IEEE 802.15.4/ZigBee Measurements Made Easy Using the N4010A Wireless Connectivity Test Set

Application Note 1572

Abstract

When developing a ZigBee solution it is essential to comprehensively test the physical (PHY) RF layer. This application note discusses the test requirements as specified by the IEEE 802.15.4 standards document and guides the engineer towards practical test procedures using the Agilent N4010A wireless connectivity one box test set solution. The key test issues confronted by development engineers will be addressed, of which the need for automated measurements is a prime example. This document seeks to help develop an early integration of a systematic automated test, which could ultimately result in a faster development cycle.

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Agilent Technologies

Introduction

ZigBee™ is a new standard being developed in the personal area network section of the emerging communications market. It is the only standards-based technology that is aimed at delivering low cost and low power radios for wireless network applications. Key areas of interest for this technology include building installation and industrial sensors. This is often focused in areas such as lighting, security, and asset management, but potential end user applications are as numerous as they are varied. Such applications increasingly benefit from new low-power radio technology. Combined with advances in digital circuit design, the reduction in size of electromechanical circuitry and increased interest in mesh network implementation, sensor networks are set to proliferate more widely in our everyday lives.

The low cost aspect is achieved due to the requirements set for lower data rates and quality of service. However, the mesh networking capability of ZigBee ensures that networks can offer a high level of network reliability, often described as being be "self-healing". If a particular device cannot be enabled an alternative route will be used. This principle provides a reliable and secure structure for sensing and control applications.

Using frequency bands at 868/915-MHz and the worldwide ISM band at 2.4 GHz, ZigBee devices have the capacity to attach, exchange information and detach, before quickly going back to sleep to save on power. Unlike *Bluetooth*® technology, for example, ZigBee does not frequency hop and offers greater range passing small packets over larger networks. Radios operate with very low duty cycles to allow sensing and monitoring applications to run for years on inexpensive batteries, whereas other technologies like *Bluetooth* require main power or regular battery charging. The benefits of using ZigBee devices in mesh networking technology brings increased complexity into the higher levels of the protocol stack and where often much interest is focused.

Due to this focus and the fact that ZigBee is still in the relatively early days of development, often the practicalities of RF test are not fully understood or are not tackled effectively. This concerns what is required to be tested, how it may be tested, what RF instrumentation exists for 802.15.4/ZigBee test and how these questions relate to various stages of the product lifecycle where test demands differ. In this application note the importance of the physical layer is not forgotten as the basis for delivering much of the promises of the 802.15.4/ZigBee standard.

The ZigBee Alliance

The ZigBee Alliance enables interoperability, certification testing, and the branding of this global open standard. It defines the network, security, and applications layers, which are positioned above the media access control (MAC) and physical (PHY) layer specified by the IEEE 802.15.4. Analogous to the *Bluetooth* world and the *Bluetooth* SIG, the ZigBee Alliance actively facilitates and promotes the technology, providing support for developers, promoters, and members' interests. There are currently several hundred ZigBee Alliance members, including Agilent Technologies.

Physical Layer Test

Familiarity of the IEEE 802.15.4 specification [1] is important when preparing to test the PHY layer. It defines the main requirements of the radio addressing activation and deactivation of the radio transceiver, energy detection (ED), link quality indication (LQI), channel selection, clear channel assessment (CCA), and transmitting as well as receiving packets across the air interface.

Figure 2 shows the PHY and MAC layers. In the PHY layer you can see the preamble, start of frame delimiter, and frame length fields.

At 2.4 GHz, ZigBee radios use 2 Mchips/s (62.5 ks/s*32) direct sequencing spread spectrum (DSSS) with each symbol mapped to a 32 chip sequence. This results in a chip rate 32 times the symbol rate.

At 2.4 GHz ZigBee uses offset quadrature phase shift keying (O-QPSK) modulation. A half-sine reference filter is used so that the constellation changes from a square to a circle and ideal state circles are moved to the I and Q axes. This turns the O-QPSK signal into a constant envelope modulation and the O-QPSK now resembles MSK.

$$p(t)= \begin{cases} \sin\left(\pi\dfrac{t}{2T_C}\right), 0 \leq t \leq 2T_C \\ 0, \ otherwise \end{cases}$$ where T_C is the offset of the I-phase and Q-phase chip modulation.
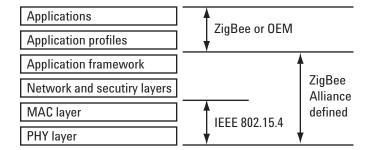

Figure 1. The ZigBee stack

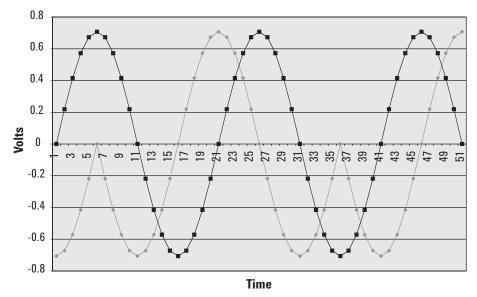| Octets				2	1	4 to 20	n	2
MAC sublayer				Frame control	Data sequence number	Address information	Data payload	FCS
Octets	4	1	1	5+(4 to 20) + n				
PHY layer	Preamble sequence	State of frame delimiter	Frame length					

Figure 2. MAC and PHY layer

Physical Layer Test (continued)

Data taken from a reference trace in the 89601A Vector Signal Analyzer (Figure 3) produced by a transmitting ZigBee device shows that the two streams are offset by half a symbol, or 1 chip, as each symbol is 2 bits. It also demonstrates that I and Q transitions never occur at the same time.

In a constellation diagram the O-QPSK constant envelope modulation can be seen to limit the phase-shift to no more than 90 degrees at a time, unlike QPSK which can vary up to 180 degrees.

O-QPSK modulation permits the use of a more power efficient and less linear RF amplifier. In practice this results in improved power efficiency and lowering costs of integrated circuits.

ZigBee hardware architecture is primarily a trade-off between performance, cost of silicon area versus external components and power consumption. As the market grows it is expected that there were be a variety of solutions available, perhaps with a division between low cost and high cost chips offering different performance levels, heavily influenced by the end application. For a hardware designer these factors must be accounted for when deciding a route towards implementation.
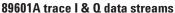
89601A trace I & Q data streams

Figure 3. I and Q data for O-QPSK after half-sine pulse shaping

Physical Layer Test

Testing challenges

Test and measurement of the PHY layer is critical in many areas of development moving towards an end product. This makes this application note relevant to many parties in the ZigBee 'food chain'.

Performing comprehensive PHY layer tests will be essential if ZigBee is to fulfill its aspiration of delivering low cost, reliable applications in areas such as industrial control, monitoring, and home automation. Understanding the test and measurements requirements as early as possible in the development lifecycle can save both time and money. There are a number of routes to final hardware implementation.

1. Reference design

At the top of this chain, ZigBee chip companies are designing their next generation of system on a chip (SoC) solutions. They must ensure:

- Conformation to specifications

- Automation for efficient characterization of their devices

- Tight tolerances through process monitoring

- Quality

- Interoperability

- Accurate datasheet information

- Provision of tools for customers

Major chipset companies are producing their own reference designs. They must accurately characterize their chipsets and define datasheet specifications for successful proliferation of their design in the industry. This is a continual process of optimization for quality control, automating tasks to speed investigation and free up RF laboratory equipment. Providing adequate tools to their customers is also vitally important, including test and measurement expertise. With a test solution such as the N4010A one box tester and the 89601A Vector Signal Analyzer (VSA), companies can easily share test expertise and custom developed test code. For example, sharing of VSA test setups and chipset recordings can illustrate expected transmit results. Arbitrary waveforms can be adopted by chipset customers to eliminate a golden radio approach to receiver testing. This facilitates easy comparison, faster problem solving and takes a similar approach to other wireless technologies such as *Bluetooth* and wireless local area networks (WLANs).

2. Custom design

Customizing and optimizing a chipset solution is another potential way to progress. In this area the demands for test and measurement expertise is readily understood as a fast and logical way of improving design.

3. Module design

Module designers adopt the role of integrators, where they have the opportunity to modify designs and produce RF modules. For example, they can add value to their solution by taking away the need for sourcing many components, a requirement even for SoC solutions. They can also choose to provide a pre-qualified solution and have virtually all of the RF testing complete.

However, it is evident that many vendors involved with ZigBee are entering the RF world for the first time, implementing new technology in areas such as lighting, consumer white goods, safety, and security. Agilent's test and measurement approach and expertise in wireless communications can help de-mystify much of the detail of the physical layer test. An example is the reduced complexity of a one-box tester approach.

Similar to the chip companies, automation of tests and characterization is essential to test for tolerances and spot problems both in design and production. The challenges of high volume manufacture are also apparent, especially when aiming to achieve lower costs and to make mass production more viable.

4. End product

When RF work is virtually complete, test and measurement may be required for ensuring that field installation is successful. For example, having acquired a module, built a custom profile, and modified the antenna, power may need to be monitored after fitting the end device into an industrial environment.

Summary

In all the above cases development must be achieved in the quickest possible time using equipment that can be automated, provide traceable results through the lifecycle, and which can be flexible and cost effective to meet the demands of wide laboratory use and business pressures. Agilent's N4010A Wireless Connectivity Test Set is an example of a one-box tester which may be adopted to address the variety of RF challenges faced by many ZigBee developers that work in different parts of the food chain.

Whichever approach is taken, the demands for test and measurement is equally important. Moreover, throughout the development cycle it is worth considering future test needs, for example, moving to an automated test approach within a chosen software environment.

Agilent have a long history of designing, integrating, testing, and certifying wireless products, providing the measurements required to verify that designs meet wireless functional specifications, operate correctly and address unforeseen problems around physical layer test.

N4010A Wireless Connectivity Test Set Overview

The N4010A test set is the industry standard instrument for emerging communications and has been developed to address R&D, integration and verification, and manufacturing, providing traceable measurements from R&D to production environments. It provides an alternative solution to separate spectrum analyzers, power meters, power sensors, the golden radio, and other test system components. A one-box test set approach often speeds measurements and improves throughput.

The N4010A with Options 102/103 integrates a wide bandwidth signal analyzer and a vector signal generator into one test component. The wideband (40 MHz digitizer) signal analyzer captures complete ZigBee signal bursts for transmitter measurements, such as error vector magnitude (EVM). The integrated vector signal generator emulates ZigBee signals for receiver measurements so

the need for a golden radio is eliminated. Option 104 allows the user to download and encrypt new arbitrary files to the N4010A to offer additional benefits for receiver testing. The ability of this is discussed in more detail in receiver testing. The flexible multi-format N4010A test set can also include *Bluetooth* and WLAN formats, helping to reduce the cost of test equipment ownership.

N4010A Wireless Connectivity Test Set and 89601A VSA software combination

As shown throughout this application note, the full range of ZigBee related results are obtainable from the N4010A when used in association with the 89601A vector signal analyzer software. The N4010A measuring receiver functions as a generic digitizer to provide data to the PC-based measurement application 89601A over GPIB, LAN, or USB. N4010A Option 110

and 89601A Option 300 enables this functionality with I/O connectivity.

The 89601A VSA software is a PC-based package designed to measure the RF and modulation quality of most digitally modulated signals. Its large array of demodulators, filters, displays, and analysis tools make it ideally suited for evaluating and troubleshooting modulated signals in the R&D lab. For ZigBee, the package contains demodulation presets for each of the three frequency bands. The software also permits measurements beyond R&D using COM API Active X programming.

89601A Option AYA provides the following analysis tools required to make ZigBee measurements in the 868, 915, and 2450 MHz bands. It contains three standard presets for all three bands and the half sine filter for the 2450-MHz band.

Other Agilent solutions

The ESA spectrum analyzer offers flexible mask testing and 89601A can also be used to extend its capabilities. The PSA series of spectrum analyzers also offers flexible mask testing. However, with flexible demodulation options (Option 241) it can provide digital modulation analysis of ZigBee signals, including EVM, offset EVM, eye and constellation diagrams. For signal generation, the ESG series of vector signal generators provide real time and arbitrary waveform generation of IEEE 802.15.4/ZigBee signals.

RF Tests (IEEE 802.15.4 reference [1])	89600 Series vector signal software[1]	PSA, ESA-E Series spectrum analyzers	E4438C ESG vector signal generator	N4010A Wireless Connectivity Test Set	P-Series, EPM-P Series power meters
Transmitter tests					
Output power (6.7.5)	■	■		■	■
Power rise/fall	■	■		■	■
Spectrum PSD mask (6.5.3.1)	■[7]	■		■	
Transmission spurious (6.1.5)		■			
Center frequency tolerance (6.7.4)	■	■		■	
Constellation error	■	■		■	
Error vector magnitude (6.7.3)	■	■[3]		■[3]	
Receiver tests					
Symbol rate error tolerance			■[5]	■[5]	
Sensitivity (6.5.3.3)			■[5]	■[5]	
Max input level (6.7.6)			■[5]	■[5]	
Jamming resistance (6.5.3.4)			■[2]	■[2]	
Energy detect[6] (6.7.7)			■[5]	■[5]	
Link quality indication[6] (6.7.8)			■[5]	■[5]	
Transceiver tests					
Out-of-band spurious emission		■			
Tx-Rx/Rx-Tx turnround[4] (6.7.1, 6.7.2)	■		■	■	

1. The software can be used with a variety of digitizers including, ESA-E and PSA Series spectrum analyzers, N4010A wireless connectivity test set, VXI, oscilloscopes, and logic analyzers.
2. Requires a second source (e.g. N4010A or E4438) outputting a ZigBee signal waveform file. Such a file can be either user-designed (e.g. MATLAB) or created with IQ data capture from a real DUT (e.g. use N4010A with 89600 Series VSA software to view and capture signal, save a recording, and then download to the N4010A for playback).
3. Demodulation measurements using the ESA-E or N4010A requires the use of 89600 Series VSA software. PSA only requires Option 241.
4. This test may require specific test modes. An oscilloscope such as the 54800 Series Infiniium may be required.
5. Requires a user-designed waveform file or one created with IQ data capture from a real DUT. The E4438C may be used to create a real-time signal from a baseband signal.
6. Link quality indication, energy detect, and clear channel assessment tests may be conducted if the required test modes are available.
7. Capture a complete burst from the DUT. Use 100 kHz Gaussian filter with free run trigger and continuous peak hold to give evaluation of the spectrum as stated in the specification.

Table 1. ZigBee RF tests

A Guide to PHY Testing

Before commencing a test plan, it is important to acquire and understand control of the ZigBee device under test (DUT). Depending upon testing requirements and level of expertise, this may simply require communication with the DUT through software provided by the manufacturer. However, testing is very often more specific. For example, DUT control may need to be customized with a high level of control over memory register settings to emulate device states, or an antenna design requires optimization. Agilent has been working with major chipset manufacturers in order to understand the elements of test more fully.

In terms of making effective measurements, it is generally a good idea to have a well-organized measurement approach.
This applies to any test and measurement but perhaps more so with emerging communications technology and rapidly evolving chipset revisions. Making measurements in a relatively well defined sequence reduces the influence of setup conditions and ensures a good appreciation of what state the DUT is in. The 89601A VSA software makes test and measurement more accessible with interfacing on a PC. However, it is a very powerful and configurable package so it does make sense to change only one variable at a time, saving setups and signals as testing progresses. For example, a methodical approach when working with 89601A VSA software should help to understand the use of span, triggering, and burst parameters. By doing so, this forms a basis for more advanced setups, often exposing problems at the earliest stage of analysis. Moreover, saved settings will allow future replication.

Remember that it is not necessary to use full digital demodulation features immediately. While the demodulation features of the 89601A VSA software are extremely insightful, working with both the time and frequency trace will yield a good appreciation of setup and measurement errors. This verifies that the basic principles are in place. Only then is it recommended to complete demodulation. This stage of analysis provides insight into signal quality, such as Error Vector Magnitude (EVM), based on an understanding of measurement setup such as triggering. Finally, it may be necessary to move on to make more specific and advanced measurements. This may include additional investigation using the 89601A VSA software but also using external equipment, or alternatively, the N4010A interacting with other devices. A final and critical last step is to replicate key measurements in an automated manner.

A Guide to PHY Testing (continued)

Transmitter testing

For demonstration, the following key transmit measurements are investigated, referencing the 802.15.4 specification where necessary:

- Relative power spectral density

- Absolute power spectral density

- Maximum transmit power

- Center frequency tolerance

- EVM

- Offset EVM

With a DUT in the correct transmitting mode, the 89601A VSA software can be used for analysis. The 89601A VSA settings require adjustment to suit the particular packet being transmitted. In order to stress the device appropriately it is sensible to use the full packet length. For a typical ZigBee device the following parameters are a good starting point for a transmit test on a 802.15.4 (channel 11):

89601A basic settings for maximum packet length

Range	0 dBm
Frequency	2.405 GHz
Trigger	IF triggering
Trigger IF level	10 mV
Trigger hold-off	20 ns
Trigger delay	–50 µs
Span	10 MHz
Main time length	5 ms
Number of points	51201

Table 2.

The range setting is required for optimization to the expected signal power into the instrument from the device. A suitable choice will provide good sensitivity without reducing the dynamic range of the analog to digital converter. Frequency is the chosen 802.15.4 channel at which the device is transmitting. Triggering defaults to free run, which is a continuous trigger in which the analyzer processes the input as quickly as possible without waiting for any kind of triggering signal condition. It is possible to see a burst appearing but only IF triggering will provide a steady signal for investigation. This is particularly important for making consistent and reliable measurements. A small negative trigger delay is usually advisable to show the full ramp of the power within the time trace. The span setting determines how wide the signal capture requirement is, depending on how many side lobes must be included. It also has an influence on the speed of measurement. The main time length parameter determines the length of the main time record and should be adjusted to show the whole burst. By default this is limited by the span and number of frequency points. It may be necessary to increase the value of the main length and so the number of frequency points should be increased. Alternatively the span may be adjusted.

A Guide to PHY Testing (continued)

With a suitable setup complete a ZigBee spectrum may be observed. Each ZigBee channel is separated by 5 MHz and the main lobe occupying around 2 MHz. A twin view of frequency and time is shown in Figure 4 with a burst captured within the main time length that was previously defined.

The time and frequency traces can expose lots of useful information by fine tuning settings. For example, adjusting settings and enabling a large trigger delay can show the signal before the main ZigBee spectrum. In the following figures, an unexpected signal appeared within the span used to characterize the 2.405-GHz channel. The LO leakage appeared from the DUT at 2.402-GHz. Increasing the trigger level in real time meant that the main ZigBee signal started to appear again (similar to Figure 4) and a ramp observed in the main time trace.

Irregularities often require further investigation and so the signal can be captured for post processing. Using the player control, the area that contains the graphical slider bar represents the length of the recording. When a recording is played, a slider moves left to right to indicate the relative position in the recording.
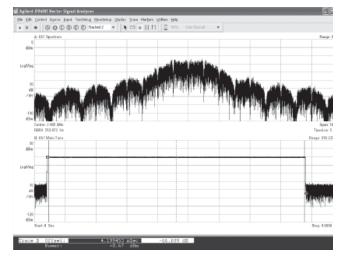

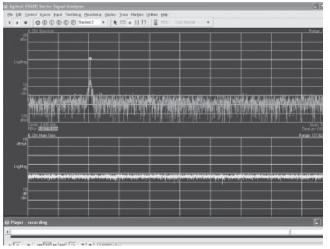Figure 4. 89601A VSA showing ZigBee spectrum and time trace

Figure 5. Device LO leakage captured as a recording

The alternative spectrogram view in Figure 6 shows a trigger on the LO leakage very clearly but also the occasional ZigBee burst captured across the span.

By advancing time using the player controls, a power ramp becomes apparent before eventually being hidden from view by the main ZigBee lobe.

Stopping the recording and adjusting parameters revealed the two step 'ramp' better on the main time using a span of 10 MHz and lower resolution bandwidth around 6 kHz.
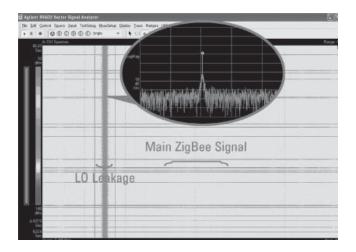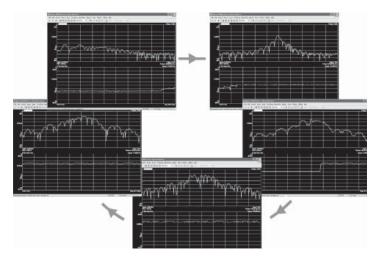

Figure 6. Spectrogram view

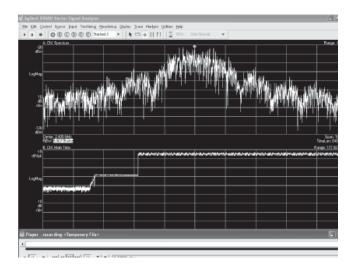**Figure 7. Power ramp observed using 100 kHz RBW and recording playback control**

Figure 8. Power ramp

A Guide to PHY Testing (continued)

Having introduced frequency and time domain analysis briefly, a progression can be made onto the IEEE 802.15.4 specified measurements.

Transmit relative power spectral density (PSD) mask
(see section 6.5.3.1 [1])
The transmitted spectral products at frequency f shall be less than –20 dB, where the reference level shall be the highest average spectral power measured within ±1 MHz of the carrier frequency (fc), with |f – fc| > 3.5 MHz, measured using a 100 kHz resolution bandwidth.

Limit lines provide pass and fail information based on a predefined mask. Adjacent channel power (ACP) tools provide the ratio of power measured in adjacent channels relative to the power in the reference channel. A combination of these functions can provide more detailed information about the spectrum from a device. With

a full burst recorded, a free run trigger and continuous peak hold allows evaluation of the spectrum.

In Figure 9, the three light gray shaded areas indicate the adjacent channels specified in the ACP measurement tool. The reference channel is centered at the reference frequency with 1-MHz bandwidth. The upper and lower channels are also set with a bandwidth of 1-MHz and offset by 4-MHz. The results show that the upper and lower adjacent channels are –34.0 and –34.3-dB respectively, referencing the center channel.

The occupied bandwidth marker (OBW) shaded in dark gray shows where a specified percentage of the power lay on the trace, in this case 99 percent. The OBW marker shows an occupied bandwidth of 2.632 MHz, a centroid (or mid-point) frequency of 2.4050-GHz, and an offset frequency (difference between the specified

center frequency and the centroid frequency) of –17.1 kHz.

Transmit absolute power spectral density (PSD) mask
(see section 6.5.3.1 [1])
The transmitted spectral products at frequency f shall be less than the absolute limit of –30-dBm with |f – fc| > 3.5-MHz measured using a 100-kHz resolution bandwidth.

The lines visible in Figure 9 are limits which determine pass and fail criteria. They are set at –30-dBm with an offset of ±4-MHz from the center frequency. The results show the frequency and delta of the point closest to the limit. The other limit lines observed are used to set a margin line offset from the mask line and can be used as soft pass/fail limit testing. You can see that the device passed the absolute test by –9-dB on lower frequencies and –13-dB on the higher frequencies.
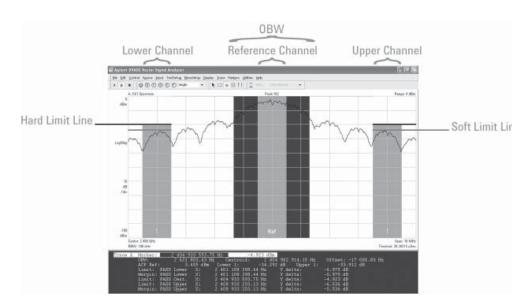

Figure 9. Transmit relative and absolute power spectral density test example

A Guide to PHY Testing (continued)

Minimum transmit power
(see section 6.7.5)
Transmit power must be equal to or greater than –3 dBm.

The N4010A signal analyzer is specified from +23 dBm down to –70 dBm. Power measurements are easily obtained from 89601A VSA software by using band power markers on the time domain view across the burst.

Figure 10 shows a transmit power of approximately –10 dBm from a device using the band power markers. Time markers show the burst is about 4 ms long with markers offset by 24 dB.

Maximum transmit power
The maximum transmit power of the device is limited by regulatory bodies. As before, band power markers can be used to determine power levels.

Transmit center frequency tolerance
(see section 6.7.4 [1])
Transmit center frequency tolerance shall be a maximum of ±40 ppm.

Center frequency tolerance can be determined using a bursted signal (similar to the tests above) or using a unmodulated signal. For an unmodulated signal, FM demodulation and auto carrier frequency may be used. Auto carrier frequency has the advantage of ensuring readings are consistent, as opposed to using a peak marker search, for example. Once selected, the analyzer uses an algorithm to estimate the carrier frequency and is calculated independently for each time record.

However, non-bursted signals are not representative of how the device will work in the real world. A quick way to demodulate

ZigBee signals is to use the ZigBee preset provided. Switch digital demodulation under the 'MeasSetup' menu, then choose 'Demod Properties', choosing the 'ZigBee 2450 MHz' preset under the 'Preset to Standard' option. The preset will set the symbol rate at half the chip rate to 1000 symbols per second. The symbol rate is the frequency of the I (or Q) clock, not twice the frequency sometimes associated with the I to Q clock frequency. The result length is the number of symbols that the analyzer will display and defaults to 1001 symbols. The choice of 1001 symbols has relevance when discussing the measurement of offset EVM. The Filter tab shows that the preset loads the reference half sine filter for measurements. Under the Search tab the search length of a burst may be adjusted to lock to the full burst.

Example demodulation settings for maximum packet length

Format	Offset QPSK
Result length	0 dBm
Symbol rate	1 MHz
Points/symbol	10
Search length	4.5 ms
Pulse search	On

Table 3.

Figure 10. ZigBee power measurement

A Guide to PHY Testing (continued)
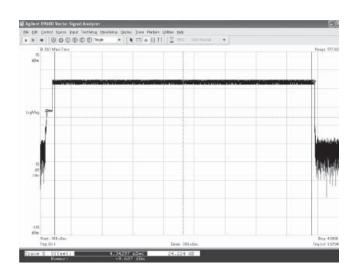
The preset presents a suite of measurements and each trace window can be configured.

The 'Symbol Table/Error Summary' trace can be used to display the center frequency offset.

The frequency tolerance is easily calculated by checking the frequency error in the table and referencing the current channel in use. Here we have a tolerance of approximately 0.76 ppm.

EVM (see section 6.7.3 [1])
An IEEE 802.15.4 transmitter shall have EVM values of less than 35 percent when measured for 1000 chips.

EVM is obtained from the symbol table/error summary trace as above. It is computed by calculating the ideal reference signal corresponding to the measured signal, computing the error vector which is the measured value minus the reference. EVM is the RMS level of the error vector computed at each symbol time. EVM spectrum and time traces may be observed.
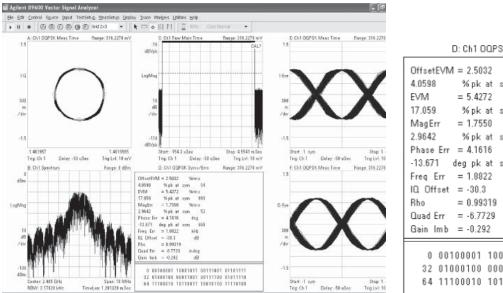
Offset EVM
Offset EVM is a special value computed only for O-QPSK demodulation. It is similar to EVM except that it is computed by combining the measured I part at the start of each symbol, and the Q part at the middle of each symbol, so that there is a single complex value for each symbol time. The analyzer does not use the last half of the last O-QPSK symbol in the result length and so that is why the result length from before was set at 1001 symbols.

Both the RMS and peak values are provided for both EVM and offset EVM.

In the results previously, the device has an EVM value of 5.4 percent and a peak of 17 percent at symbol 669. The offset EVM value is 2.5 percent with a peak of 4 percent occurring at symbol 54.

Additional information
Figure 12 shows that the symbol table/error summary displays a variety of different parameters. It also includes magnitude and phase error (which may be graphed as required), IQ offset, rho, quadrature error, and gain imbalance. Also of use are the traces of IQ phase error, PDF, CCDF, and reference time.

Figure 11. 89601A VSA software ZigBee demodulation

Figure 12. Basic O-QPSK symbol table/error summary

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Receiver testing

The following key receiver measurements are investigated, referencing the IEEE 802.15.4 specification where necessary:

• Receiver sensitivity

• Symbol rate error tolerance

• Receiver jamming resistance

• Maximum input level

• Energy detection

• Clear channel assessment

• Link quality indication

As with transmit measurements, the DUT must be put into the correct mode to receive packets. Moreover, packet error rate (PER) must be available from the device to permit many of the receiver measurements. In general, the receiver measurements require more in-depth knowledge of the chipset in order to query relevant data. The prime use of the N4010A test set is to act as a source and replace golden radio type testing. The use of its flexible arbitrary waveform generator is explained and the benefits of this approach.

Receiver sensitivity
(see section 6.5.3.3 [1])
The threshold input signal power achieving –85 dBm or better that yields a specified PER of < 1 percent, over which the physical service data unit (PSDU) length is 20 octets using at least 1000 packets and power measured at antenna terminals. No interferer should be present.

For this test the N4010A's internal arbitrary waveform generator can be used to send packets out to the DUT, dropping the power level until the error criteria is met. In the example below, Agilent VEE was used to control both the device and the instrument to complete this test.

The program set the target PER level, the number of packets required for test at each power level and the size of the power level decrements. The results were then passed to a spreadsheet. Figure 14 demonstrates how PER increased as the power level dropped. In this case the PER level was set at 100 percent to show the breakdown in performance.
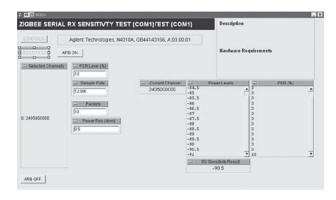

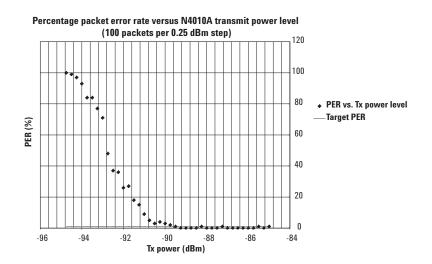**Figure 13. ZigBee receiver sensitivity test**

Figure 14. PER measurements

Symbol rate error tolerance

The sampling rate of the waveform played out from the instrument can be changed. The PER may be measured to determine the maximum deviation that the receiver can tolerate.

Receiver center frequency tolerance
Often chipsets are tested with signals with a small frequency offset from a test set and PER investigated.

Adjacent channel rejection
(see section 6.6.3.5 [1])
The desired signal shall be a compliant 2450 MHz IEEE 802.15.4 signal of pseudo random data, input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity. In the adjacent channel, an IEEE 802.15.4 signal is input. The receiver shall attain a minimum jamming resistance of 0 dB with the adjacent channel until error criteria is met. The test shall be performed for only one interfering signal at a time.

This test requires a power splitter and another source, such as a E4438 signal generator. The advantage of using two instruments is the greater flexibility to output WLAN, *Bluetooth*, and ZigBee signals.

Alternate channel rejection
(see section 6.6.3.5 [1])
The desired signal shall be a compliant 2450 MHz IEEE 802.15.4 signal of pseudo random data, input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity. In the alternate channel, an IEEE 802.15.4 signal is input. The receiver shall attain a minimum jamming resistance of 30 dB with the alternate channel until error criteria is met. The test shall be performed for only one interfering signal at a time.

The requirement for test equipment is similar to that for adjacent channel rejection.

Receiver maximum input level
(see section 6.7.6 [1])
The receiver shall have a maximum input level greater than or equal to –20-dBm for which the error criteria is met.

This is a similar test to receiver sensitivity except that power is being incremented while PER is being measured from the device.

Energy detection
(see section 6.7.7 [1])
The receiver energy detection measurement is intended for use by the network layer as part of the channel selection algorithm. It is an estimate of the received signal power within the bandwidth of an IEEE 802.15.4 channel. No attempt is made to identify or decode signals on the channel. The energy detection time shall be equal to 8 symbol periods.

The energy detect result shall be reported as an 8 bit integer ranging from 0x00 to 0xFF. The minimum energy detection value shall indicate received power less than 10 dB above the specified receiver sensitivity, and the range of received power spanned by energy detection values shall be at least 40 dB. Within this range, the mapping from the received power in dB to energy detection value shall be linear with an accuracy of ± 6dB.

This measurement requires detailed knowledge and access to device settings using the N4010A Wireless Connectivity Test Set as a calibrated source.

A Guide to PHY Testing (continued)

Clear channel assessment
(see section 6.7.9 [1])
The IEEE 802.15.4 PHY shall provide the capability to perform clear channel assessment according to at least one of the following three methods:

1. CCA Mode 1: Energy above threshold. CCA shall report a busy medium upon detecting any energy above the energy detect threshold.

2. CCA Mode 2: Carrier sense only. CCA shall report a busy medium only upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4. The signals may be above or below the energy detect threshold.

3. CCA Mode 3: Carrier sense with energy above threshold. CCA shall report a busy medium only upon the detection of a signal with the modulation and spreading characteristics with energy above the energy detect threshold.
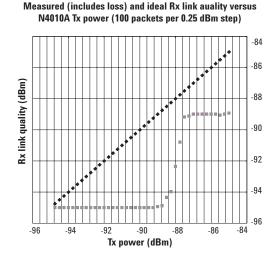
Similar to the energy detect test, this requires the retrieval of energy detect data from the device. The N4010A test set acts as a source.
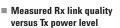
Link quality indication
(see section 6.7.8 [1])
The link quality indication (LQI) measurement is a characterization of the strength and/or quality of a received packet. The measurement may be implemented using receiver energy detect, a signal-to-noise ratio estimation, or a combination of these methods. The use of the LQI result by the network or application layers is not specified in this standard.

The LQI measurement shall be performed for each received packet, and the result shall be reported as an integer ranging from 0x00 to 0xFF. The minimum and maximum LQI values (0x00 and 0xFF) should be associated with the lowest and highest quality IEEE 802.15.4 signals detectable by the receiver, and link quality values in between should be uniformly distributed between these two limits. At least eight unique values of LQ shall be used.

In the example program used for receiver sensitivity testing from before, link quality indication was also obtained. Figure 15 shows how link quality indication breaks down as the receiver sensitivity is reached. Ideal receiver link quality is plotted for reference.

Measured (includes loss) and ideal Rx link auality versus N4010A Tx power (100 packets per 0.25 dBm step)

- ▪ Measured Rx link quality versus Tx power level
- ◆ Ideal Rx link quality versus Tx power level

Figure 15. Link quality indication

N4010A transceiver testing to 802.15.4 specification

Rx-to-Tx turnaround

(see section 6.7.2 [1])

Rx-to-Tx turnaround time shall be measured at the air interface from the trailing edge of the last chip (of the last symbol) of a received packet until the transmitter is ready to begin transmission of the resulting acknowledgment, with a maximum turnaround time of 12 symbol periods. The actual transmission start times are specified by the MAC sublayer.

Rx-to-Tx turnaround is often calculated in software using higher level protocol, checking timestamps on packets. However, the N4010A test set can permit this test with advanced control of the chipset.

Tx-to-Rx turnaround

(see section 6.7.1 [1])

The Tx-to-Rx turnaround time shall be measured at the air interface from the trailing edge of the last transmitted symbol until the receiver is ready to begin the reception of the next physical layer packet, with a maximum time of 12 symbol periods.

See the previous test.

Extending receiver testing capability

The N4010A's internal flexible arbitrary waveform generator (AWG or ARB) is used to setup, sequence and playback signals required for receiver testing. Segment file(s) (*.wf1 extension files) are individual waveforms that can be played back from volatile memory. They can be acquired in a number of ways.

1. MATLAB® is a commonly utilized tool in R&D which can create segment files to exact design specifications.

2. A practical signal may be acquired from a transmitting device. The IQ data from the instrument can be exported and saved as a segment file or in CSV format. This permits acquisition of signals from a variety of devices and chipsets as required.

3. Segment files from Agilent Signal Generators can be used in the N4010A test set. For example, 89601A VSA software and a N4010A can digitize signals from a device to make recordings. Playback can then be configured using an E4438 as a source. The subsequent files generated in the E4438 may be retrieved and downloaded to the N4010A.

Management of your AWG files is aided by the N4010A utility, a PC-based software application that works in a complementary manner with the N4010A test set. Using the N4010A's remote command set, its main functionality is to provide the ability to download, manage waveform files and configure playback settings. As indicated above, it also permits extraction and saving of IQ data. The software provides the following features:

- Download waveform files

- Save waveform files to computer

- List the contents of volatile and non-volatile memory

- Display volatile and non-volatile free memory space

- Copy waveform files from volatile to non-volatile memory

- Copy waveform files from non-volatile to volatile memory

- Delete waveform files

- Specify playback settings
  - Output power (dBm)
  - Frequency (GHz)
  - Sample rate (MHz)
  - Continuous
  - Triggered

- Playback waveform files

- Specify IQ data instrument settings
  - Frequency (GHz)
  - Input power (dBm)
  - Acquisition time (ms)
  - Trigger holdoff (ms)
  - Trigger delay (ms)
  - External
  - Free run
  - IF magnitude
  - Trigger level

- Extract and save IQ data

The N4010A also supports sequence file(s) (*.seq extension files) which are held within non-volatile memory. A simple sequence file can play the same segment file 0 to 65535 times and the DUT and DUT software used to calculate PER. In addition, a complex sequence file can play different segment files in any order or number 0 to 65535 times. For WLAN testing this is seen as a very useful feature

and similarly ZigBee testing can benefit with the correct test setup.

With the ability to capture IQ data from the instrument using the N4010A Utility software, the use of 89601A to make recordings, and the ability to integrate the N4010A with MATLAB applications, there are a variety of ways of which IQ data may be edited. For example, data can be impaired to make additional receiver sensitivity measurements. Additionally, 'perfect' signals may be created by extracting reference IQ data from 89601A based on a practical device recordings (like the data plotted in Figure 3). These waveforms provide further comparative testing opportunities to stress devices in different ways.

Receiver tests can be extended by using WLAN AWG waveforms. The IEEE 802.15.4 specification only requires a ZigBee signal as an interferer.
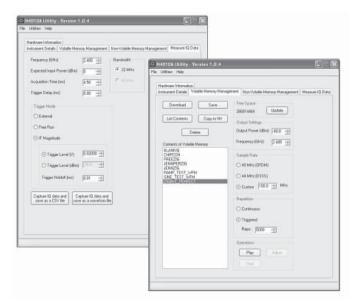

Figure 16. N4010A Utility playback and I/Q capture

N4010A Automated Measurements

Automated transmitter testing

The 89601A VSA software allows the test engineer to experiment and test with a high degree of configurability, investigating problems, improving design and understanding test parameters for transmit testing. With experience this leads to improved efficiency in test by acquiring an understanding of relevant measurement parameters. The benefits of using setups and recordings is also understood and the next logical step is to build on them using macro functionality.

Macro automation

Macros let you automate a series of manual operations into a single command. All 89600-series products use VBScript for their macro programming language. VBScript is a popular scripting language based on a subset of the Visual Basic® programming language. 89601A has all the tools required to record, save, run, recall, and edit macros. Editing can be carried out within the program or using an external code editor of your choice.

This kind of automation within the 89600 VSA software environment provides an excellent basis for trying out different procedures and routines. It provides a visual representation of how the measurements are acquired. For example, it could be the first time the test engineer combines external software automating the device (to put it into the appropriate transmit states) with test results. This then allows fine-tuning of test automation based on preliminary manual testing and evaluation.

The next stage in automation is to develop software that integrates device control with test characterization together more closely and within the realms of a test plan.

Figure 17. ZigBee Tx demodulation setup using macros N4010A Utility playback and I/Q capture

Software development for automation
The 89601A VSA provides an application programming interface to its component object model, or COM API. Measurement, computational, and display objects may be accessed to control measurement setup, acquire results, and integrate into test plans. Exposed objects are accessible to any application, programming tool, or language that implements automation. Examples are Agilent VEE, LabVIEW, Visual Basic, and Visual C++®.

If macros have been used prior to the development of custom software, much of the code may be leveraged. In some instances it is in fact quicker to record a macro and utilize the result as opposed to using the COM API reference help for every simple task. Further, programs can be used to run macros already in use and make use of existing setup files.

As discussed above, the step to custom test development in a chosen software environment is not a great leap. As an example of the possibilities, the following example program was developed using Agilent's graphical programming language Visual Engineering Environment (VEE) in Figure 18.

The program begins by starting the 89600 VSA software and setting it up with the requirements for carrying out a number of tests. This includes defining status flags to determine the progression of measurements within VEE. The program acquires user input to decide what tests are required and on which IEEE 802.15.4 channel(s). The device can be set into the correct transmitting state by communication through a serial link. The DUT itself requires setup to define the channel for transmission, the frame length, the payload data, the number of repetitions, and the gap between each. Once complete, the program executes each measurement, waits for completion, transfers data to the example program, accesses this data, and returns the results to the screen.
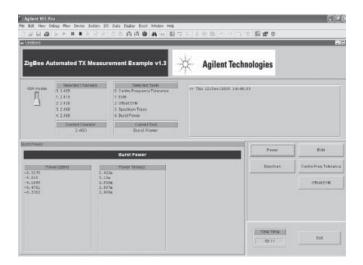

Figure 18. Agilent VEE ZigBee automated transmit measurement example

Such results can be stored and processed in relation to pass/fail criteria according to the IEEE specification, or, for example, compared with previous data acquired through an extensive process monitoring project. Often this kind of testing provides a better idea of what components may be failing, or, the variation in results compared to datasheet specifications. By timing the measurements, the program provides some indicative test time results.

It is also possible to display 89601A VSA software as the program executes. In the same way macros may be observed as they run, this program can set the VSA to be visible, providing the user with the chance to verify the correct operation of the measurements.

For example pseudo code for making measurements please see *Appendix A: 89601A Programming Pseudo Code.*

Automated receiver testing

Automated receiver testing has already been demonstrated with receiver sensitivity (see Figure 13) and with LQI. Communication with the N4010A test set can be achieved using direct SCPI commands or .NET commands sets using driver-based software. The instrument is equipped with GPIB, USB 2.0, and TCP-IP LAN interfaces. PER is measured from devices using manufacturer firmware and the chosen software environment provides the logic to sequence test and determine pass/fail criteria.

As discussed, eliminating a golden radio approach to test offer a variety of advantages. Configuration of waveforms in the instrument brings flexibility and consistency to test, with the N4010A test set offering a variety of interfaces for communication. Test speed can be increased by reducing time spent configuring a device and waiting on multiple packet transmission. The N4010A offers more advanced triggering and playback of waveforms in sequences.

Agilent Results Traceability

Since this application note centers upon Agilent's one box test approach, a comparison is conducive to highlight its benefits and flexibility. Further, it also demonstrates synergy between Agilent's solutions and how many different individual products can be effective for doing RF measurements, troubleshooting, improving performance, and understanding compatibility.

The following results are a comparison between the N4010A one-box tester used with 89601A VSA software and a PSA with full IFBW (10-MHz). PSA settings were as shown in Table 4.

PSA settings

Modulation format	OQPSK
Averaging	Off
Meas filter	No filter
Average nos	N/A
Ref filter	Half sine
Average mode	Repeat
Alpha/BT	0.22
Trace average type	RMS
Symbol rate	1 MHz
FFT window type	Flat top
Meas interval	1000 symbols
Trig source	RF burst
IF BW	10 MHz
Carrier lock	Normal
IF bandwidth mode	Manual
Sync	RF amplitude
EQ filter	Off
Burst search threshold	−20 dB
EQ filter length	5
Peak burst trigger setup	−20 dB
EQ convergence	1
Search length	5 ms
EQ hold	Off
Sync word length	10 sym
Sync pattern	N/A
Sync offset	0 sym

Table 4.

Agilent Results Traceability (continued)

The waveform used was initially formed from a capture using 89601A VSA software and the N4010A test set. The results were then based on playback using the N4010A as a source.

The following figures show the results from the PSA spectrum analyzer.

Figure 19. PSA settings screenshot

Figure 20. PSA demodulation results

Figure 21. PSA demodulation results

Figure 22 shows the results obtained using the N4010A test set and 89601A software.

Table 5 summarizes the results for direct comparison and demonstrates dependable results from both instruments. With no averaging employed and accounting for the wideband PSA measuring over the signal's sidebands, results indicate a high level of consistency. The delta in results certainly does not exceed what may be obtained over individual measurements and drifting signal characteristics.
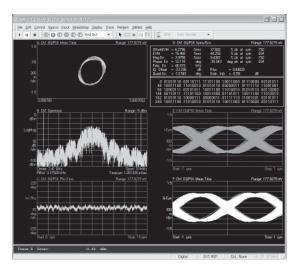

Figure 22. 89601A VSA software illustrating ZigBee 2.4 GHz demodulation results

Summary of N4010A Wireless Connectivity Test Set & 89601A VSA versus PSA demodulation results

Measurement	PSA	N4010A & 89601A
Offset EVM (%)	6.43	6.2796
RMS EVM (%)	15.7	15.466
Peak EVM (%)	45.50 at sym 832	44.259 at sym 834
RMS mag error (%)	4.04	3.9758
Peak mag error (%)	9.05 at sym 790	9.4387 at sym 792
RMS phase error (º)	12.3	12.118
Peak phase error (º)	−36.17 at sym 832	−35.043 at sym 834
Freq Error (kHz)	46.86	46.915
IQ offset (dB)	−23.28	−23.296
Quadrature skew (º)	−13.10	−13.545
IQ gain imbalance (dB)	−0.71	−0.58
Rho	0.95116	0.94829
RF power (dBm)	−9.54	−9.58

Table 5.

Conclusion

The N4010A Wireless Connectivity Test Set test set quickly ensures standards-compliance design performance for ZigBee RF physical layer testing through use of powerful signal analysis capabilities using the 89601A vector signal analyzer software. The key benefits of the solution presented are as follows:

- Get designs to market quickly

- The only one box test available

- Integrates a calibrated wideband analyzer and source to replace golden radio/node test methodology

- Spend less time on calibration

- Powerful demodulation capability

- Consistent results moving through the test lifecycle

- Ability to test burst signals for more real-life stressing of the device under test

- Extensible measuring tool that can include *Bluetooth* and WLAN formats

- Reduce overall cost of test

- Flexible test environment

For a full suite of systematic transmit and receiver automated measurements, the 89601A Vector Signal Analyzer, the N4010A instrument, DUT control, and DUT packet error rate output must be developed together in a software environment. These elements can then be brought together in a test plan.

89601A COM API allows integration of transmit automated test into a variety of software environments. Using SCPI and .NET driver-based control with the N4010A test set over GPIB, USB 2.0, or TCP-IP LAN permits receiver-automated test development, controlling the N4010A's integrated vector signal generator. Custom designed waveforms, acquiring practical signal capture, and management of stored AWG waveforms extends test possibilities.
Support for existing emerging communication signal formats offers further potential.

This combination of features results in an easier and more understandable approach to ZigBee test software development, addressing the challenges faced in automating key measurements for faster device and design characterization of the IEEE 802.15.4 RF physical layer. This application note has demonstrated how ZigBee developers can tackle the challenges of RF more readily, primarily for R&D and integration stages. This is particularly relevant as the practicalities of RF test have not been fully realized by some ZigBee developers as they contend with the difficulties of higher level protocol. It is also significant for those interested parties anticipating growth and adoption of ZigBee technology. A good base in RF PHY test knowledge and equipment is required in order to understand and draft future plans towards automated production test, similar to what has been seen with other emerging technologies.

References

[1]   IEEE Standard 802.15.4-2003

Appendix A

89601A Programming Pseudo Code

This pseudo code provides guidance on how to obtain measurements. Exact syntax will vary depending on the software environment.

```
/**** declare variables ****/

set pVsaApp = CreateObject("AgtVsaVector.Application");
// creates the object pVsaStat referencing the AgtVsaVector library

set pVsaStat = pVsaApp.Measurement.Status;
// create measurement status

pVsaApp.Visible = VSA_visible;
// good to start off with the VSA visible to configure settings with expected DUT output

/**** setup ****/

// define basic settings
pVsaApp.Measurement.Inputs.InpChannels(1).Range = .316227766016838; pVsaApp.
Measurement.Inputs.Trigger.Channel = 1;
pVsaApp.Measurement.Inputs.Trigger.Style = vsaTrigStyleMagLevel; pVsaApp.
Measurement.Inputs.Trigger.MagLevel = .005;
pVsaApp.Measurement.Frequency.Span = 5000000;
pVsaApp.Measurement.Frequency.ResBW = 100000;
pVsaApp.Measurement.Frequency.Points = 3201;

pVsaApp.Measurement.DemodConfig = vsaMeasDemodCnfDigital;
// digital demod

pVsaApp.Measurement.DigDemod.SetStandard(vsaDigDemStaZigBee2450);
// use ZigBee standard Offset OQPSK

// setup the display if required
pVsaApp.Display.Traces.Layout = vsaTrcLytGrid2x3;
pVsaApp.Display.Traces(3).DataName = "Search Time1";
pVsaApp.Display.Traces(5).Active = True;
pVsaApp.Display.Traces(5).DataName = "IQ Meas Time1";
pVsaApp.Display.Traces(5).Format = vsaTrcFmtEyeI;
pVsaApp.Display.Traces(6).Active = True;
pVsaApp.Display.Traces(6).DataName = "IQ Meas Time1";
pVsaApp.Display.Traces(6).Format = vsaTrcFmtEyeQ;

.
... setup DUT to transmit at appropriate frequency ...
.
```

```
/**** Do measurements ****/

pVsaApp.Measurement.Continuous = False;
// single measurement
pVsaApp.Measurement.Pause();
pVsaStat.PositiveMask = vsaStatusBitMeasDone;
eStat = pVsaStat.PositiveEventSum;
// clear previous events

pVsaApp.Measurement.Start();
// start measurement

if (bitAnd(pVsaStat.PositiveEventSum, saStatusBitMeasDone)==vsaStatusBitMeasDone)
// wait for completion
{
    ...
    Break;
    ...
}

/**** return results ****/

// all results below are obtained after demodulation
EVM = pVsaApp.Display.Traces(4).RawDataDemodInfo(vsaTrcDemInfoEVMRms);
EVM_PEAK = pVsaApp.Display.Traces(4).RawDataDemodInfo(vsaTrcDemInfoEVMPeakRm
s);
OEVM = pVsaApp.Display.Traces(4).RawDataDemodInfo(vsaTrcDemInfoOffsetEVMRms);
OEVM_PEAK = pVsaApp.Display.Traces(4).RawDataDemodInfo(vsaTrcDemInfoOffsetEVMP
eak);
FREQ_ERR = pVsaApp.Display.Traces(4).RawDataDemodInfo(vsaTrcDemInfoFreqErr);

// spectrum dump
SPECTRUM_X = pVsaApp.Display.Traces.Item(2).Data(4, vsaTrcDataX, TRUE);
// get x data for trace;
SPECTRUM_Y = pVsaApp.Display.Traces.Item(2).Data(4, vsaTrcDataY, TRUE);
// get y data for trace;
POWER = pVsaApp.Display.Traces.Item(3).Marker.BandPowerResult;

pVsaApp.Quit();
// dispose of application
```

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