		
Term	Definition	Conditions
Receiver sensitivity	Lowest input power for which the PER conditions are met	<ul style="list-style-type: none"> <li>• PSDU length: 20 octets</li> <li>• PER: &lt; 1%</li> <li>• Interference: None</li> </ul> Note: Power measured at antenna terminals
Packet error rate (PER)	Average fraction of transmitted packets that are not correctly received	Average measured over random PSDU data

**Table 6: IEEE 802.15.4 – Receiver Sensitivity Definition**

##### 4.1.1.2 Requirement

Under the conditions specified in *Table 6*, a compliant device with an O-QPSK PHY shall be capable of achieving a receiver sensitivity of -85 dBm or better. The receiver shall meet the PER criteria defined in *Table 6* under these conditions.

##### 4.1.1.3 Measurement

The desired signal shall be a compliant O-QPSK PHY signal, as defined in chapter 1.1.1 of pseudo-random data. The desired signal is input to the receiver at a level equal to or below the maximum allowed receiver sensitivity (see chapter 4.1.1.2).

## 4.1.2 Receiver Interference Rejection

### 4.1.2.1 Requirement

An O-QPSK PHY shall support following minimum interference rejection levels:

IEEE 802.15.4 – Receiver Interference Rejection	
Interfering Channel	Minimum interference rejection
Adjacent	0 dB
Alternate	30 dB

**Table 7: IEEE 802.15.4 – Receiver Interference Rejection**

The adjacent channels are on either side of the desired channel closest in frequency to the desired channel whereas the alternate channels follow close upon the adjacent channels. For example, when channel 15 is the desired channel, channel 14 and channel 16 are the adjacent channels, and channel 13 and channel 17 are the alternate channels.

The receiver shall meet the PER criteria defined in *Table 6* under these conditions.

### 4.1.2.2 Measurement

The adjacent channel rejection shall be measured as follows:

The desired signal shall be a compliant O-QPSK PHY signal, as defined in chapter 1.1.1 of pseudo-random data. The desired signal is input to the receiver at a level 3 dB greater than the maximum allowed receiver sensitivity (see 4.1.1.2).

In either the adjacent or the alternate channel, a compliant O-QPSK PHY signal is input at the level specified in *Table 7* relative to the desired signal. The test shall be performed for only one interfering signal at a time.

## 4.1.3 Receiver maximum Input Level

### 4.1.3.1 Requirement

The O-QPSK PHY shall have a receiver maximum input level greater than or equal to -20 dBm.

The receiver shall meet the PER criteria defined in *Table 6* under these conditions.

### 4.1.3.2 Measurement

The desired signal shall be a compliant O-QPSK PHY signal, as defined in chapter 1.1.1 of pseudo-random data. The desired signal is input to the receiver at a level as specified in chapter 4.1.3.1.

## 4.2 ETSI EN 300 440-1/2 Receiver Requirements

ETSI EN 300 440-1 and 2 [20][21] specify following receiver requirements and related essential test cases for receivers of category 1 and/or category 2.

### 4.2.1 Adjacent Channel Selectivity

The adjacent channel selectivity is a measure of the capability of the receiver to operate satisfactorily in the presence of an unwanted signal that differs in frequency from the wanted signal by an amount equal to the adjacent channel.

#### 4.2.1.1 Requirement

The adjacent channel selectivity of the equipment under specified conditions shall not be less than the levels of the unwanted signal as stated in following table:

ETSI EN 300 440-1/2 – Adjacent Channel Selectivity	
Receiver Category	Unwanted Signal Level
1	-30 dBm + $k$
2	No limit
3	No limit

$k = -20 \log f - 10 \log BW$ ; but  $0 < k \leq 40$  dB

$f$ : Channel frequency [GHz],  $BW$ : Channel bandwidth [MHz]

**Table 8: ETSI EN 300 440-1/2 – Adjacent Channel Selectivity**

The receiver shall give sufficient response under these conditions.

#### 4.2.1.2 Measurement

Two signal generators shall be connected to the receiver via a combining network to the receiver, either:

- via a test fixture or a test antenna to the receiver integrated, dedicated or test antenna; or
- directly to the receiver permanent or temporary antenna connector.

One signal generator shall provide the desired (wanted) signal at the nominal frequency of the receiver, with normal modulation.

The second interfering generator shall be unmodulated and shall be adjusted to the adjacent channel center frequency immediately above that of the wanted signal.

Initially the interfering signal generator shall be switched off and using the wanted signal generator the level that still gives sufficient response shall be established. The level of the wanted signal shall then be increased by 3 dB.

Afterwards the RF level of the interfering signal generator is switched on and adjusted (increased) as long as the wanted criteria are met. The maximum interference level shall be recorded.

This measurement shall be repeated with the adjacent channel center frequency adjusted to the adjacent channel center immediately below the wanted signal.

## 4.2.2 Blocking or Desensitization

Blocking is a measure of the capability of the receiver to receive a wanted modulated signal without exceeding a given degradation due to the presence of an unwanted input signal at any frequencies other than those of the spurious responses or the adjacent channels or bands.

### 4.2.2.1 Requirement

The blocking level, for any frequency within the specified ranges, shall not be less than the values given by following table, except at frequencies on which spurious responses are found:

ETSI EN 300 440-1/2 – Blocking or Desensitization	
Receiver Category	Unwanted Signal Level
1	-30 dBm + $k$
2	-45 dBm + $k$
3	No limit

$k = -20 \log f - 10 \log BW$ ; but  $0 < k < 40$  dB

$f$ : Channel frequency [GHz],  $BW$ : Channel bandwidth [MHz]

**Table 9: ETSI EN 300 440-1/2 – Blocking or Desensitization**

The receiver shall give sufficient response under these conditions.

### 4.2.2.2 Measurement

Two signal generators shall be connected to the receiver via a combining network to the receiver, either:

- via a test fixture or a test antenna to the receiver integrated, dedicated or test antenna; or
- directly to the receiver permanent or temporary antenna connector.

One signal generator shall provide the desired (wanted) signal at the nominal frequency of the receiver, with normal modulation.

The second interfering generator shall be unmodulated and shall be adjusted to a test frequency at approximately 10 times, 20 times and 50 times of the receive channel bandwidth above upper band edge of the receive channel.

Initially the interfering signal generator shall be switched off and using the wanted signal generator the level that still gives sufficient response shall be established. The level of the wanted signal shall then be increased by 3 dB.

Afterwards the RF level of the interfering signal generator is switched on and adjusted (increased) as long as the wanted criteria are met. The maximum interference level shall be recorded.

The measurement shall be repeated with the frequency of the interfering generator at approximately 10 times, 20 times and 50 times of the receive channel bandwidth below the lower band edge of the receive channel.

## 5 Abbreviations

6LoWPAN	IPv6 over Low power WPAN (IETF)
BSN	Beacon Sequence Number
CDM	Custom Digital Modulation
DSN	Data Sequence Number
FCS	Frame Check Sequence
GTS	Guaranteed Time Slot
IEEE	Institute of Electrical and Electronics Engineers
IFS	Inter Frame Spacing
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
OSI	Open Systems Interconnection
O-QPSK	Offset QPSK
LIFS	Long Inter Frame Spacing
MAC	Medium Access Control (Layer)
MFR	MAC Footer
MHR	MAC Header
MPDU	MAC Protocol Data Unit
PAN	Personal Area Network
PDU	Protocol Data Unit
PER	Packet Error Rate
PHR	PHY Header
PHY	Physical Layer
PN	Pseudo-random Noise
POS	Personal Operating Space
PPDU	PHY Protocol Data Unit
PRBS	Pseudo Random Bit Sequence
PSDU	PHY Service Data Unit
QPSK	Quadrature Phase Shift Keying
RF4CE	Radio Frequency for Consumer Electronics
SFD	Start of Frame Delimiter
SHR	Synchronization Header
SIFS	Short Inter Frame Spacing
VSA	Vector Signal Analyzer
VSG	Vector Signal Generator

## 6 References

### Manuals:

- [1] R&S, SMW200A User Manual
- [2] R&S, SMU200A Operating Manual
- [3] R&S, SMATE200A Operating Manual
- [4] R&S, SMJ100A Operating Manual
- [5] R&S, SMBV100A Operating Manual
- [6] R&S, SGT100A Operating Manual
- [7] R&S, WinIQSIM2 Software Manual

### Application Notes:

- [8] R&S, 1GP96, CDM-Toolbox – Digital Modulation in a simple way
- [9] R&S, 1EF55, EVM measurements for ZigBee™ signals in the 2.4 GHz band
- [10] R&S, MapWiz, Modulation mapping wizard
- [11] R&S, FiltWiz, Shaping filter design wizard

### Standards and Specifications:

- [12] IEEE Std 802.15.4-2011;  
IEEE Standard for Local and metropolitan area networks-  
Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)
- [13] IEEE Std 802.15.4e-2012;  
IEEE Standard for Local and metropolitan area networks  
Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)  
Amendment 1: MAC sublayer
- [14] IEEE Std 802.15.4f-2012;  
IEEE Standard for Local and metropolitan area networks  
Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)  
Amendment 2: Active Radio Frequency Identification (RFID) System Physical  
Layer (PHY)
- [15] IEEE Std 802.15.4g-2012;  
IEEE Standard for Local and metropolitan area networks  
Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)  
Amendment 3: Physical Layer (PHY) Specifications for Low-Data-Rate,  
Wireless, Smart Metering Utility Networks
- [16] IEEE Std 802.15.4j-2013;  
IEEE Standard for Local and metropolitan area networks  
Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)  
Amendment 4: Alternative Physical Layer Extension to Support Medical Body  
Area Network (MBAN) Services Operating in the 2360 MHz – 2400 MHz Band
- [17] IEEE Std 802.15.4k-2013;  
IEEE Standard for Local and metropolitan area networks  
Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)  
Amendment 5: Physical Layer Specifications for Low Energy, Critical  
Infrastructure Monitoring Networks.
- [18] ZigBee™ Alliance, ZigBee 2012 Specification
- [19] ZigBee™ Alliance, [ZigBee Standards](#)
- [20] ETSI EN 300 440-1 V1.6.1 (2010-08)  
Electromagnetic compatibility and Radio spectrum Matters (ERM);

Short range devices;  
Radio equipment to be used in the 1 GHz to 40 GHz frequency range;  
Part 1: Technical characteristics and test methods  
Part 2: Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive

- [21] ETSI EN 300 440-2 V1.4.1 (2010-08)  
Electromagnetic compatibility and Radio spectrum Matters (ERM);  
Short range devices;  
Radio equipment to be used in the 1 GHz to 40 GHz frequency range;  
Part 2: Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive

**Miscellaneous:**

- [22] dresden elektronik; [deRFusb 23E00](#), IEEE 802.15.4/ZigBee™ analyzer USB stick
- [23] Luxoft; [Bitcatcher](#), IEEE 802.15.4/ZigBee™ wireless network analyzer software

## 7 Appendix

### 7.1 O-QPSK – Modulation Mapping File

The modulation mapping file '15.4-OQPSK.vam', created with the R&S MATLAB application MapWiz [10], is provided with this application note.

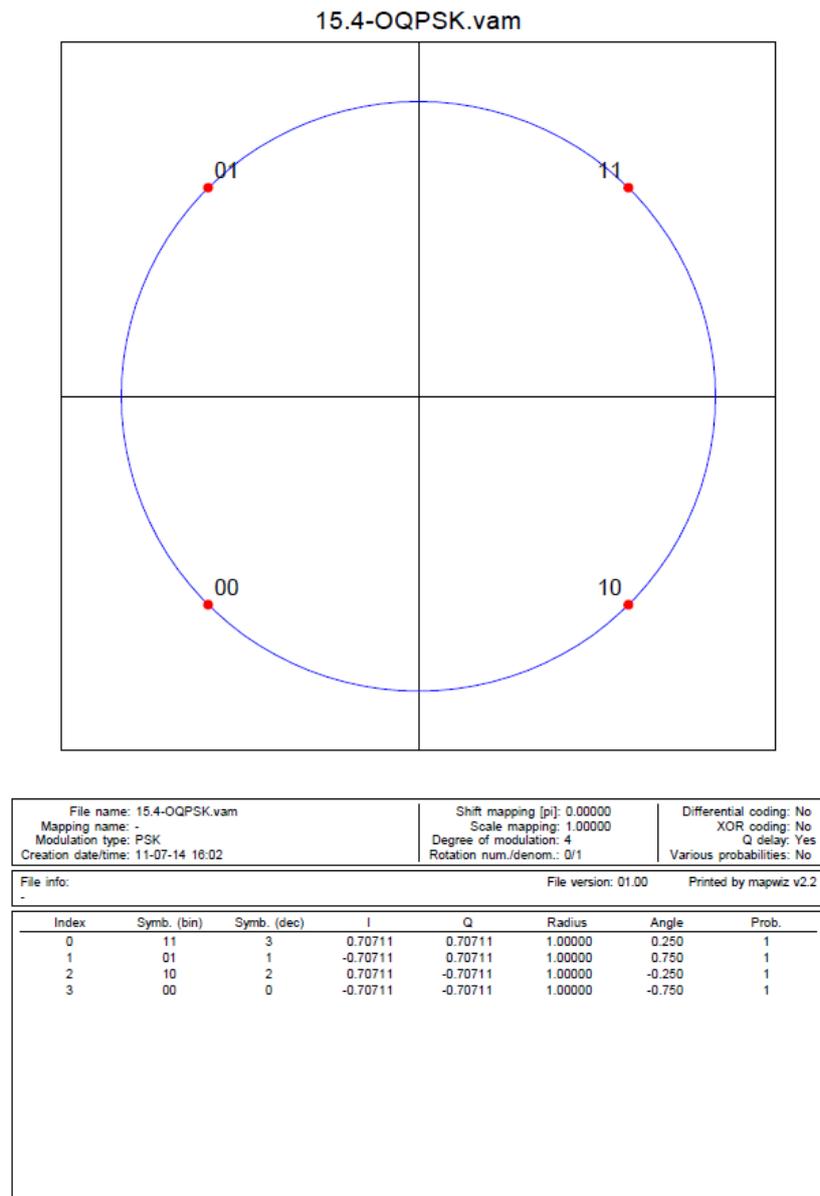
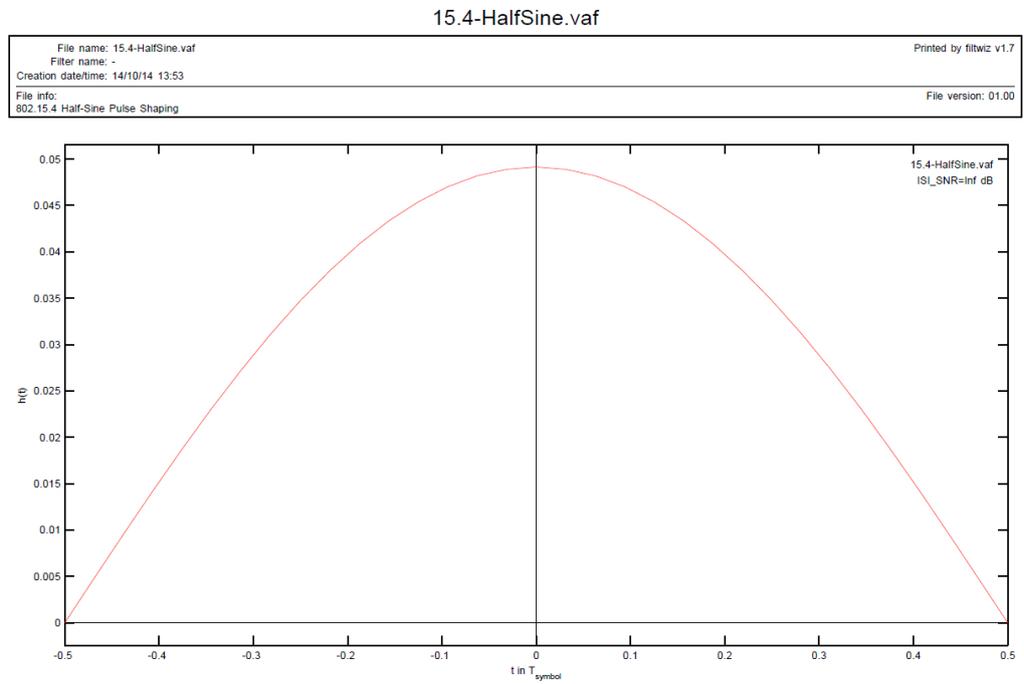


Figure 50: O-QPSK – Modulation Mapping File

## 7.2 Half-Sine – Pulse Shaping Filter File

The pulse shaping filter file '15.4-HalfSine.vaf', created with the R&S MATLAB application FiltWiz [11], is provided with this application note.



**Figure 51: O-QPSK – Half-Sine Pulse Shaping Filter File**

## 7.3 IEEE 802.15.4 Data Frame – Data/Control List File

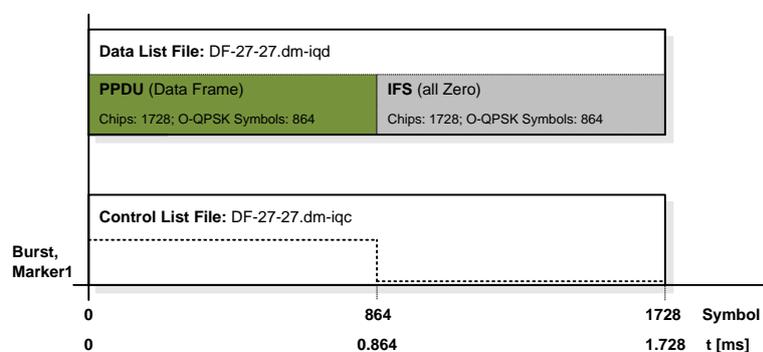
To illustrate the data and control list file usage a data- and a related control list file are provided with this application note. Both of them were created by using the *Frame Builder* spreadsheet.

The data list file 'DF-27-27.dm-iqd' contains the chip sequence of a PPDU (data frame) of 27 bytes in length and an additional IFS period of 27 bytes.



**Figure 52: Custom Digital Modulation – PPDU Data**

Therefore the data list contains  $27 \times 2 \times 32 = 1728$  data frame chips and 1728 IFS chips (all zero) which results in  $1728 / 2 = 864$  O-QPSK frame symbols and 864 O-QPSK IFS symbols.



**Figure 53: Custom Digital Modulation – Data/Control List Example**

The control list file 'DF-27-27.dm-iqc', defines 2 marker tags, 'Marker1' and the so-called 'Burst' marker.

'Marker1' may be output by the VSG to synchronize auxiliary test equipment (see chapter 3.1.1.5 for details). The 'Burst' marker is used to control the power ramping (see chapter 3.1.1.1 for details).

Both markers are high during the PPDU transmission phase and low during the IFS period.

## 8 Ordering Information

Please visit the Rohde & Schwarz product websites at [www.rohde-schwarz.com](http://www.rohde-schwarz.com) for ordering information on the following Rohde & Schwarz products:

- [R&S® SMW200A vector signal generator](#)
- [R&S® SMU200A vector signal generator](#)
- [R&S® SMATE200A vector signal generator](#)
- [R&S® SMJ100A vector signal generator](#)
- [R&S® SMBV100A vector signal generator](#)
- [R&S® SGT100A vector signal generator](#)

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## Regional contact

Europe, Africa, Middle East

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[customersupport@rohde-schwarz.com](mailto:customersupport@rohde-schwarz.com)

North America

1 888 TEST RSA (1 888 837 87 72)

[customer.support@rsa.rohde-schwarz.com](mailto:customer.support@rsa.rohde-schwarz.com)

Latin America

+1 410 910 79 88

[customersupport.la@rohde-schwarz.com](mailto:customersupport.la@rohde-schwarz.com)

Asia Pacific

+65 65 13 04 88

[customersupport.asia@rohde-schwarz.com](mailto:customersupport.asia@rohde-schwarz.com)

China

+86 800 810 82 28 | +86 400 650 58 96

[customersupport.china@rohde-schwarz.com](mailto:customersupport.china@rohde-schwarz.com)

## Sustainable product design

- Environmental compatibility and eco-footprint
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**Rohde & Schwarz GmbH & Co. KG**

Mühlendorfstraße 15 | D - 81671 München

Phone + 49 89 4129 - 0 | Fax + 49 89 4129 - 13777

[www.rohde-schwarz.com](http://www.rohde-schwarz.com)