



Products: R&S® SMU200A Vector Signal Generator, R&S® WiniQSim Simulation Software, R&S® FSQ Vector Signal Analyzer and option R&S® FSQ-K70

Generation and Analysis of ZigBee™ IEEE802.15.4 signals in the 2.4 GHz band

Application Note

IEEE 802.15.4 (ZigBee™) uses OQPSK with a half-sine pulse shaping filter as modulation. This application note describes how to generate and analyze ZigBee™ signals. Simple test signals can be setup with the free-of-charge simulation software R&S WiniQSIM™ and transferred to the vector signal generator R&S SMU200A. It describes how to setup the vector signal analyzer R&S FSQ with option R&S FSQ-K70 for ZigBee™ signal demodulation and how to analyze modulation quality such as error vector magnitude (EVM).



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1 Introduction

The ZigBee™ standard aims to provide flexibility and mobility by building wireless intelligence and capabilities into every day devices. The ZigBee™ technology will enable remote monitoring and control applications for low-power and at low cost applications while maintaining simplicity and reliability. The nature of the application calls for low-data rate and low duty cycle technology.

The standard defines different modulation types depending on the frequency band:

Band	Frequency (MHz)	Chip Rate (kchip/s)	Modulation Type	Pulse shaping filter
868/915	868 - 868.6	300	BPSK	RRC (root raised cosine)
	902 – 928	600	BPSK	RRC
2450	2400 – 2483.5	2000	OQPSK	Half-Sine

Table 1: IEEE 802.15.4 Frequency Bands and Modulation Types

BPSK with RRC-filtering can be generated with most standard vector signal generators and demodulated and measured with most standard vector signal analyzers. But OQPSK with half-sine pulse shaping is often not available because of the special transmit filter. This application note describes how this task can be accomplished with the Signal Generator R&S SMU200A and Signal Analyzer R&S FSQ with Vector Signal Analyzer option R&S FSQ-K70. It describes how to setup a ZigBee™ transmit frame in the generator, how to import the correct ZigBee™ filter and how to set up the analyzer for best EVM (Error Vector Magnitude) performance.

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

This chapter gives a short overview on modulation type, pulse shaping and frame format of the Air interface for the 2,4 GHz band.

2.1 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 amplitude modulation 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™.

Modulation type OQPSK

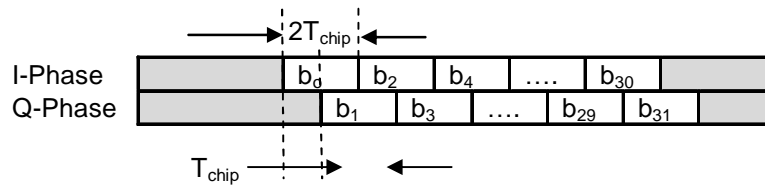


Fig. 1: Timing offset as defined in IEEE std 802.15.4

The chip rate is 2 MChip/s. Vector signal analyzers set the modulation rate usually in terms of symbol rate. For OQPSK this is half the bit rate (or chiprate for ZigBee™) since one OQPSK symbol consists of two chips. So the symbol rate has to be set to 1 MSymbol/s. Since I and Q are decoupled, only one can change at a given time. This limits phase changes to a maximum of 90°. With QPSK the maximum would be 180°, causing a zero crossing. The lack of zero crossings in OQPSK reduces the envelope variations significantly and allows more efficient RF amplification.

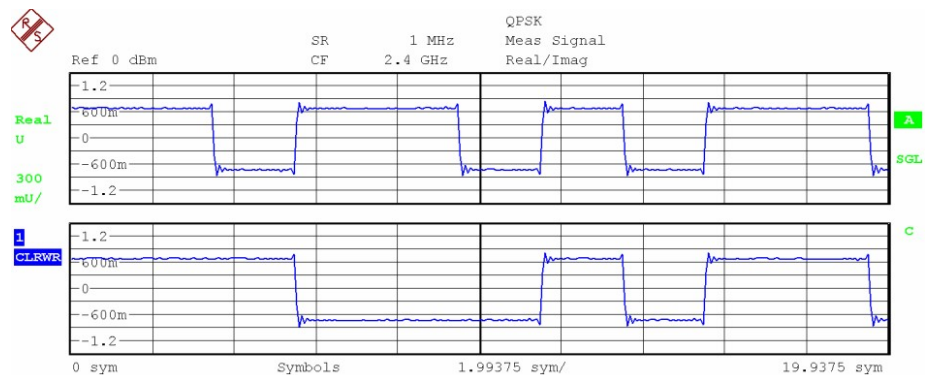


Fig.2a: For QPSK, I and Q transitions occur at the same time instance. A simultaneous change is equivalent to a 180° phase shift.

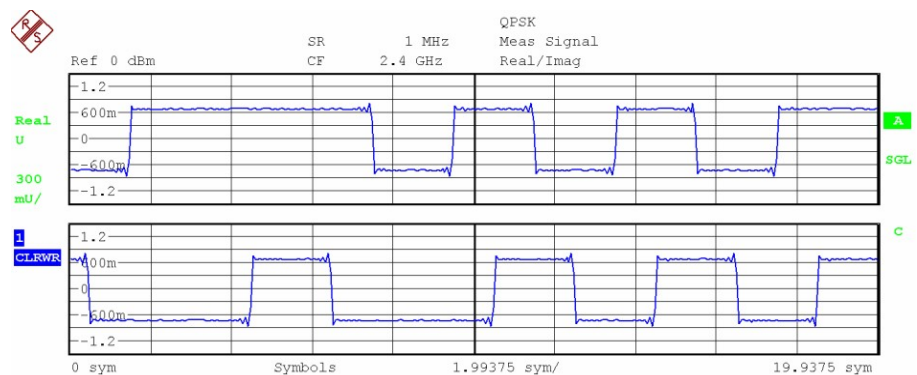


Fig. 2b: For OQPSK I and Q transitions never occur at the same time instance. This limits the maximum phase change to 90° and reduces amplitude variations.

Half-Sine Pulse Shaping Filter

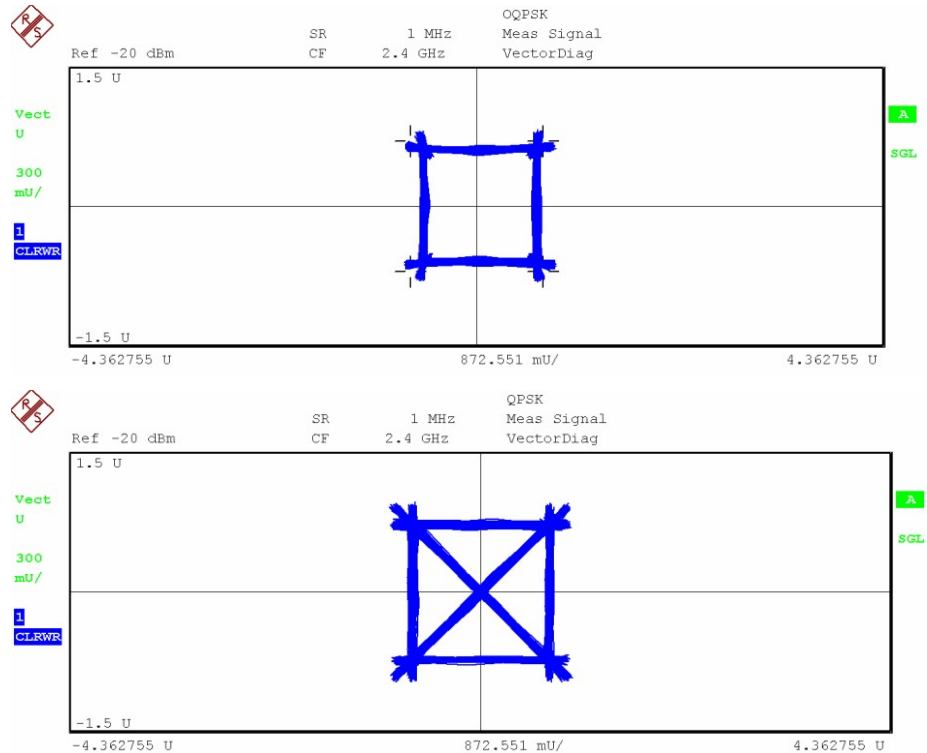


Fig. 3: The vector diagram for unfiltered OQPSK (above) shows no transitions through the origin of the vector diagram in contrast to the QPSK (below).

2.2 Half-Sine Pulse Shaping Filter

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

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

Fig.4: Definition of half-sine pulse shape

The half-sine pulse shaping filter changes the vector diagram of the OQPSK from a square to a circle. So it eliminates any amplitude variations and turns the OQPSK into a constant envelope modulation. The OQPSK now resembles a MSK. Actually some text books consider MSK as a special version of OQPSK.

Frame Format

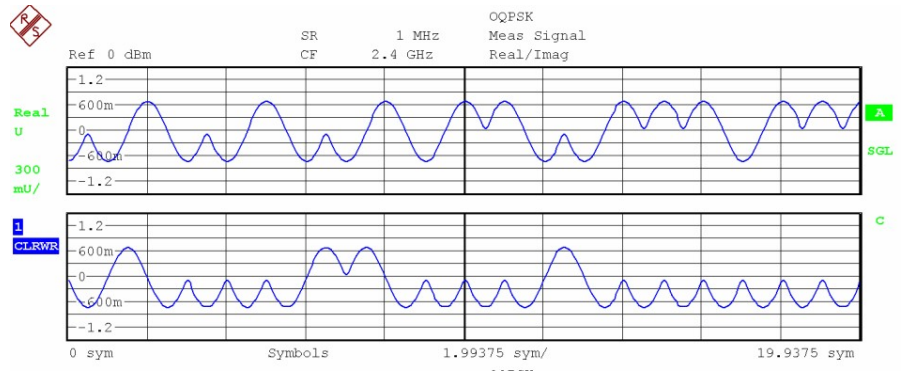


Fig. 5: I and Q display for OQPSK after sine pulse shaping

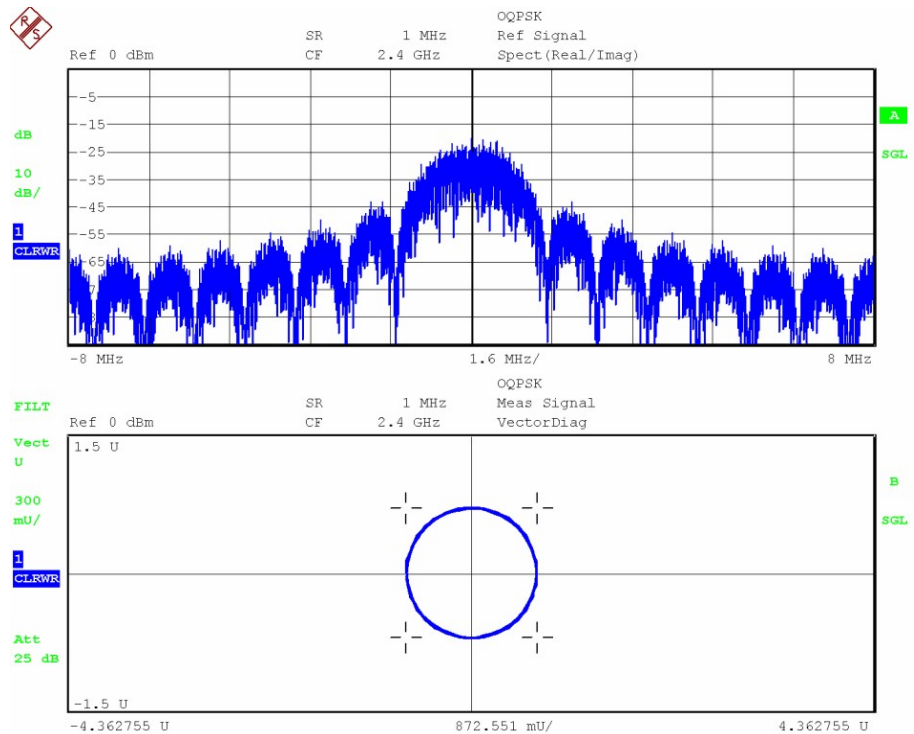


Fig 6: The vector diagram of the half-sine filtered OQPSK shows a constant envelope, just like MSK. The spectrum MSK reveals the sidelobes of an unfiltered MSK

2.3 Frame Format

Zigbee™ uses a framed transmission method, i.e. bursts of data in a defined format are sent intermittently. There are several types of frames defined: Beacon Frame, Acknowledge Frame, Data Frame etc. Frames can have different lengths. The length information is contained in the first bits of the frame. The general structure of a frame can be seen in the following table:

4 Octets	1 Octet	1 Octet		Variable
Preamble	Start Frame Delimiter SFD	Frame length (7 bits)	Reserved (1 bit)	Data Unit PSDU

Table 2: Structure of IEEE 802.15.4 Frame

All data is grouped in octets (=8 databits). Zigbee™ uses data spreading with a spreading factor of 8. This means that the chiprate of the modulated data (2Mbps) is 8 times higher than the net datarate (250kbps). In order to get the correct spreading sequence, each octet is divided in two 4-bit groups. Any possible 4-bit group has a unique 32-bit spreading sequence as defined in the IEEE 802.15.4 standard §6.5.2.3.

3 WinIQSim Setup

3.1 Setup WinIQSim for Single Carrier Operation

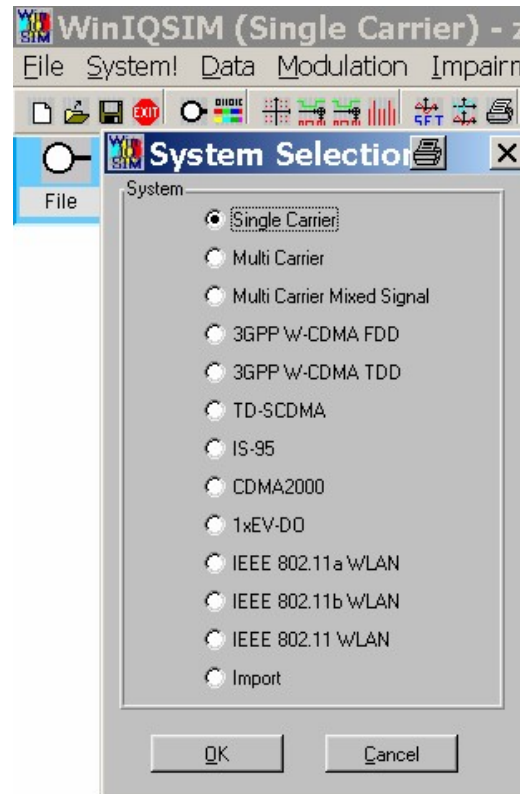


Fig. 7: Setup WinIQSim for Single Carrier Operation

3.2 Settings in the Modulation Panel

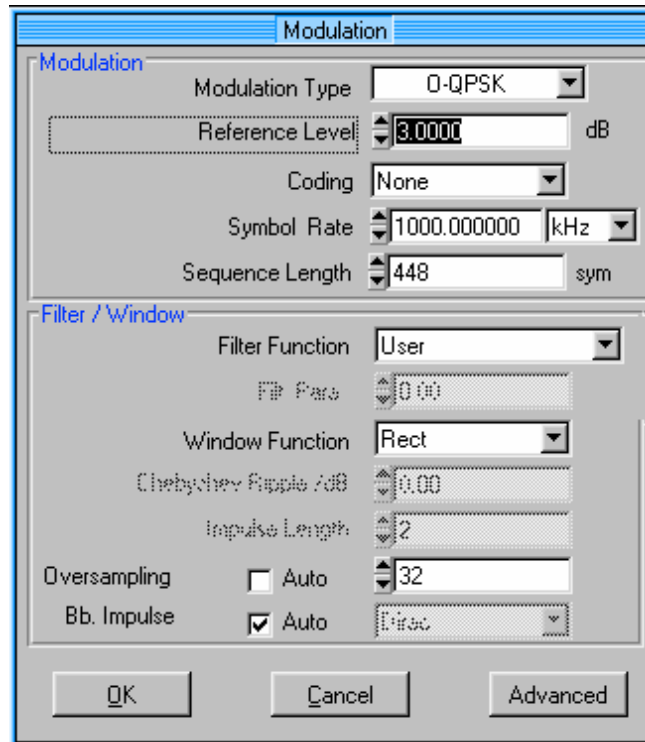


Fig. 8: Settings in the Modulation Panel

- Modulation Type =O-QPSK
- Symbol Rate = 1000 kHz (this corresponds to a chiprate of 2000 kchip/s because each QPSK symbol contains 2 chips)
- Sequence length is variable. If the data editor is used (see next chapter), then the sequence length is set automatically
- Filter function = User. Here a user-defined half-sine-shaped filter has to be uploaded. Select the provided file "zigbee.ifl" which contains a half-sine filter with oversampling=32.

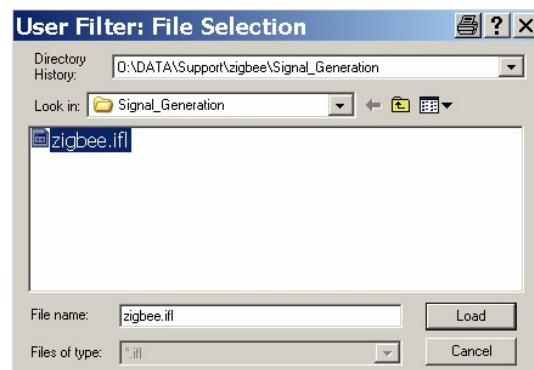


Fig. 9: User Filter

3.3 Settings in the Data Panel

There is the possibility to send unframed data (e.g. for amplifier tests) or framed data (for receiver tests). The following chapters line out the respective settings.

3.3.1 Unframed Transmission

Open the Data Panel and select for example a PRBS (=pseudorandom binary sequence).

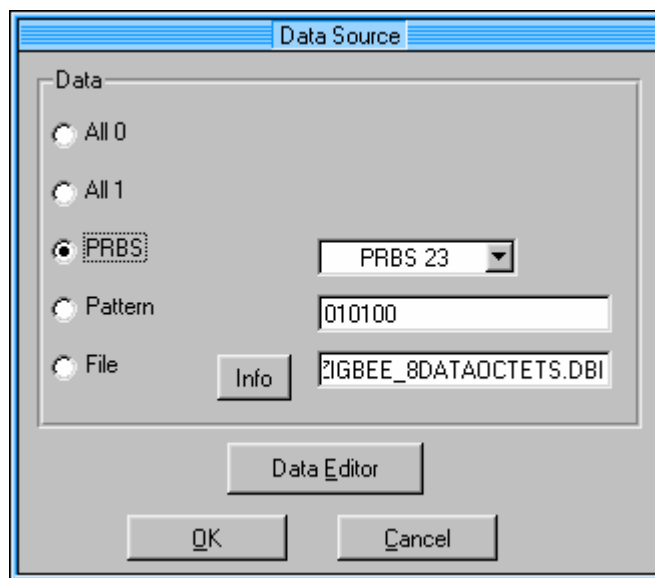


Fig. 10: Data Source

This causes a continuous random data input to the modulator. The modulator output will be continuously modulated without any frames or power ramping. This can be used e.g. for spectrum measurements where framed signals are hard to trigger.

The baseband output looks like this. Please note the correct half-sine pulse shaping.

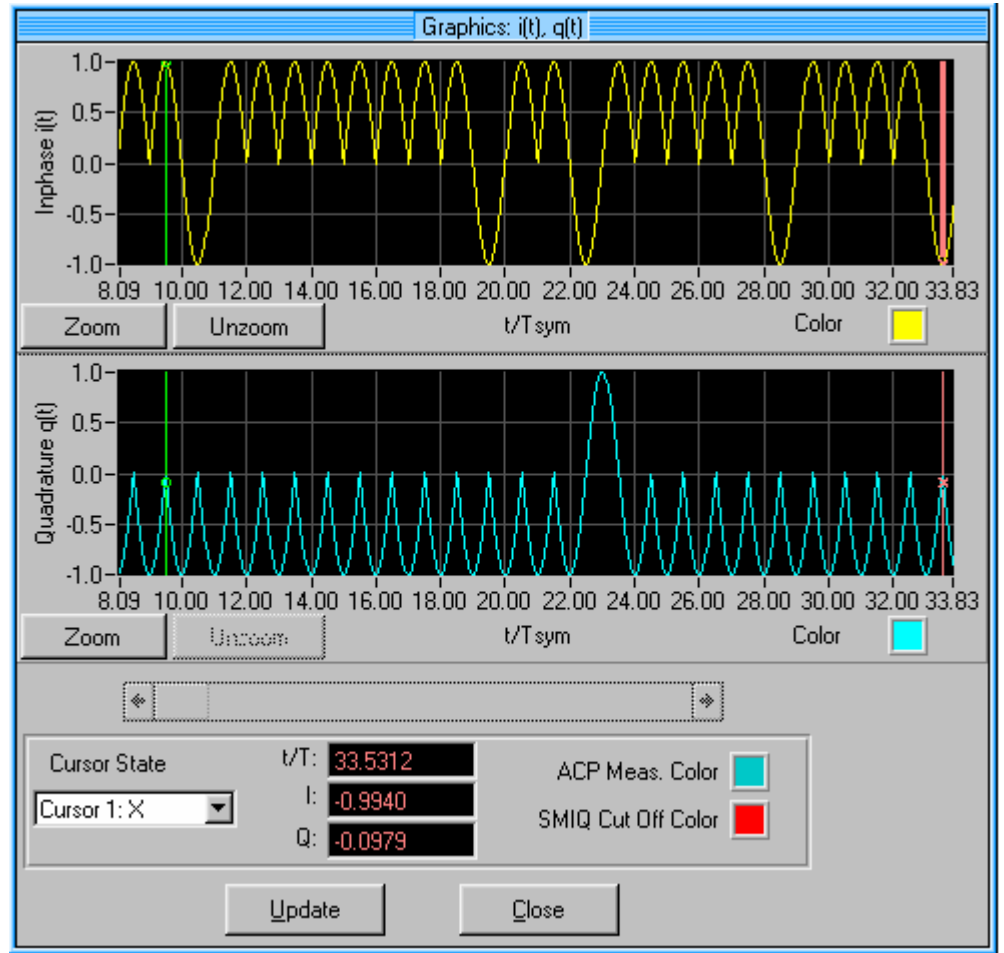


Fig. 11: Baseband output

3.3.2 Framed Transmission

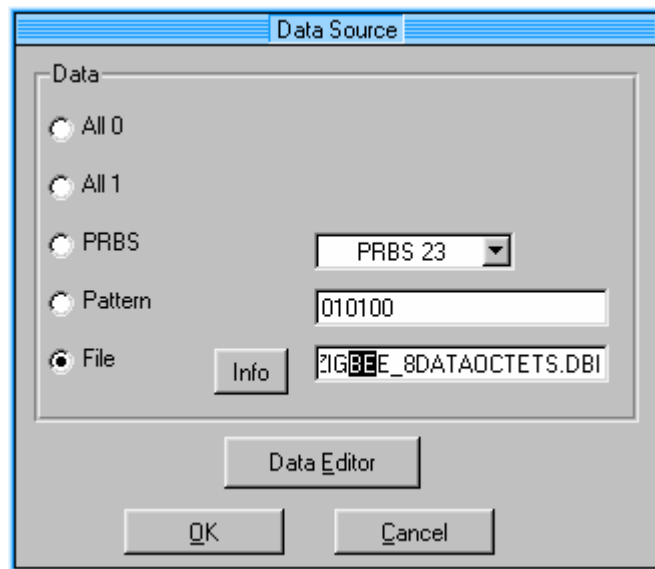


Fig. 12: Data Source

Settings in the Data Panel

For framed operation, a datafile which contains the correct bit settings including the preamble information etc. has to be uploaded. Check "File" and select a predefined datafile (*.dbi file). Datafiles can be created with WinIQSim using the Data Editor in the Data Panel. For a description please see next chapter.

In order to have transmission only during the time when the data inside the datafile contains a valid frame, the power ramping has to be specified.

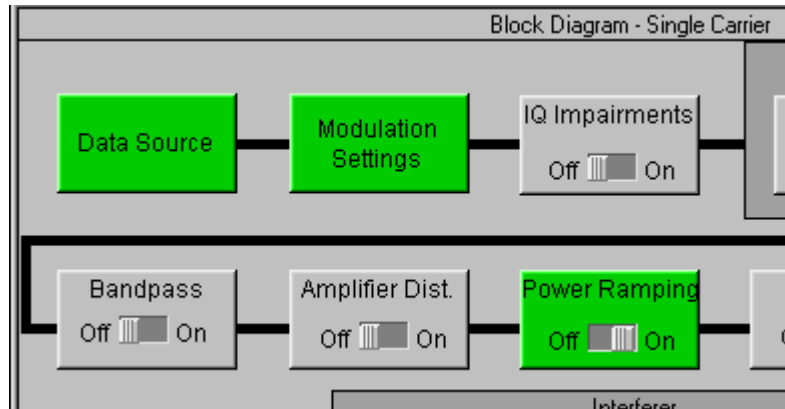


Fig. 13: Block Diagram

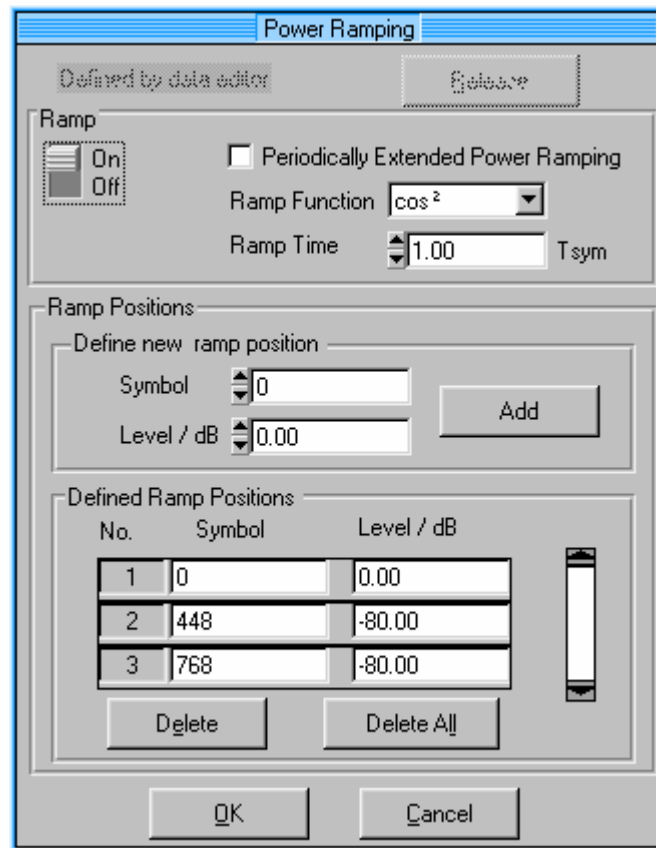


Fig. 14: Power Ramping

Settings in the Data Panel

In this example, the datafile contains a valid frame within the first 896 chips (=448 QPSK Symbols). The remaining contents of the datafile between symbol 448 and 768 (=between chips 896 and 1536) are unimportant, the output shall not be modulated during this time. For this reason, a high attenuation (in the example -80dB) is used. In this case, the baseband signal looks as follows. Please note the attenuated signal after symbol 448.

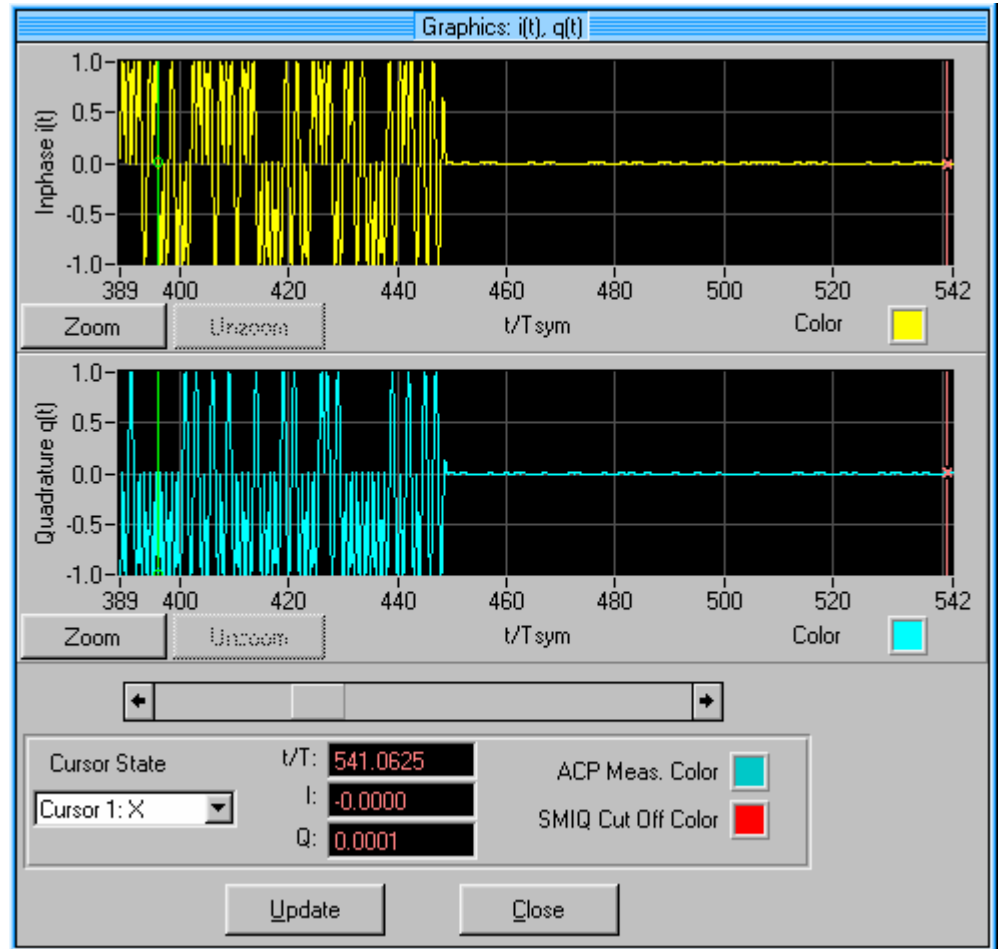


Fig. 15: Baseband signal

4 Zigbee Frame Structure with WinIQSim

Load the included .iqs files for ZigBee in WinIQSIM

The frame structure of Zigbee can be implemented into WinIQSim and simple test frames can be generated. A frame structure can be saved into a datafile with the ending "*.dbi". This file can then be uploaded into the data pane to be used for transmission.

To setup the frame structure, enter the Data Panel and select "Data Editor".

Settings in the Data Panel

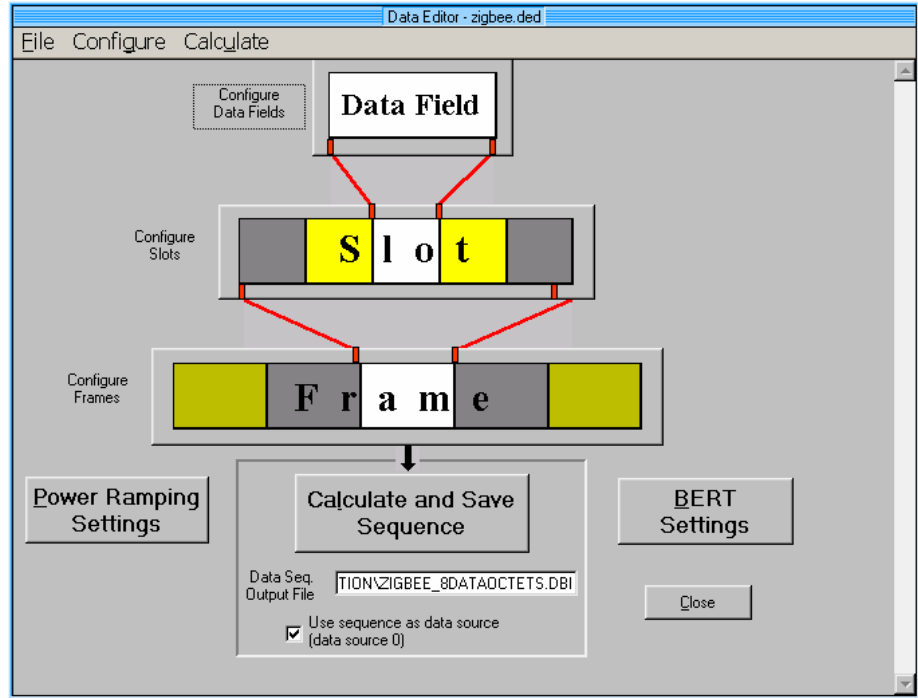


Fig. 16: Data Editor

Data fields contain a sequence of data which can be used in higher levels of the frame structure. For Zigbee, it is suitable to define the 16 Data symbols of length=32chips each.

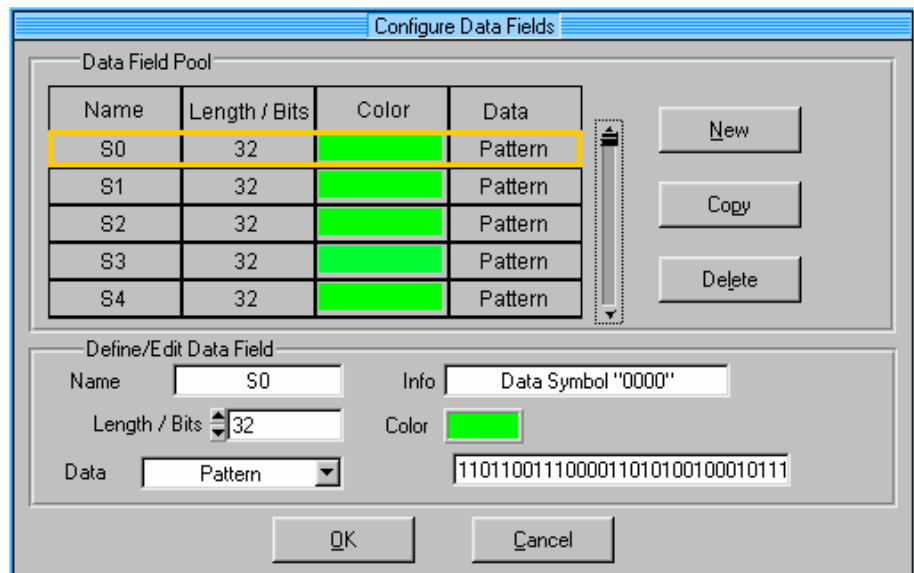


Fig. 17: Configure Data

In the above dialog, you can see for example the definition of data field "S0", which corresponds to the Data Symbol "0000" (see IEEE specification, §6.5.2.3., Table 20). The chip values can be seen in the lower right corner.

Settings in the Data Panel

In the next steps, the predefined datafields can be used to create so-called slots:

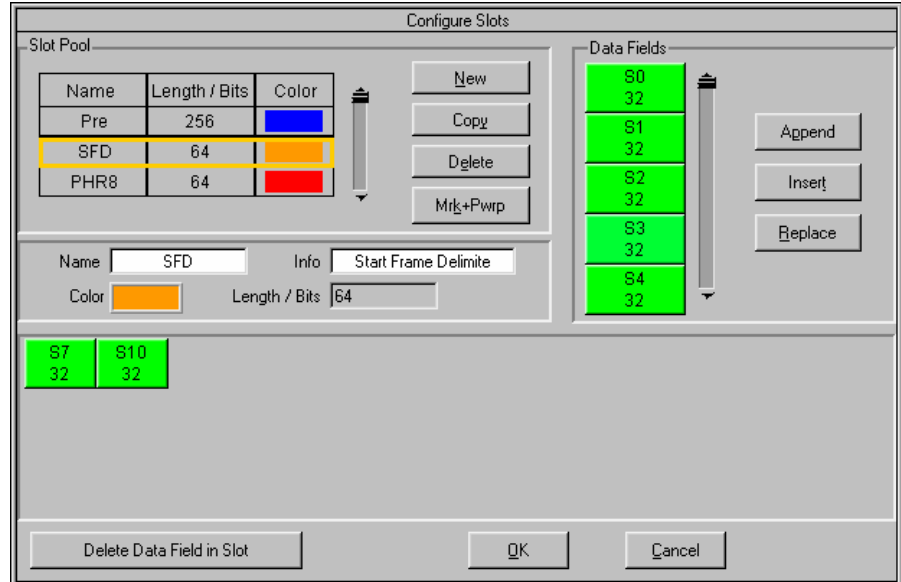


Fig. 18: Configure Slots

A slot is a concatenation of several datafields. In the above example, you can see a slot for the Preamble (4 octets of "0"), a slot for the Start Frame Delimiter (SFD) and a slot for the frame length. In case of the SFD, the contents of the slot are composed of Data Fields S7 ("1110") and S10 ("0101"). This yields the defined contents of the SFD=11100101.

In the last step, the predefined slots are concatenated to form the frame:

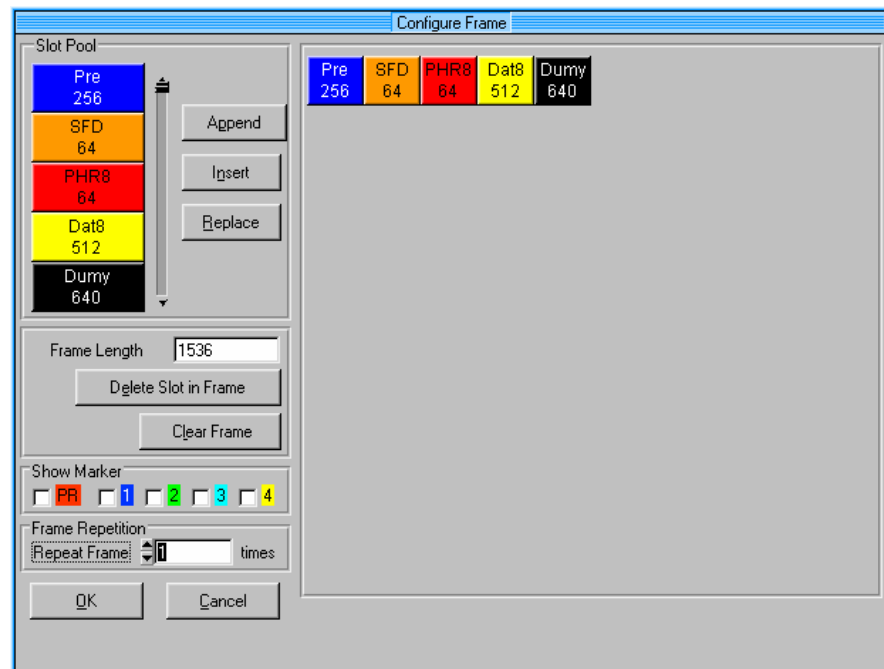


Fig. 19: Configure Frame

Settings in the Data Panel

In this example, the Frame consists of a Preamble (256 chips = 4 octets), an SFD (64 chips = 1 octet), an frame length field (1 octet) which contains the information that 8 octets of data will follow. The next slot (labelled "Dat8") contains 8 octets of random data ($8 \times 2 \times 32 = 512$ chips). Finally, there is a dummy slot of 640 chips. During the dummy period, the signal shall be attenuated to Zero using the power ramp function. By doing so, a burst frame is sent. If you do not insert the Dummy period, the same burst will be sent continuously.

When the frame is setup, you can save your settings to a data editor definition file (ending *.ded)

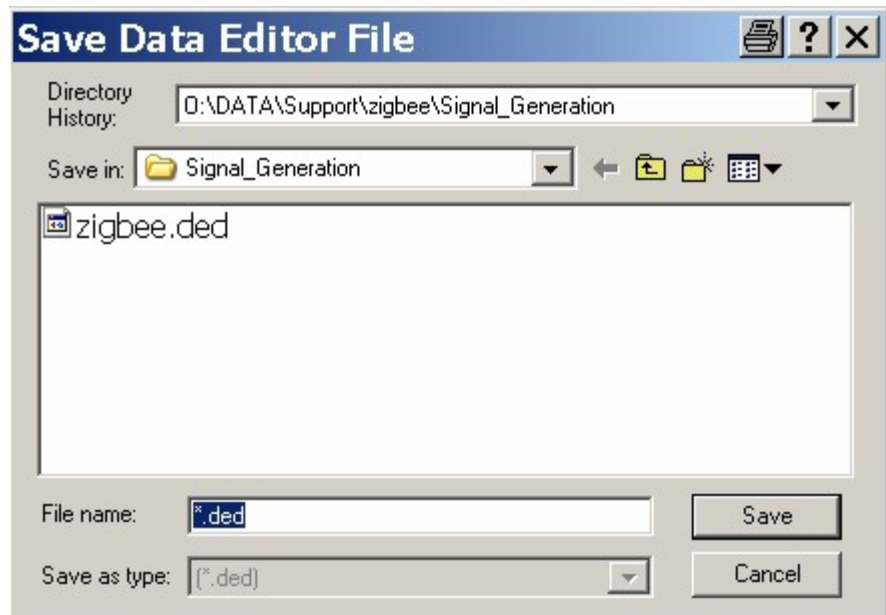


Fig. 20: Save Data Editor File

As a next step, the frame has to be calculated. Enter the name of the wanted datafile (*.dbi) in the field and press "calculate and save sequence"

**Calculate and Save
Sequence**

5 Set-up of FSQ

Preparing the measurement

The Vector Signal Analyzer Option FSQ-K70 comes with a variety of predefined filters such as root-raised cosine filters or Gauss filters. For special filter characteristics such as the ZigBee™ filter, the FSQ has the possibility to import user-defined filters. For example MatLab™ from MathWorks can be used to design the filters. These can be converted into the FSQ-K70 format by the tool FILTWIZ. This tool is free and can be downloaded from the R&S website [3] as an add-on for MatLab™. An appropriate filter (zigbee.vaf) for ZigBee™ comes with this application note [2].

5.1 Importing the Half-Sinusoidal Pulse Shaping Filter

The Vector Signal Analyzer Option FSQ-K70 has the possibility to import user-defined filters. For example MatLab can be used to design the filters, and these can be converted into the FSQ-K70 format by the tool FILTWIZ. This tool can be downloaded from the R&S website and is an add-on for MatLab. 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 3.5" floppy disk and insert it into the floppy drive of the FSQ.

- 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

5.2 Creating a User-defined 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
- Select in the same way the filter type NONE as receive 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.

5.3 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 filterset USER(X) in MODULATION FILTER
- Set the modulation to PSK – OQPSK in MODULATION & MAPPING
- Set POINTS/SYMB to 16

As mentioned above, OQPSK with half-sine pulse shaping filter is equivalent in the spectrum and vector diagram to an unfiltered MSK. Unfiltered MSK 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 with the oversampling ratio in the POINTS/SYMBOL parameter. Setting points/symbol to 16 will increase the sampling rate to 16 MHz, which gives a demodulation bandwidth of 8 MHz.

5.4 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 done: 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.

6 Measurement

6.1 Measurement of continuous signals

Using a signal generated with the signal generator R&S SMU200A an EVM of app. 0.3% (-30 dB) has been measured. This EVM is the residual EVM with contributions from both the signal generator and the signal analyzer.

FILT		SR	1 MHz	OQPSK		
Ref -20 dBm		CF	2.4 GHz	Sym&Mod Acc		EXT
		MODULATION ACCURACY			SYMBOL TABLE (Hexadecimal)	
		Result	Peak	atSym	Unit	00000 2 0 3 0 3 0 3 0 1 3 3 3 1 0 2 0 2 2
		EVM	0.261	0.708	54 %	00018 1 1 3 2 3 0 1 1 3 2 1 2 3 3 3 1 3 1
		Magnitude Err	0.173	0.702	54 %	00036 3 1 1 2 3 3 2 0 3 3 3 1 0 2 3 2 3 0
		Phase Error	0.16	-0.48	149 deg	00054 2 0 2 3 0 2 1 3 3 2 2 1 2 3 2 3 0 2
		CarrierFreq Err	234.31m		Hz	00072 2 1 2 2 2 2 3 3 2 0 2 2 3 2 2 3 3 2
1		Ampt Droop	0.00		dB	00090 3 1 3 0 2 2 0 3 2 0 2 3 2 2 0 3 3 3
CLRWR		Origin Offset	-71.61		dB	00108 3 1 2 1 2 3 3 2 0 0 2 1 3 2 2 3 2 3
		Gain Imbalance	-0.01		dB	00126 3 3 3 0 3 2 0 2 3 0 3 0 3 0 0 3 1 2
		Quadrature Err	0.02		deg	00144 3 3 2 0 2 3 1 3 1 1 3 2 3 1 2 2 3 3
Att		RHO	0.999987			00162 1 1 3 3 2 2 0 3 3 1 2 1 2 2 1 3 3 2
5 dB		Mean Power	-32.54	-31.74	281 dBm	00180 2 1 3 2 3 1 3 2 2 1 2 3 3 3 2 3 0 2
		SNR (MER)	51.68		dB	00198 2 2 2 3 3 1 0 3 2 0 1 2 3 3 1 3 1 3
						00216 3 2 3 1 3 1 0 3 3 1 2 0 2 3 3 0 1 2

Fig. 21: EVM results of demodulating a continuous O-QPSK stream

6.2 Measurement of bursted signals

In order to get a correct and stable measurement for bursted Zigbee™ signals, additional settings have to be made at the signal analyzer.

As a first step, the signal is checked in zero span mode to get some information on the nature of the bursts.

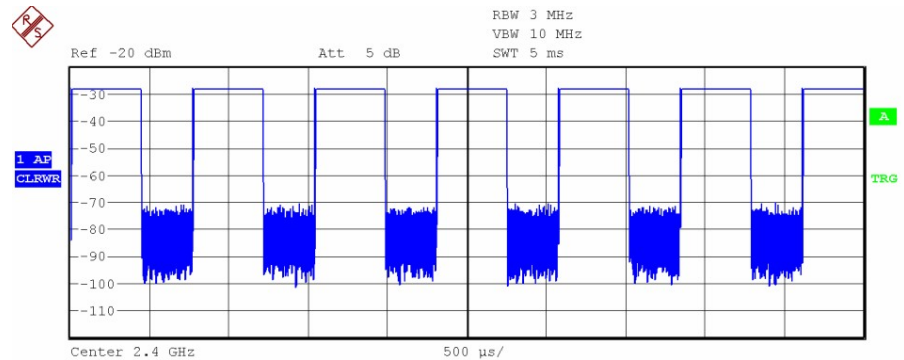


Fig. 22: Bursted Zigbee™ signal in zero-span (time domain).

Then the signal analyzer is setup for the basic Zigbee™ parameters. The previously generated Zigbee™ standard setting can serve as starting point. Next step is to get a stable triggering. The IF power trigger is a good choice here. An appropriate capture time and trigger delay is selected so that one full burst can be seen in the display.

The scope of the EVM evaluation can be limited to the wanted time interval by usage of limit lines. In the following example, the limit lines were set to the beginning and end of the burst. Unless the effect of power ramping is of interest, it is recommended to place the evaluation lines a little inside the burst (a few symbols). This way the power ramping is not taken into account for the EVM calculation.

Measurement of bursted signals

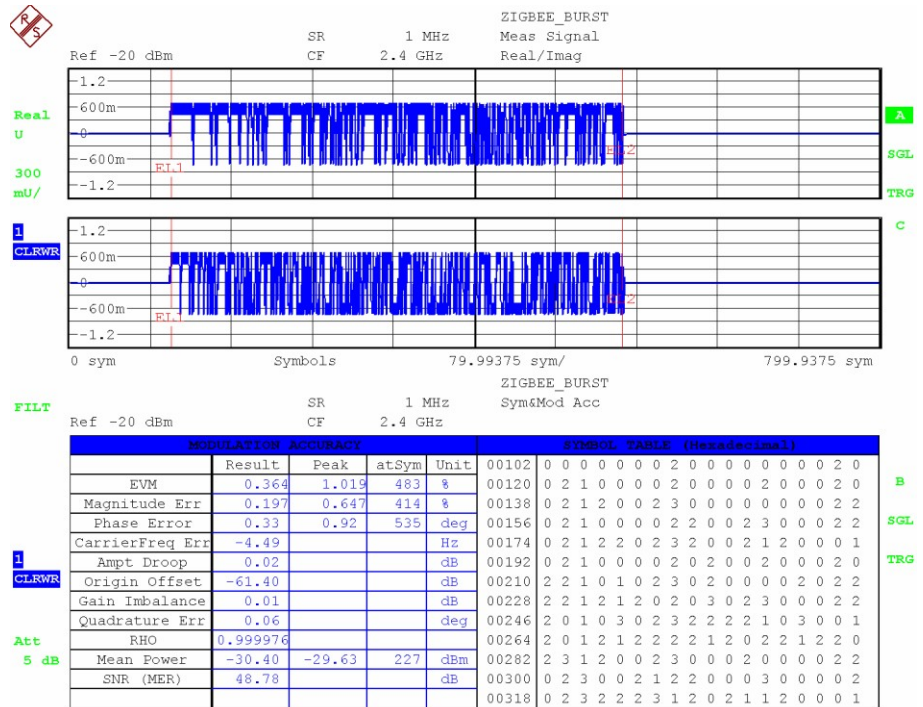


Fig. 23: FSQ screenshot showing both Zigbee™ frame (I and Q signal) and demodulation results of bursted measurement

It can be seen from the above result display that a residual EVM $\ll 1\%$ was achieved with this setup. This is an extremely good value showing a near-ideal modulation and demodulation in the instruments. 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.

The display of eye-diagram with wide eyes and precise definition of the signals during the sample phase confirms the very good modulation quality. It can also clearly be seen how I and Q signals are shifted in time by half the symbol duration for the O-QPSK Modulation of ZigBee™.

Measurement of bursted signals

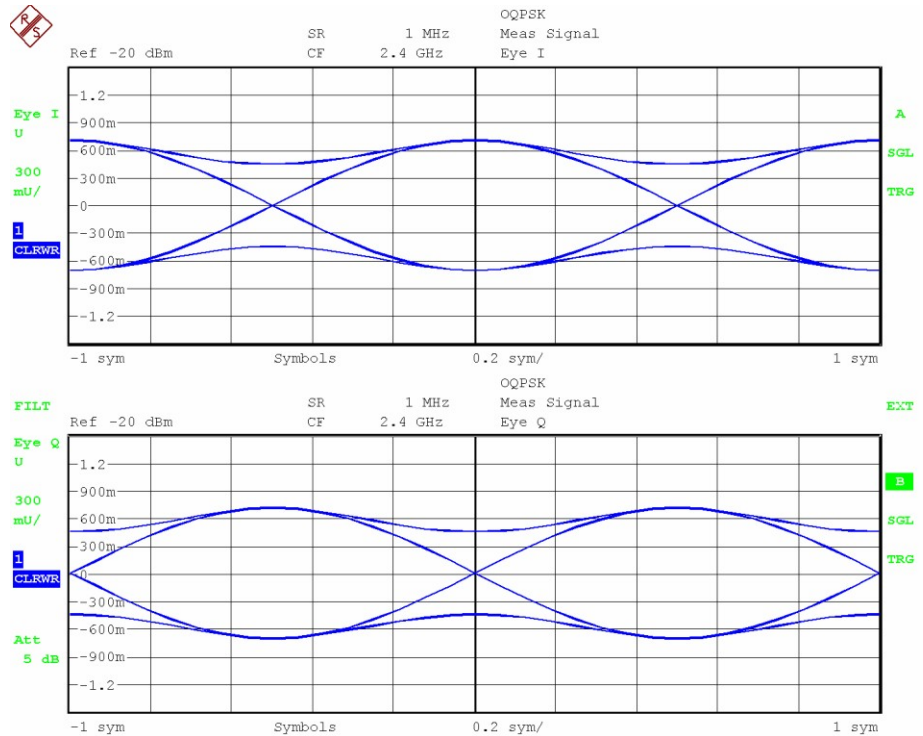


Fig. 24: FSQ screenshot showing the eye-diagram of the received bursted Zigbee™ signal

7 Conclusion

This Application Note has shown how to setup the R&S Vector Signal Generator SMU200A together with the free simulation software WinIQSIM for generating a bursted Zigbee™ signal with correct modulation and baseband filtering as well as the correct frame structure. Parameters of the frame can easily be changed with WinIQSim. It has also been shown how to setup the R&S Vector Signal Analyzer for demodulation and analysis of a typical ZigBee™ Burst. Several result views including Eye Diagram and Vector Constellation have been achieved. For the generated signal, an EVM of approx. 0.5% has been shown. This is an extremely good value suitable for high performance tests in R&D and production.

Literature:

- [1] IEEE 802.15.4 standard
- [2] <http://www.rohde-schwarz.com/appnote/1EF55.html>
- [3] <http://www.rohde-schwarz.com>

8 Appendix

Convention of filenames:

- *.iqs WinIQSim Setup file. This file contains the settings of the WinIQSim Workbench
- *.ifl WinIQSim Filter file. This file contains a user-specific filter, for example a half-sine filter (zigbee.ifl)
- *.ded Data Editor setup file. This file contains the definitions of data fields, slots and frames
- *.dbi Data file. This file contains the formatted data including header information etc. as defined in the data editor.
- *.vaf Filter file. This file contains the filter parameters for the FSQ vector analyzer.



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