

# EVM Measurements for ZigBee Signals in the 2.4 GHz Band

## Application Note

### Products:

- R&S®FSW
- R&S®FPS
- R&S®FSV
- R&S®FSQ

IEEE 802.15.4 (ZigBee) uses Offset QPSK with a half-sine pulse-shaping filter as modulation. This application note describes how to set up the Rohde & Schwarz signal analyzers together with the corresponding vector signal analysis (VSA) personality for modulation quality measurements, especially EVM, for ZigBee.

### Note:

Please find the most up-to-date document on our homepage.

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# 1 Overview

IEEE 802.15.4, also known as ZigBee, is a standard for low-data rate and low duty cycle applications. Typically, remote sensors with extremely long battery life (years) requirements implement ZigBee as communication standard. The standard defines different modulation types depending on the frequency band:

Band	Frequency (MHz)	Chip Rate (kchip / s)	Modulation	Pulse Shaping Filter
<b>868</b>	868.0 - 868.6	300	BPSK	RRC (Root Raised Cosine)
<b>915</b>	902.0 - 928.0	600	BPSK	RRC
<b>2450</b>	2400.0 - 2483.5	2000	OQPSK	Half-Sine

BPSK signals with RRC-filtering can be demodulated and measured with most standard vector signal analyzers, whereas Offset QPSK (OQPSK) in combination with half-sinusoidal pulse shaping filter is not available on older instruments.

This application note describes how to use the Rohde & Schwarz signal analyzers along with the corresponding Vector Signal Analysis (VSA) personality to demodulate ZigBee. It describes the measurement setup for best EVM (Error Vector Magnitude) performance.

## 2 A Brief Description of the 802.15.4 Air Interface for the 2.4 GHz Band

### Modulation type OQPSK

OQPSK (Offset Quadrature Phase Shift Keying) is 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 trajectories passing through the origin of the vector diagram, which introduces variations to the amplitude of the modulation envelope and requires linear amplifiers.

In OQPSK the transitions for I and Q are offset by half the symbol time. Since one OQPSK symbol consists of 2 bits, the time offset corresponds to the bit period. This bit period is referred to as chip period in ZigBee.

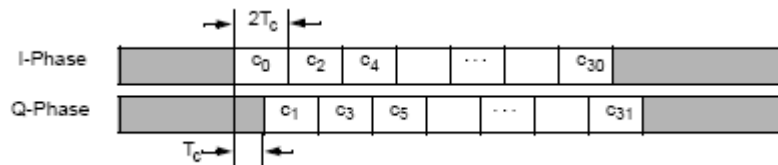


Fig. 2-1: Timing offset as defined in IEEE std 802.15.4

The chip rate is 2 MChips/s. Vector signal analyzers set the modulation rate usually in terms of symbol rate. For OQPSK this is half the bit rate (or chip rate for ZigBee). Therefore, the symbol rate has to be set to 1 MSymbols/s.

Since I and Q are decoupled, only one can change at a given time. This limits phase changes to a maximum of  $90^\circ$ . In QPSK, the maximum phase shift is  $180^\circ$  and corresponds to a zero crossing.

Avoiding the zero crossing reduces the envelope variations significantly and allows for a more efficient RF amplification.

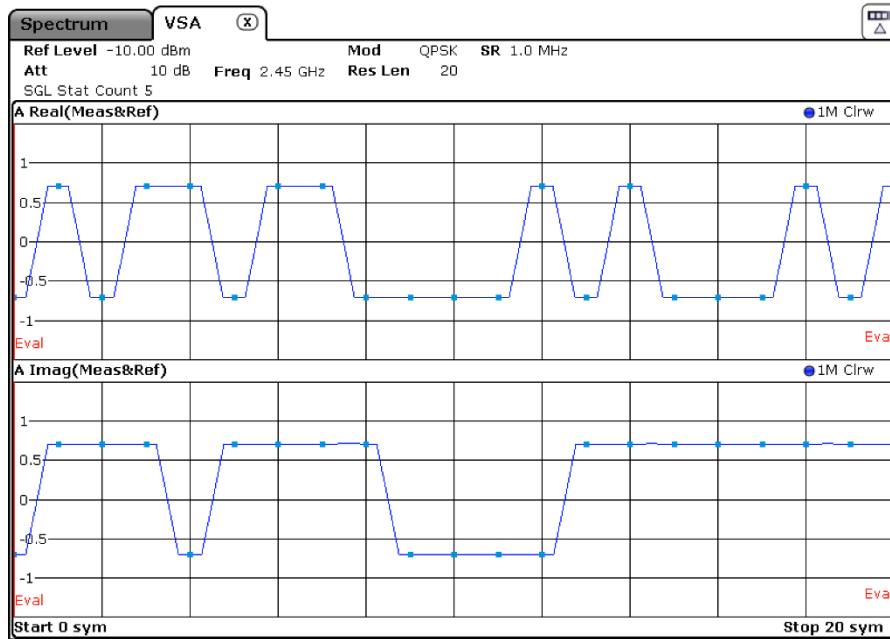


Fig. 2-2: For QPSK, I and Q transitions occur at the same time instance. A simultaneous change is equivalent to a 180° phase shift

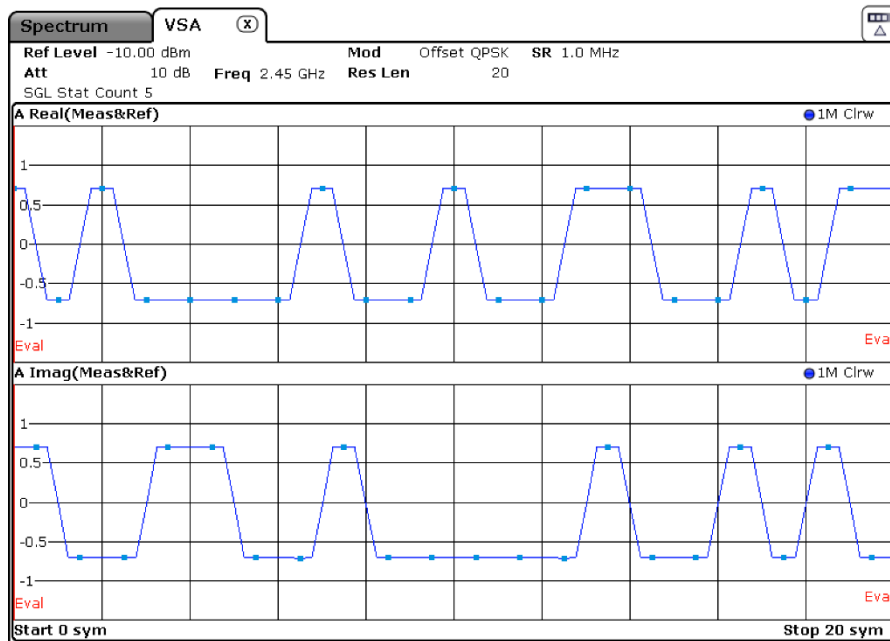


Fig. 2-3: For OQPSK I and Q transitions never occur at the same time instance. This limits the maximum phase change to 90° and reduces amplitude variations

### Half-Sine Pulse Shaping Filter

Instead of rectangular or RRC-filtered baseband pulses, ZigBee uses half-sinusoidal pulses, see equation below:

## A Brief Description of the 802.15.4 Air Interface for the 2.4 GHz Band

Setting up the R&S FSW, R&S FPS, or R&S FSV for ZigBee

$$p(t) = \begin{cases} \sin\left(\pi \frac{t}{2T_c}\right), & 0 \leq t \leq 2T_c \\ 0, & \text{otherwise} \end{cases}$$

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

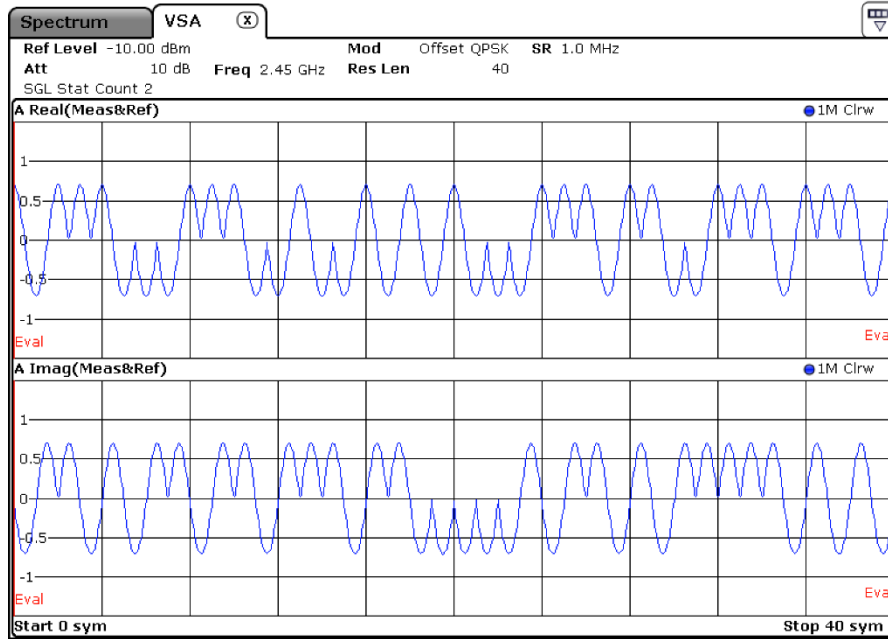


Fig. 2-4: I and Q display for OQPSK after pulse-shaping

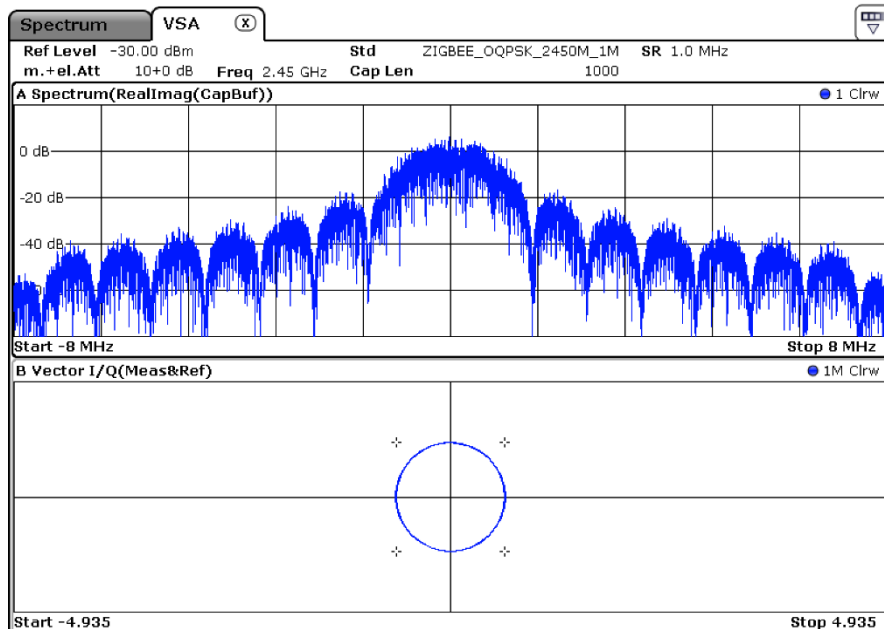


Fig. 2-5: The vector diagram of the half-sine filtered OQPSK shows a constant envelope

## 3 Preparing the Measurement using OQPSK Demodulation

### 3.1 Setting up the R&S FSW, R&S FPS, or R&S FSV for ZigBee

The R&S FSV-K70 (as well as the R&S FSW-K70 and R&S FPS-K70) come with a predefined standard for ZigBee. To load the predefined standard:

- Press HOME within the K70 application
- Select "Digital Standards"
- Change into the "ZIGBEE" subdirectory
- Choose the applicable ZigBee standard file, e.g. "ZIGBEE\_OQPSK\_2450\_1M.xml", for the 2450 MHz band ZigBee standard.

All settings are automatically loaded for the respective standard.

#### Burst Signals

The predefined ZigBee standards are configured for burst signals, which is the normal ZigBee signal shape.

For a correct EVM measurement, it is important to set the Evaluation Range to the number of symbols to be evaluated for the total EVM.

FSV-K70 (as well as FPS-K70 and FSW-K70) has three time parameters that can be set independently:

- Capture Length: Specifies the number of symbols to be captured and stored in the signal analyzer's I/Q memory. The number of I/Q samples results from symbol rate and oversampling ratio (Capture Oversampling) as

$$\text{NIQsamples} = \text{NSymbols} \times \text{Symbol Rate} \times \text{Capture Oversampling}$$

- Result Length: Specifies the number of symbols to be demodulated and displayed in the result screens that have a time axis, e.g. EVM vs. Symbols.
- Evaluation Range: Specifies the number of symbols to be evaluated for measurements that do not have a time axis, e.g. the Result Summary or I/Q Constellation. The Evaluation Range is indicated in all result screens with time axis by vertical red lines in the diagram marked with the letters "Eval", whereas all screens without time axis are marked with two red bars in the headline, in case the Evaluation range is smaller than the Result Range. Symbol numbering can be controlled using the Symbol Number at Reference value in the Result Range dialog.

To reduce the Evaluation Range:

- Press MEAS CONFIG
- Press Range Setting

## Preparing the Measurement using OQPSK Demodulation

Setting up the R&S FSW, R&S FPS, or R&S FSV for ZigBee

- Change to Evaluation Range tab
- Uncheck Entire Result Range
- Enter the range of symbols to be evaluated.

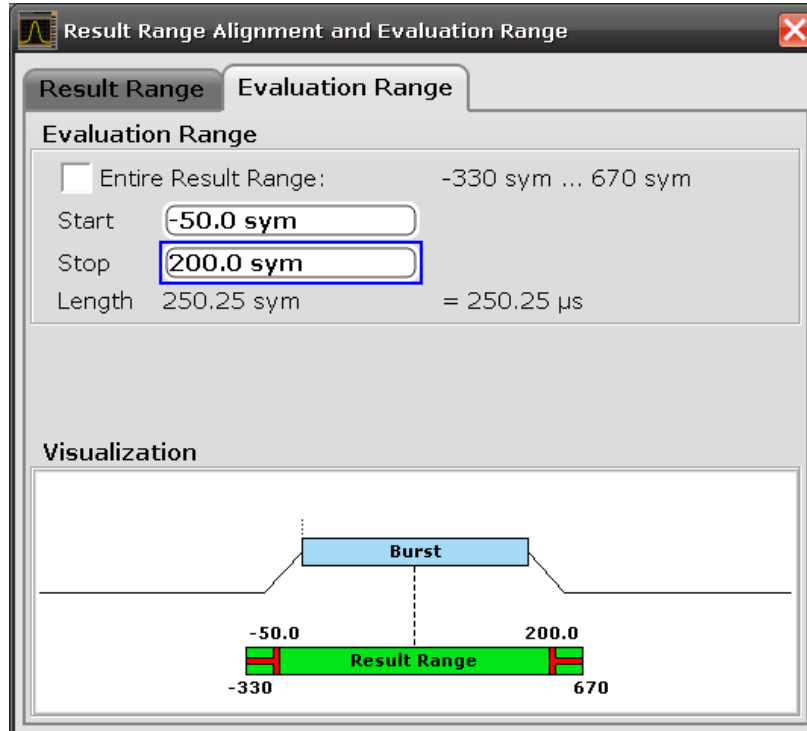


Fig. 3-1: Evaluation Range dialog

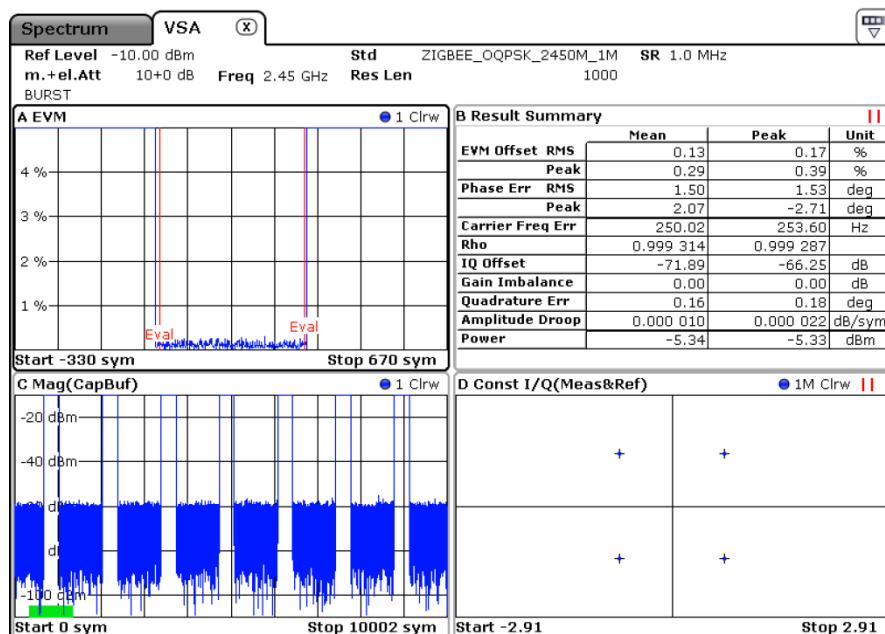


Fig. 3-2: FSV-K70 result screens: Evaluation Range indicated by vertical lines in the EVM plot and red double bars in the headlines of the Result Summary and the Constellation diagram



## Continuous Signals

In case a continuous signal is connected to the FSV, a warning “Burst Not Found” will be displayed in the Status Bar of the FSV. Nevertheless measurements can be performed. To avoid the warning, change the Signal Type to “Continuous”. The Signal Type can be modified pressing

- MEAS CONFIG
- Modulation/Signal Description
- Choose Signal Description tab
- Change Signal Type from Burst to Continuous

Alternatively, the Signal Type can be left as “Burst Signal”, but only the Burst Search can be switched off

- MEAS CONFIG
- Burst/Pattern Search
- Move the selection from On to Off, Auto mode will automatically be disabled

## 3.2 Setting up the R&S FSQ for ZigBee

Set modulation type, modulation rate and filtering:

- Press HOME VSA – MODULATION SETTINGS.
- Set symbol rate to 1 MHz.
- Select the filter set HALF\_SINE in the MODULATION FILTER dialog. If this filter set is not yet available on your instrument, create a user defined filter set as described in section 8 and select it as described here.
- Set the modulation to PSK – OQPSK in MODULATION & MAPPING.
- Set POINTS/SYMB to 8.

As mentioned above, ZigBee uses OQPSK modulation with half-sine pulse shaping filter. As shown in Fig 6 the signal uses a rather wide spectrum, which requires a wide demodulation bandwidth in the signal analyzer. In the R&S FSQ-K70 the demodulation bandwidth is defined by the oversampling ratio in the POINTS/SYMBOL parameter. Setting points/symbol to 8 will increase the sampling rate to 8 MHz, which yields a demodulation bandwidth of 6.4 MHz, as the I/Q capturing filters have typically a relative bandwidth of 0.8 times the sampling frequency.

If the signal is a continuous signal as in this example, the above settings are sufficient. Burst search parameters can be additionally defined in BURST&PATTERN settings, in case a burst signal is investigated. Further details can be found in the R&S FSQ-K70 operating manual.

## Creating a User-defined Standard for ZigBee

For convenience, the current settings can be stored as a user-defined standard so that they can be recalled immediately.

Press HOME VSA – DIGITAL STANDARDS – NEXT – SAVE AS STANDARD

In the table, two entries have to be made: a name for this setting, for example ZIGBEE\_CONT, and a name for the generic standard, for example ZigBee.

In that way different settings, which may differ for instance in the record length, result length or burst search parameters can be easily created for the same generic standard.

### Importing the Half-Sinusoidal Pulse Shaping Filter

This step is only necessary if you operate an R&S FSQ with a firmware prior to 4.65.

The Vector Signal Analyzer Option R&S FSQ-K70 has the possibility to import user-defined filters. An appropriate filter for ZigBee comes with this application note. In order to import the half-sine pulse shaping filter for ZigBee, copy the attached file “zigbee.vaf” onto a USB memory stick and insert it into the R&S FSQ. Alternatively, the 3.5” floppy drive may be used.

- Press HOME VSA
- Select the right supplementary menu by pressing the NEXT key
- Press IMPORT – FILTER
- A selection box appears, select ZigBee and press ENTER.

### Creating the Filter Set

Now the filters used as transmit, receive and measurement filter have to be defined in a filter set:

- Press PRESET VSA
- Press HOME VSA – MODULATION SETTINGS - NEXT – NEW USER SET
- Press ENTER – a selection box with available filters for the TX filter appears
- Select ZigBee and press ENTER, now the receive filter is highlighted
- In the same way, select filter type NONE as receive (RX) and as Meas filter
- Press SAVE USER SET, the new filter set is saved as USER(X). X is a number increased automatically with every new user filter set. So the first user filter set will be saved as USER1.

## 4 Selecting the Optimum I/Q Oversampling Factor

Depending on the S/N ratio of the signal under investigation, modifying the oversampling ratio may improve the EVM measurement. The oversampling ratio describes the ratio between the sampling rate of the analog digital converter (ADC) and the symbol rate, set in the demodulator. In the R&S FSV-K70 (as well as FPS-K70 and FSW-K70), the ZigBee standard sets the oversampling ratio to a value of 16, indicating a sampling rate 16 times the symbol rate. For the 2450 MHz band, this corresponds to a sampling rate of 16 MHz.

In the R&S FSQ-K70 and the R&S FSV-K70 the I/Q data used for measuring EVM can be lowpass filtered by

- the filters used for capturing I/Q data
- the so-called "measurement filter" (MEAS filter).

ZigBee does not use a measurement filter. So only the filters used for capturing I/Q data limit the signal bandwidth.

The general formula for the total resulting I/Q data bandwidth IQBW is:

$$\begin{aligned} \text{IQBW} &= 0.8 * \text{Sampling Rate} \\ &= 0.8 * \text{Oversampling ratio} * \text{Symbol Rate}. \end{aligned}$$

Increasing the sampling rate yields a wider bandwidth taken into account for demodulation. For signals that occupy a large bandwidth compared to the symbol rate, an increased bandwidth means increased signal power and therefore an increased S/N ratio. This context holds true only as long as the signal power increases faster than the noise power as an increase in bandwidth always increases the noise power.

The spectrum of a ZigBee signal has theoretically an infinite wide bandwidth. In the real world, each transmitter applies some kind of band limitation and so does any signal analyzer. Factors that limit the increase of signal power with increasing I/Q bandwidth are:

- Band limitation of the transmitter:

If the TX bandwidth of the transmitter is significantly lower than 16 MHz, the I/Q bandwidth of the analyzer should be reduced to at least the transmitter bandwidth.

- Weak signals:

A strong signal, as displayed e.g. in Figure 5, should be captured with an oversampling ratio of 16, whereas a weak and noisy signal, as in Figure 8, may deliver better EVM results, when captured with an oversampling ratio of only 8 or lower, as noise is covering the outer parts of the signal spectrum.

To determine the ideal oversampling ratio, decrease the ratio stepwise from the maximum 16 until the optimum value has been found. The minimum value for the R&S FSQ is 1, where it is 4 for the R&S FSV.

To change the oversampling ratio on the R&S FSV

- MEAS CONFIG
- I/Q Capture
- Set the Capture Oversampling to the desired ratio.

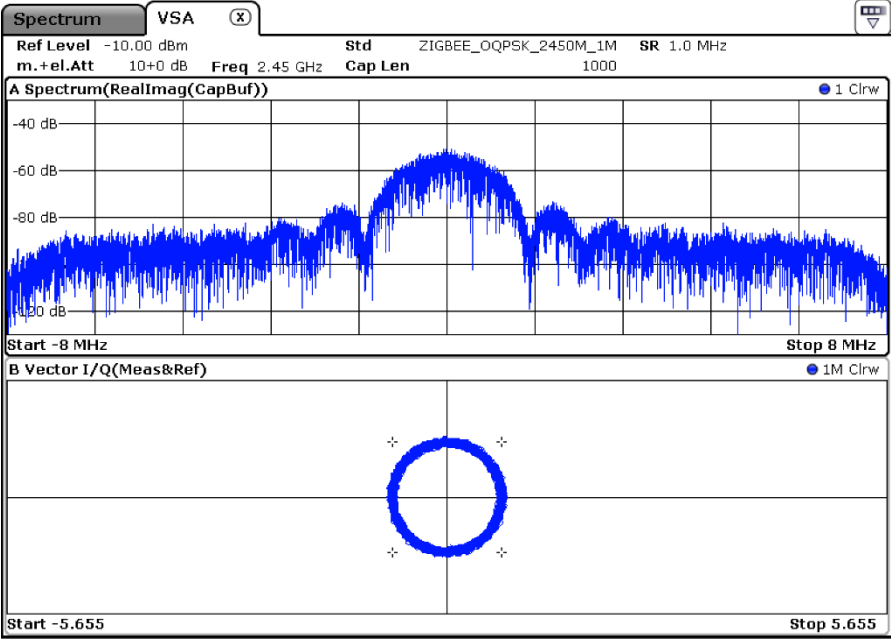


Fig. 4-1: Weak ZigBee signal resulting in low S/N

# 5 EVM Measurement Results

Using a signal generated with the signal generator R&S SMU an EVM of approx. 0.2% has been measured using R&S FSV and R&S FSQ. This EVM is the residual EVM with contributions from both the signal generator and the signal analyzer.

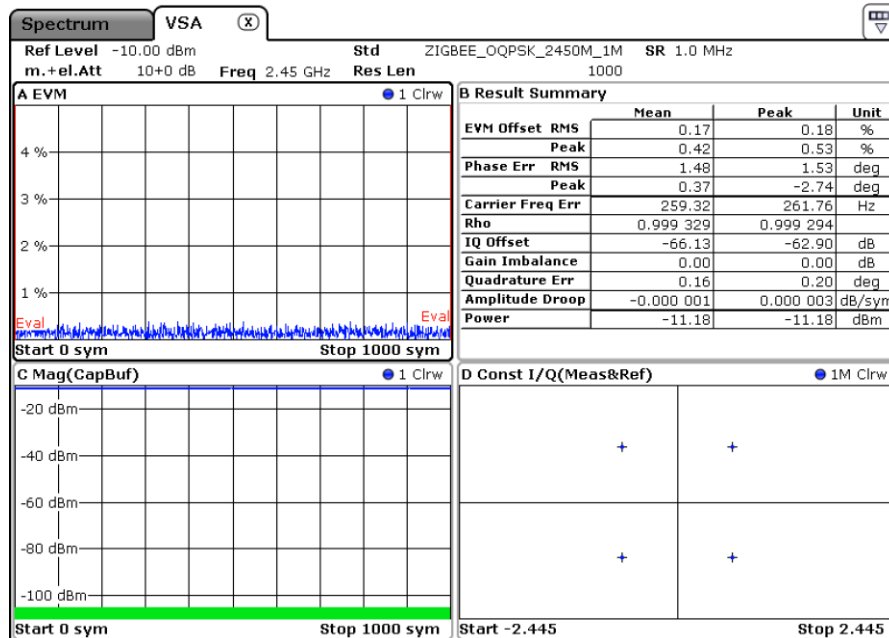
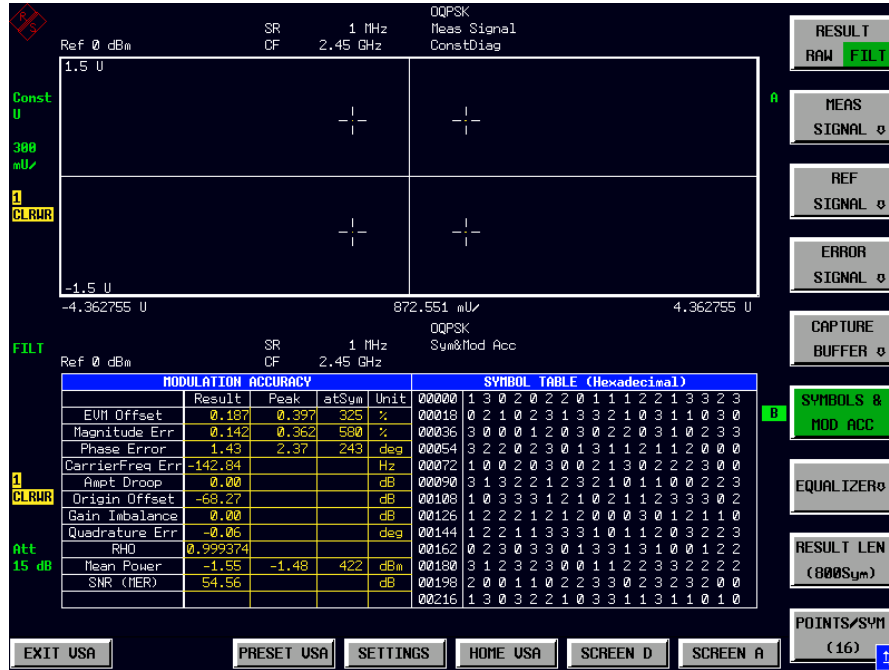


Fig. 5-1: The EVM measurements with the R&S FSQ or R&S FSV shows a residual EVM of approx. 0.2%. This is a prerequisite for accurate EVM measurements

## Parameters for EVM calculation

Three parameters influence the EVM calculation for OQPSK modulation.

At first it is the number of points per symbol that are taken into account for the calculation.

For the R&S FSV, the EVM values can be displayed for each symbol and if desired also for each sampling point, i.e. each I/Q pair. The parameter indicating the number of EVM values to display is called Display Points/Sym. It can be modified in the Display Config tab corresponding to the screen that currently shows the EVM trace. For the example shown in Figure 9, it can be set as follows:

- MEAS
- Display Config
- Select Screen A tab
- Uncheck Display Points/Sym Auto
- Set the parameter to the desired value.

The number of samples taken into account for the result summary calculation and therefore the overall EVM value can also be modified in the same way: Press

- MEAS
- Display Config
- Select respective screen, for the mentioned example Screen B tab
- Uncheck Display Points/Sym Auto

Set the parameter to the desired value.

Second, it is the EVM normalization factor. It is automatically set to normalization to mean reference power, if the R&S FSV-K70 ZigBee standard is loaded. This setting is suitable for ZigBee measurements, but it may be changed on the R&S FSV by pressing

- MEAS CONFIG
- Demod/Meas Filter
- Change Normalize EVM to in the Advanced field.

Finally, it makes a difference for the EVM calculation, whether the offset between the I and Q symbol values is compensated for or not. For explanation on the offset between I and Q see section 2. In case the offset is taken into account, the EVM is also called Offset EVM. This is the default setting for OQPSK demodulation on the R&S FSQ as well as on the R&S FSV. If necessary the EVM can be calculated as "no offset" EVM, meaning the I and Q values are taken at exactly the same point in time. This means that the offset between I and Q referenced to the RF signal is not compensated for.

To change the EVM calculation to non offset on the R&S FSV press

- MEAS CONFIG
- Demod/Meas Filter
- Select Demodulation tab

- Change the Offset EVM parameter from On to Off.

To switch of the parameter on the R&S FSQ press

- MEAS
- NEXT
- Switch OFFSET EVM from ON to OFF.

## 6 Signal Generation

The ZigBee test signal used has a symbol rate of 1MSymbols/s. It has been generated by an R&S SMU with the following settings:

Select Custom Digital Modulation in the baseband dialog of the SMU diagram.

- Symbol rate: 2 MSymbols/s
- Modulation type: MSK
- Filter: Rectangular
- State: On.

MSK has two modulation states and 1 bit per symbol. OQPSK has 4 modulation states and 2 bits per symbol. For MSK, bit rate and symbol rate are equal. For OQPSK they differ by a factor of 2. So, for the same bit rate, the symbol rate in MSK has to be set twice as high as the ZigBee (OQPSK) symbol rate.

Alternatively, the R&S SMU can be set up for standard conform OQPSK modulation as described by the application note 1GP105 [3].

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.



## 7 References

1. IEEE Standard 802.15.4 – 2003.
2. Rappaport, Theodore: Wireless communications, Prentice Hall.
3. Neuhäusler, Chlodwig, Generation of IEEE 802.15.4 Signals, Rohde & Schwarz Application Note (1GP105).

## 8 Ordering Information

Designation	Type	Order No.
Signal- and Spectrum Analyzer	R&S®FSW8	1312.8000.08
Vector Signal Analysis Personality	R&S®FSW-K70	1313.1416.02
Signal- and Spectrum Analyzer	R&S®FPS4	1319.2008.04
Vector Signal Analysis Personality	R&S®FPS-K70	1321.4127.02
Signal- and Spectrum Analyzer	R&S®FSV4	1321.3008.04
Vector Signal Analysis Personality	R&S®FSV-K70	1310.8455.02

## About Rohde & Schwarz

The Rohde & Schwarz electronics group is a leading supplier of solutions in the fields of test and measurement, broadcasting, secure communications, and radiomonitoring and radiolocation. Founded more than 80 years ago, this independent global company has an extensive sales network and is present in more than 70 countries. The company is headquartered in Munich, Germany.

## Regional contact

Europe, Africa, Middle East  
+49 89 4129 12345  
[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
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership



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