The Basics of ZigBee Transmitter Testing

Overview

ZigBee is a wireless standard for personal area network (PAN) sensor monitoring and control. Learn how National Instruments Alliance Partner SeaSolve has developed a test suite including transmit (Tx), receive (Rx) and compliance testing for ZigBee. In this application note, we will describe test methodologies and techniques for each type of testing.

Introduction to ZigBee

ZigBee, also known as IEEE 802.15.4 is a communications standard designed for low-power short-range communications between wireless devices. It is classified as a Wireless Personal Area Network (WiPAN), a term which includes the Bluetooth (IEEE 802.15.3) standard as well.

The ZigBee standard has seen increasing interest from both commercial and military customers for applications such as wireless sensor networks, home automation, and industrial control. One interesting facet of the ZigBee standard is that it is designed such that devices can form a self-forming and self-healing ad hoc or mesh networks. In this scenario, a central ‘PAN coordinator’ device oversees the health of the network configuration. In recent years, sensor networks have been the subject of much research in military / battlefield applications as well. Thus, there is significant interest in using the ZigBee standard to define the communications links in ad hoc battlefield intelligence scenarios.

One design decision of the ZigBee specification that makes it ideal for remote wireless sensors is the implementation of a low power physical (PHY) physical layer. As an overview, the physical layer specifications allow ZigBee devices to operate at one of three bands: 868 MHz (Europe), 915 MHz (North America), and 2.4 GHz (worldwide). The 2.4 GHz band, in which ZigBee transceivers are most commonly deployed, uses the OQPSK (Offset Quadrature Phase Shift Keyed) modulation stream. This scheme is a derivation of traditional QPSK and is used because it requires less power than similar schemes, while achieving the same or better throughput. OQPSK uses a maximum phase transition of 90 degrees from one symbol to the next. This prevents symbol overshoot and requires slightly less transmission power than the traditional QPSK modulations scheme. This design decision, combined with the use of a 5 MHz channel bandwidth enables devices to achieve a data rate of up to 250 kb/sec in a reasonably power-efficient manner.

Because ZigBee transceivers are designed for low-power applications, the physical layer is relatively tolerant to significant error. In fact, devices are able to tolerate an EVM of up to 35% while maintaining reasonable BER (bit error rate) performance. Thus, design validation and product request requires a variety of test methodologies. In the following sections, we will explain why specific tests much be conducted and provide tips to enable the most accurate testing methodologies.

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As an overview, we will divide our discussion into three parts. These include:

- Transmitter Testing with a Vector Signal Analyzer (VSG)
- Receiver Testing with a Vector Signal Generator (VSA)
- Automated Compliance Testing (ACT) with both VSA and VSG

ZigBee Transmitter Testing

When testing a ZigBee transceiver’s Tx signal quality, a vector signal analyzer must be used in order to characterize both spectrum information and modulated signal quality. One solution is to use the SeaSolve's WiPAN LVSA Signal Analysis toolset along with a PXI-5660 vector signal analyzer. Using this software package, we are able to perform both spectrum and modulation measurements on IEEE 802.15.4 compliant signals. It is important to remember that both measurement types are a requirement for both design validation and production test. As an overview, the spectral emissions of a ZigBee transmitter will dictate its interoperability with other devices in the ISM (industrial, scientific, and medical) band. In addition, the modulation quality of the Tx signal, combined with the antenna performance, dictates the range of distance over which the device can reliably perform. A typical test configuration is shown in the diagram below.

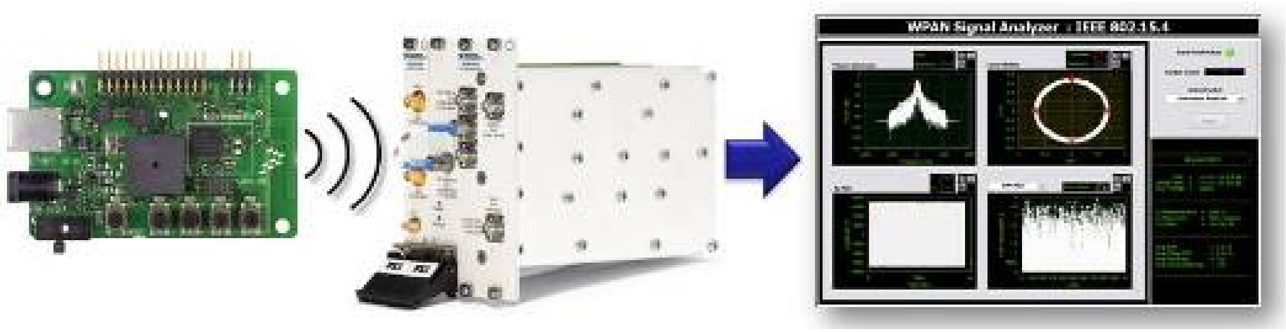

Figure 1: Typical transmitter is tested through either direct connection or air interface

The most common spectral measurements performed include: power spectral density, occupied bandwidth, power in upper/lower bands, and total power in band. In addition, typical modulation analysis tools include the: constellation plot, eye diagram, CCDF (complementary cumulative distribution function curve), and returned bitstream. Typical modulation measurements are: EVM (error vector magnitude), frequency offset, and BER (bit error rate). Note that various stages of product development will require different measurements and/or analysis. For example, the design validation and verification stage of development requires more intensive analysis tools such as a constellation plot to debug various issues in product design. On the other hand, production test requires more definitive measurements such as EVM and frequency offset such that performance can be compared to test limits.

ZigBee Tx Spectrum Analysis

Below, we describe each of the basic frequency domain measurements and explain their importance. Note that each of the following measurements can be made with either a spectrum analyzer or vector signal analyzer. In general, a vector signal analyzer is the recommended instrument because it can be used for modulation measurements (next section) as well.

Power Spectral Density (PSD)

Power spectral density (PSD) is a measurement that describes how the power of a given packet of data is spread over a broad frequency range. This measurement is used to ensure that the transmitter operates within the spectral mask requirements of the IEEE 802.15.4 standard. As figure 2 illustrates, a frequency mask is compared with the output power. The frequency mask, shown as the white line, represents the limit of power that transmitter is allowed to emit into adjacent bands. When troubleshooting a device, factors such as poor filter design or images resulting from amplifier compression can contribute to unwanted power in adjacent frequency bands.

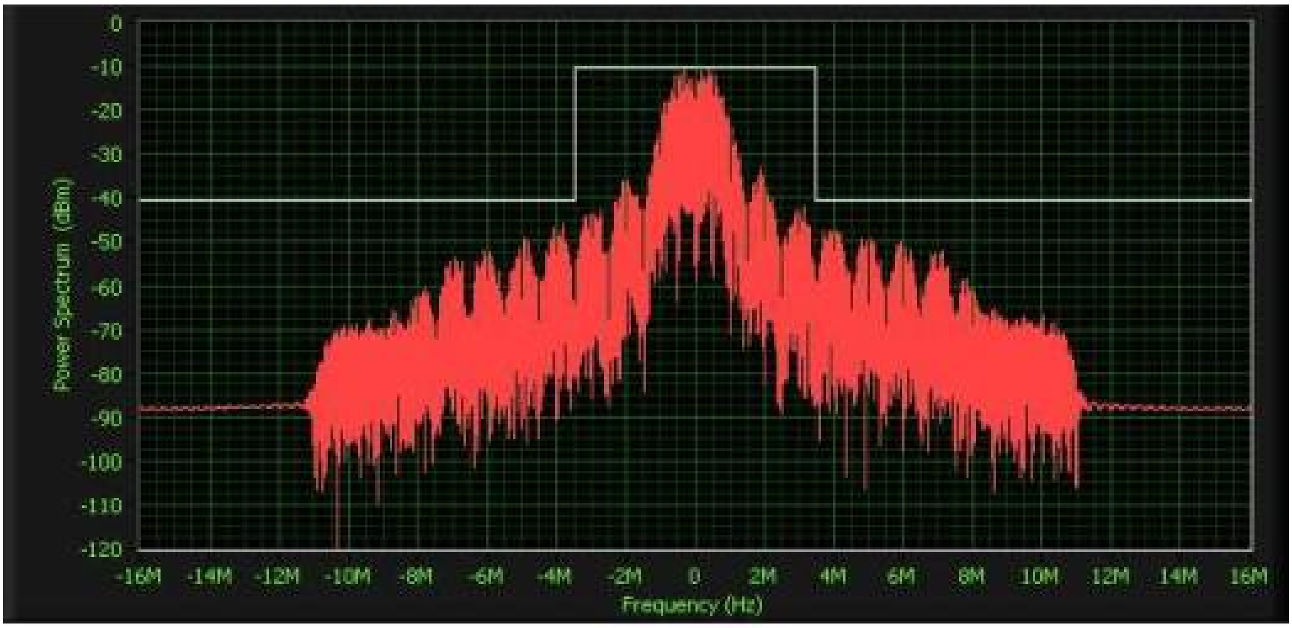

Figure 2. Plot of Power Spectral Density

Power in Band

The power in band measurement calculates the integrated power (dBm) in the specified channel or band. This measurement is used to ensure that the transmitter does not exceed power specifications of the IEEE 802.15.2 standard.

Occupied bandwidth

Occupied Bandwidth returns the bandwidth of the specified frequency band that contains 99% percent of the total power of the span.

Adjacent Channel Power

Adjacent Channel Power measurement comprises of Power in the upper and lower bands. According to IEEE 802.15.4, upper band is 5MHz towards the right of the operating frequency and the lower band is 5MHz towards the left of the operating frequency.

Baseband Measurements

Baseband parametric measurements are used to ensure that the ZigBee transmit packets will be able to be successfully decoded by the receiver. Because ZigBee transceivers are designed to operate at low-power and do not require high data throughput, modulation quality is often sacrificed to reduce power consumption. Overall, the purpose of measuring quality is to evaluate the likelihood of bit errors. As an example, we estimate BER as a function of EVM (%), shown in the figure below.

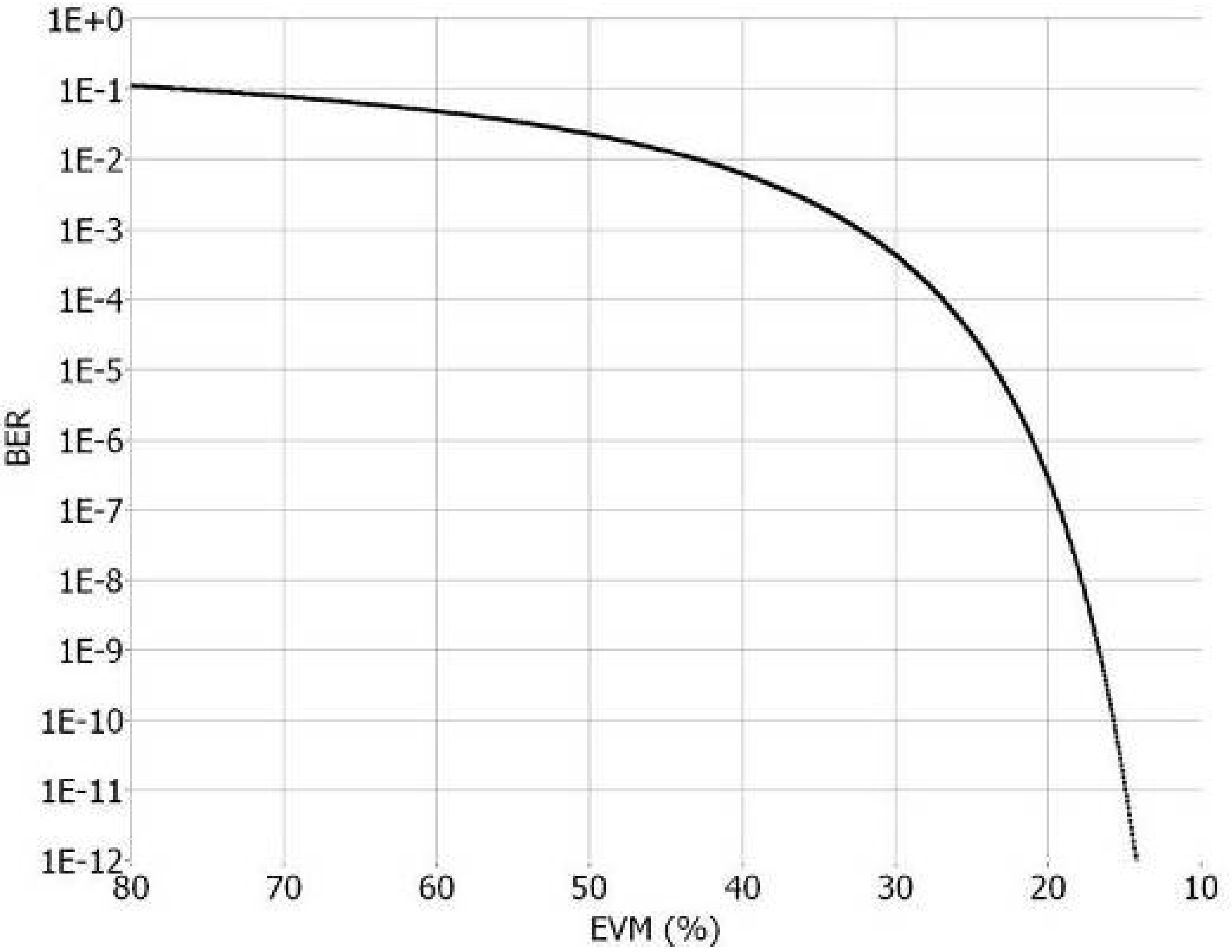

Figure 3. BER vs. EVM for a QPSK Modulated Transmission

As the graph shows, BER increased dramatically when the EVM of a QPSK transceiver increases from 15% to 30%. By contrast, most ZigBee devices are required to operate at an EVM that is below 35%. Thus, it is important to measure modulation accuracy to validate that a transceiver will operate effectively in its deployment environment. This can be done with several plots and measurements, shown below.

Error Vector Magnitude (EVM)

EVM enables you to capture various problems and impairments, such as LO (Local Oscillator) stability, IF filter, compression, symbol rate and interfering tones. By measuring EVM, the linearity and efficiency can be verified. During analysis, the user can check whether EVM always falls below the standard-specified reference of 35% which ensures good demodulation of the transmitted signals. Typically, EVM is measured both on per symbol basis, and as an RMS EVM% measurement, which captures the average EVM for the entire packet. An example of a per symbol EVM measurement is illustrated in the figure below:

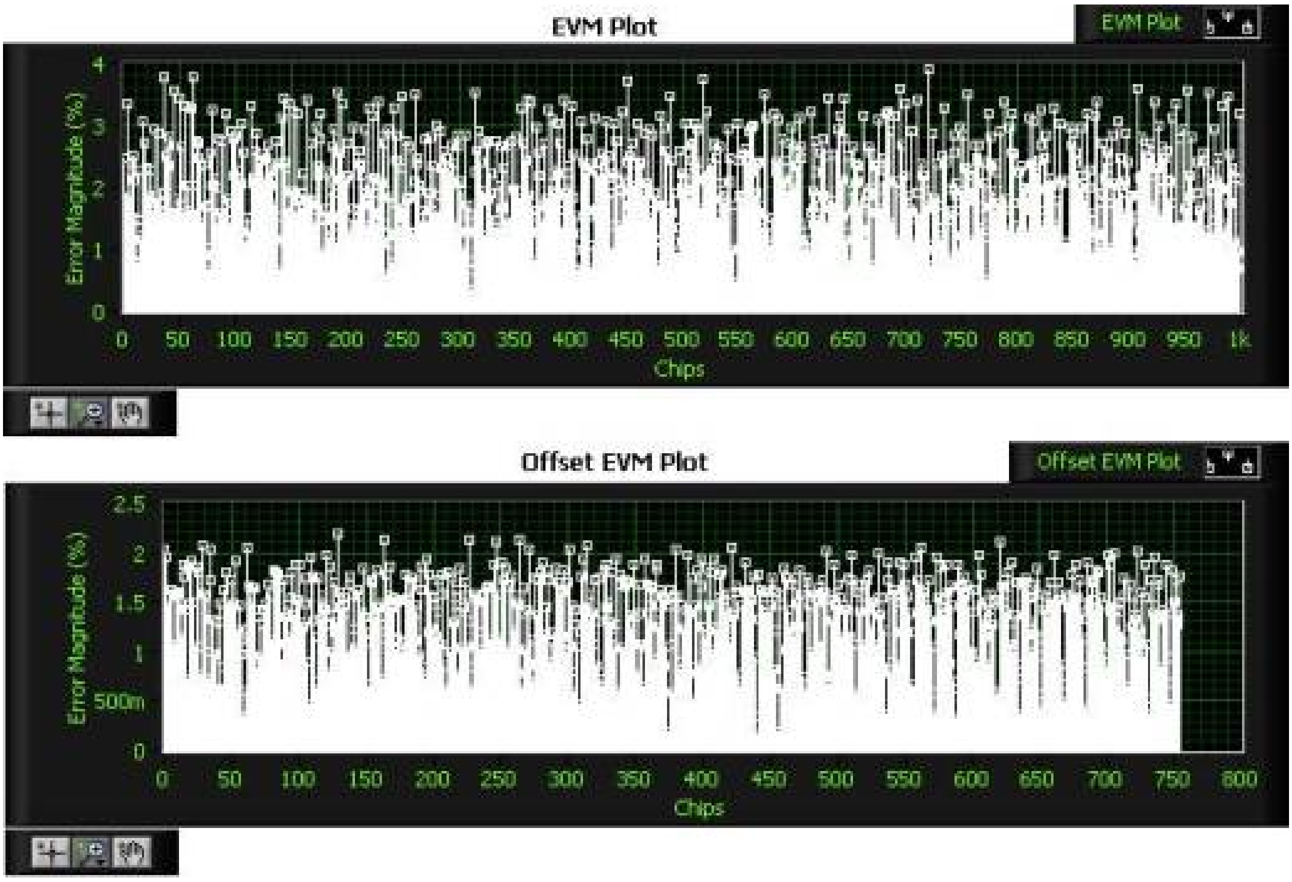

Figure 4. EVM per symbol for transmitted ZigBee packet.

Constellation Plot

The constellation plot provides a graphic representation of the demodulated baseband waveform. This diagram is one of the most valuable during the design validation stage because it can be used to identify problems such as IQ gain imbalance, DC offset, quadrature skew, and other impairments. Unlike the EVM measurement, which provides a simple numeric value, the constellation plot also provides a visual representation of the source of error as well. In this plot, shown below, recovered symbols are shown in red and symbol transitions are shown in white.

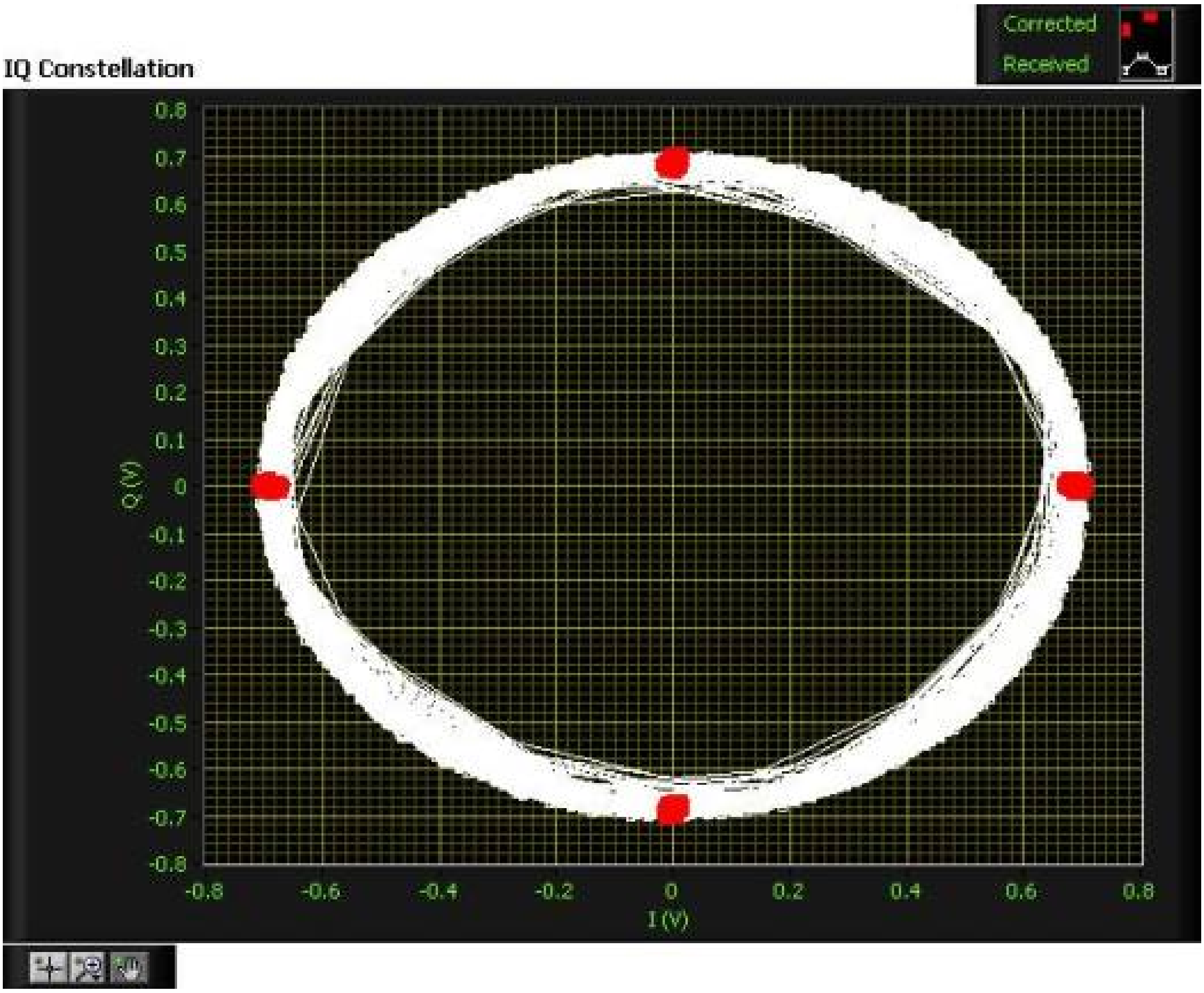

Figure 5. Constellation plot of a ZigBee transmit signal.

On a constellation plot, we observe that all of the transitions (shown in white) occur on the parameter of the diagram, and not through the center. This is a facet of the OQPSK modulation scheme, which requires less power than the traditional QPSK scheme.

While EVM provides a specific mechanism of quantifying impairments, the size and shape of the constellation plot provides us with a visible indication of the type of impairment that is present. To illustrate this, the diagram below shows the constellation plot of an impaired Tx signal.

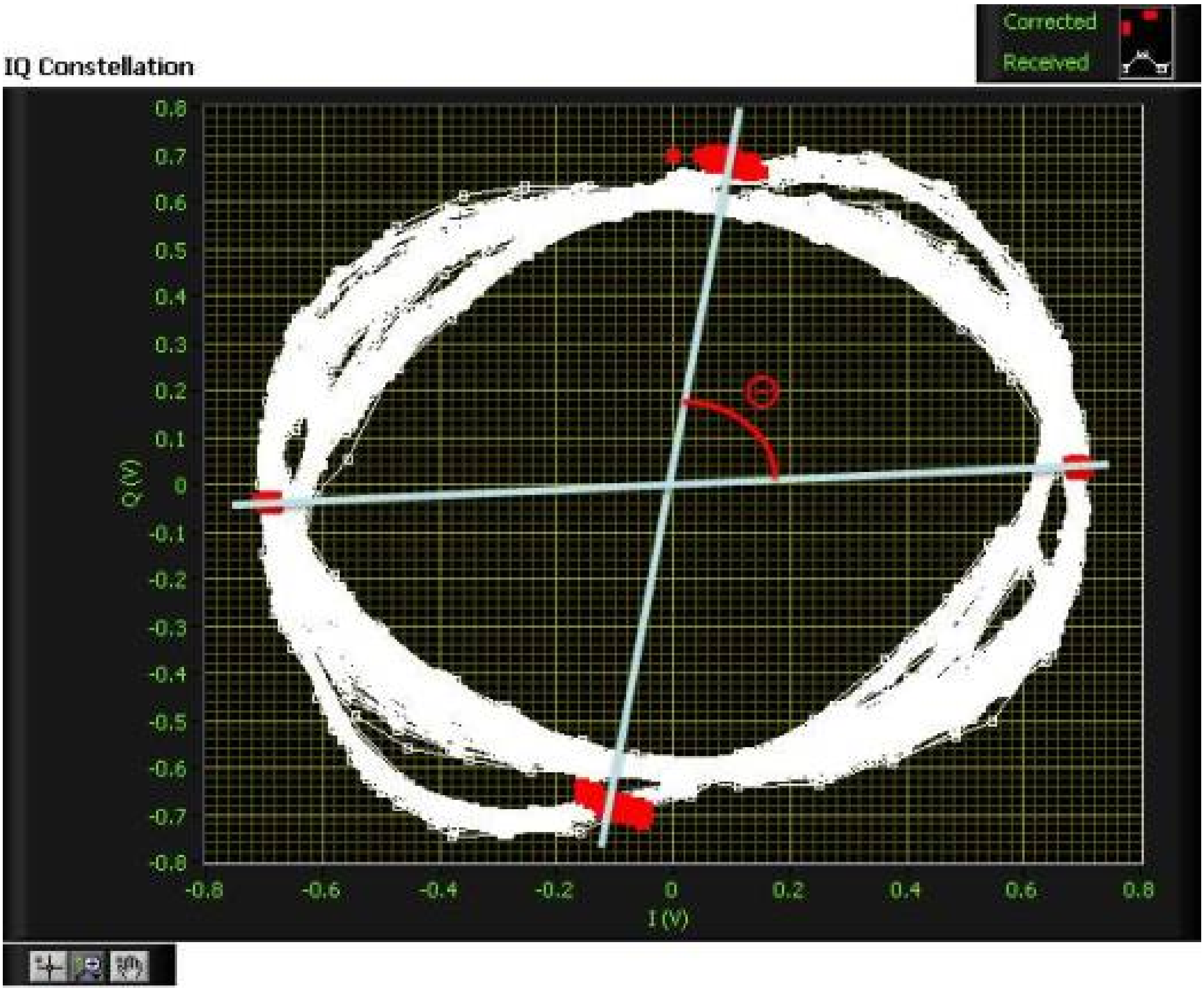

Figure 6. Constellation plot of ZigBee Tx with impairments.

In figure 6, we can determine the type of impairment that has been added by observing basic characteristics of the constellation plot. First, we note that the plot has been slightly stretched in a clockwise manner (ie. the angle Θ is less than 90 degrees). From this characteristic, we can are able to determine that the impairment that has been added is quadrature skew. In other words, the in-phase and quadrature-phase components of the LO (local oscillator) are not precisely 90 degrees out of phase. While EVM enables you to capture various impairments with a numeric value, the constellation plot enables you to identify the source of error as well.

Eye Diagram

The eye diagram also reveals the modulation characteristics of a Tx signal. In contrast with the constellation plot, it provides a time domain view of the signal and can be used to visualize shaping or channel distortions. Using this measurement, designers can decide on the optimum sampling point / decision for decoding the data. During analysis, the user can check for the maximum Eye openings in the signal after offset removal (OQPSK -> QPSK) to validate demodulation properties.

Data Bits

One of the most common metrics to quantify receiver performance is to measure BER (bit error rate). Because low EVM results in errors occurring infrequently, this measurement can be quite time consuming, depending on the modulation quality. As a result, extended BER tests are most commonly performed during the design validation phase. In production test, a much shorter BER test is used. BER measurements can be made by returning the decoded raw data is a presented as a stream of 1s and 0s. When these values are compared with a known transmission, BER can be calculated.

CCDF

Complementary Cumulative Distribution Function (CCDF) is used to analyze the power characteristics of a signal. As we discussed earlier, the ZigBee specification defines the use of the OQPSK modulation scheme to minimize power requirements. Thus, in the ideal case, the power efficiency of the transmitter is maximized when the Tx power is constant. The CCDF curve shown below, can be used to verify that power fluctuations do not occur. This is illustrated in the figure below.

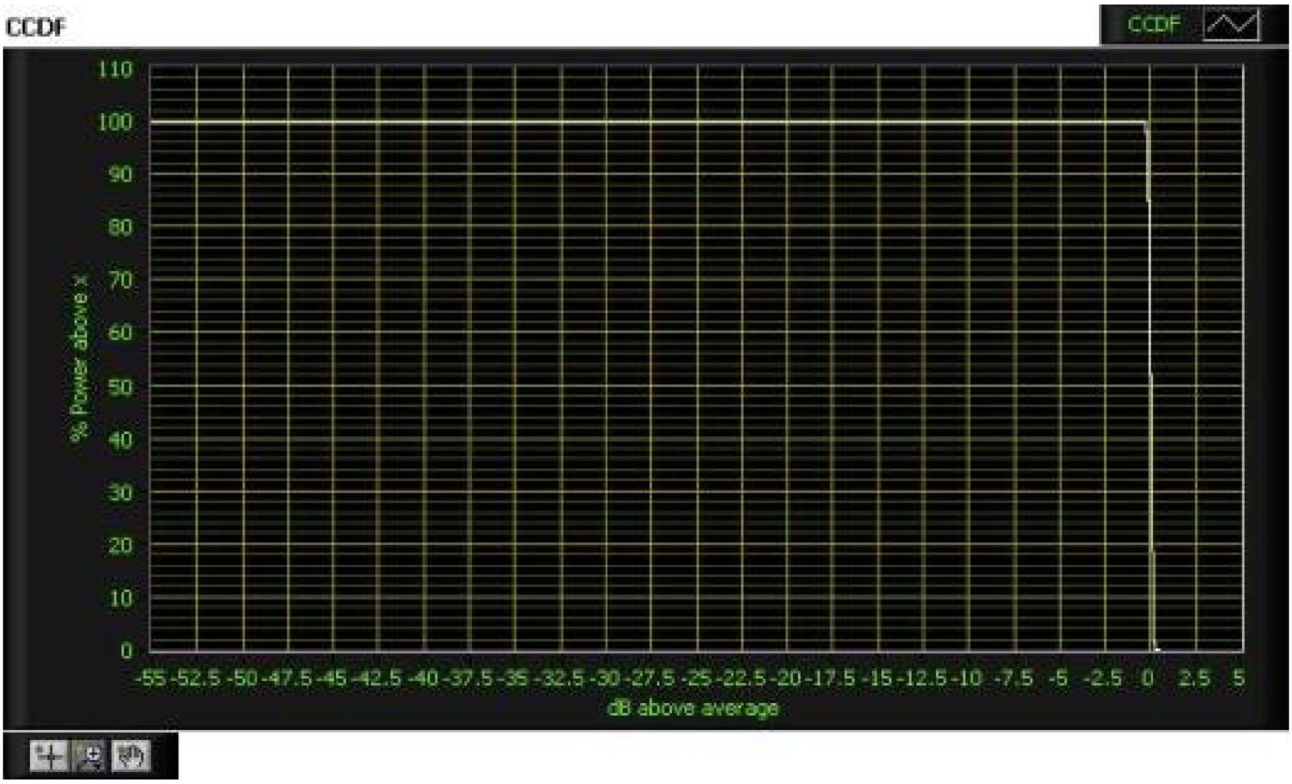

Figure 7. Complimentary cumulative distribution function or Tx packet.

As the figure illustrates, a CCDF curve can be used to represent the percentage of power above the average power. In the ideal case, the right edge of the CCDF curve is perfectly vertical. In this scenario, a power amplifier can maintain the highest power efficiency without being driven into saturation.

ZigBee Receiver Testing

The requirements for testing a ZigBee receiver can generally be broken into two requirements: MAC layer emulation and impairments testing at the physical layer (PHY). The first type, MAC layer emulation, can be used to ensure that the ZigBee receiver is able to respond appropriately to the generated commands. With the second type, impairments testing, a receiver is tested by intentionally reducing the modulation quality of the test stimulus. Both types of testing can be implementing using SeaSolve's WiPAN LVSG signal generation solution combined with a PXI vector signal generator. This is illustrated in the figure below.

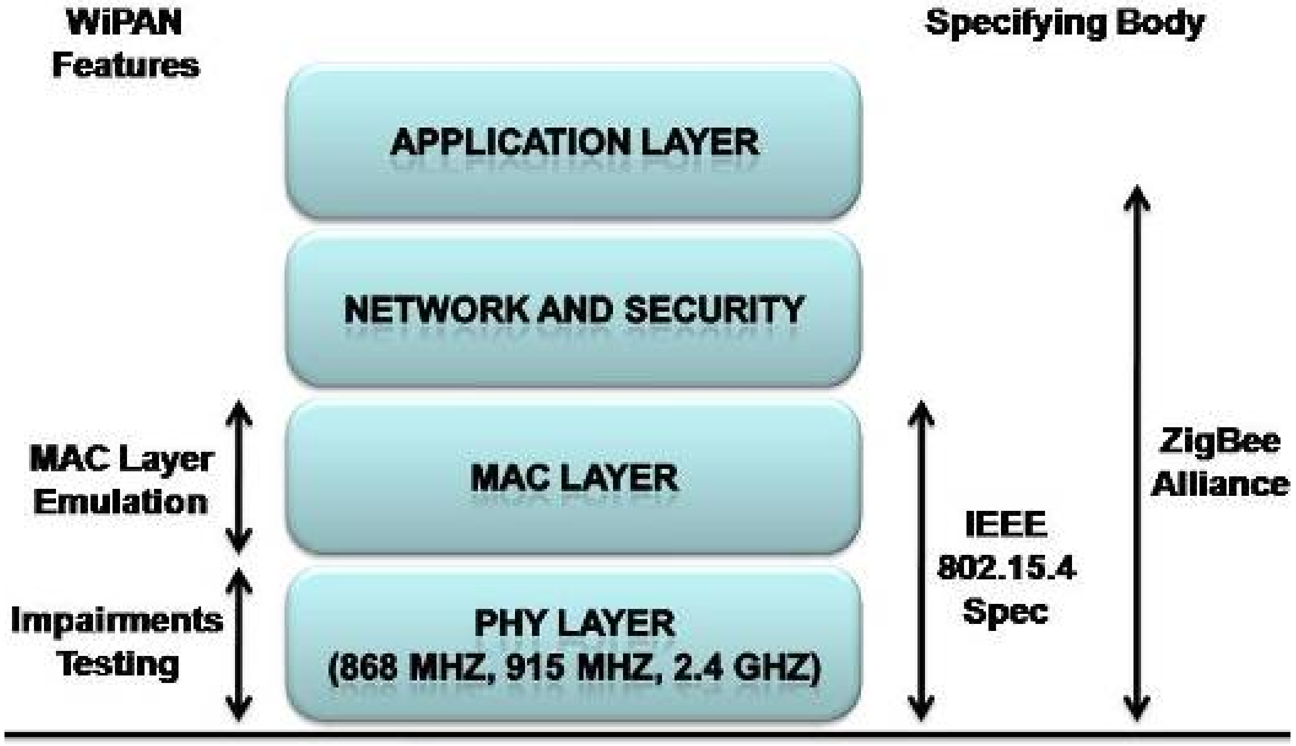

Figure 8. WiPAN mapping on ZigBee protocol stack

In the figure above, we have illustrated that the IEEE 802.15.4 standard defines the MAC and PHY layers of a ZigBee transmissions. Typical test procedures involve both MAC layer emulation through packet generation and PHY layer testing by adding impairments.

ZigBee Frame Types

The MAC (Media Access Control) layer of a ZigBee transmission defines the basic packet and frame structures. The IEEE 802.15.4 specification defines four basic frame structures that can be used for receiver test. These frame types include:

- A beacon frame is used by a coordinator to transmit beacons. The beacon packet enables a node to identify the presence of other nearby
- A data frame, is used for all transfers of data payloads
- An acknowledgment frame is used for confirmation of a successful frame reception
- A MAC command frame is used to handle MAC peer-entity control transfers

The MAC command frame is the most flexible. Thus, receiver testing also involves selection of specific sub-frames, listed by type, below:

1. Association request – is a request for association with a PAN coordinator.
2. Association response – is a reply from coordinator with association status (possibilities include: Association Successful, PAN at capacity, Access denied)
3. Disassociation notification – is used by device or coordinator to inform other nodes about disassociation.
4. Data request – is used to request data from a coordinator.
5. PAN ID conflict notification – is transmitted when a PAN identifier conflict is detected
6. Orphan notification- is used by an associated device that has lost synchronization with its coordinator
7. Beacon request – is used for synchronization and to transmit superframe information
8. Coordinator realignment – is used by the coordinator to reply to an orphan notification command. It is also used when PAN attributes change with the logical channel information. It can be transmitted to the whole PAN or to a single orphan device.
9. GTS request – is used by an associated device to request the allocation of a new guaranteed time slot (GTS) or to request the deallocation of an existing GTS from the PAN coordinator. It also defines the GTS fields such as length, direction, and type.

MAC Frame fields configuration

In addition, MAC frame fields can be configured as well. Common fields include: Frame type, Encryption, Acknowledgement, Frame pending, Inter/Intra PAN, Addressing fields, destination and source addressing modes, sequence number, Destination PAN identifier, Destination MAC address, Source PAN identifier, and Source MAC address.

Generator Impairments

Because tradeoffs must frequently be made between performance, power, and cost, it is common for ZigBee transceivers to operate with a relatively low modulation quality. Thus, testing a ZigBee receiver offers unique challenges to the test engineer. When performing tests, the worst-case environment must be simulated in the lab to ensure that transceiver meets performance specifications and complies with the IEEE 802.15.4 standard. The WiPAN LVSG software enables users to test for interoperability by applying various impairments to model imperfect transmissions and challenges of the physical channel. The specific impairments that can be added include: memoryless nonlinearity, AWGN, frequency offset, DC offset, I/Q gain imbalance, quadrature skew, and phase noise.

Memoryless Nonlinearity

Components such as a power amplifier are inherently nonlinear and introduce distortion into an transmission signal. Generally, non-linearity is particularly problematic to modulated signals because of their constant fluctuations in amplitude. Fortunately, ZigBee devices use an OQPSK modulation scheme that is less susceptible to distortion than most modulation schemes. However, because of power requirements, ZigBee transceivers are often designed such that the power amplifier is driven almost into saturation. To illustrate this concept, we show a basic simulated model of a power amplifier in the figure below.

Figure 9. Saturation of a non-ideal power amplifier

As a power amplifier approaches the point of saturation, significant distortion is often introduced to the Tx signal. Thus, receiver validation requires us to simulate this characteristic of a ZigBee transceiver.

AWGN (Additive White Gaussian Noise)

Additive white Gaussian noise is the most common mechanism for simulating the signal-to-noise ratio (SNR) of a Tx signal. The affect reducing SNR is that instantaneous phase and amplitude uncertainty is applied. This is most commonly observed on a constellation plot, where we can observe that AWGN causes symbol spreading. This is illustrated in the figure below.

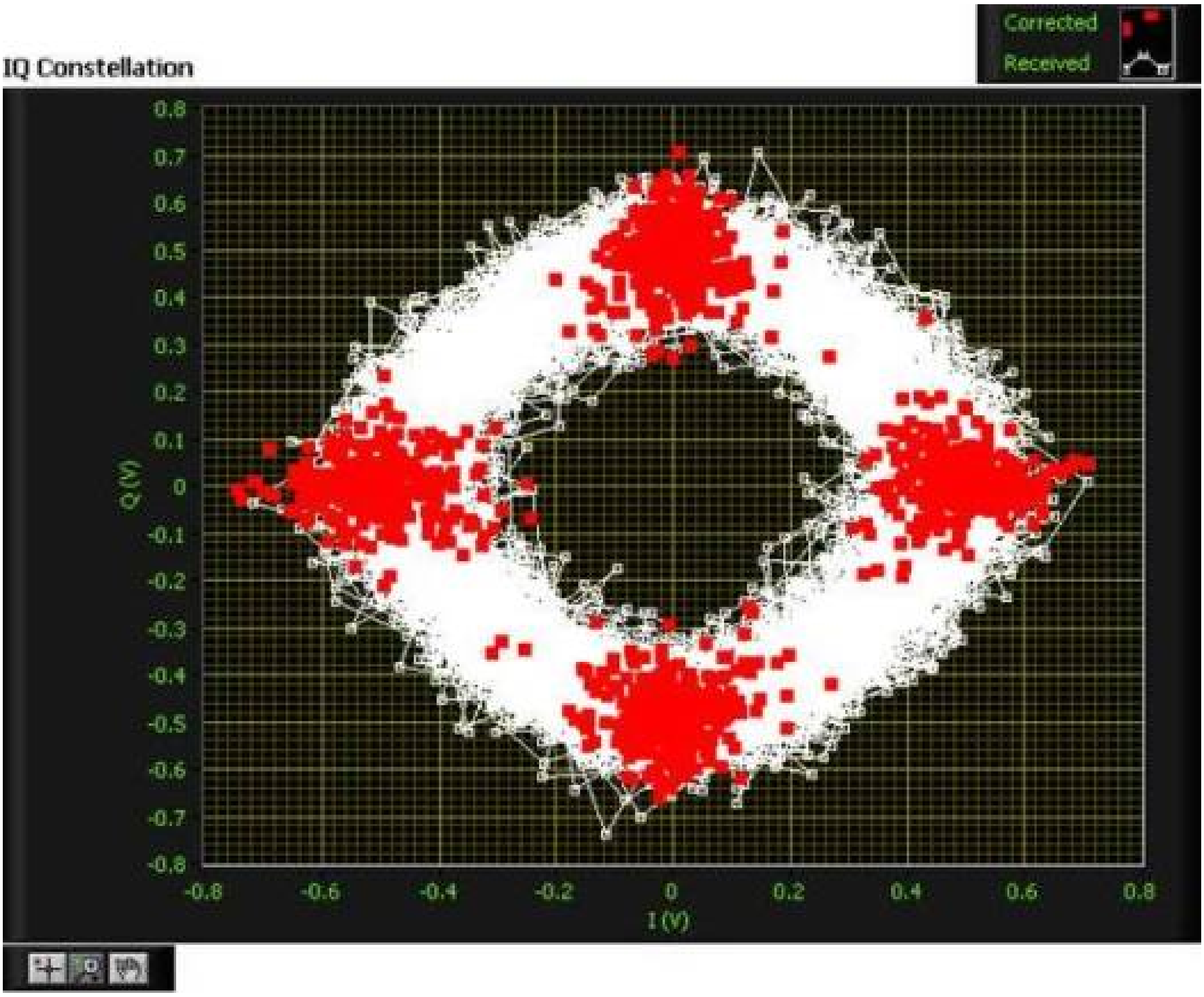

Figure 10. ZigBee transmission with 25 dB Eb/N0.

Because SNR deteriorates with transmit distance, ZigBee transmissions over a longer distance will result in reduced EVM at the receiver. As illustrated in figure 3, a higher EVM will increase the probability of bit errors and reduce system performance as a whole.

Frequency Offset

Frequency offset occurs when the Tx and Rx local oscillators of two different devices operate at slightly different frequencies. The effect of frequency offset on an RF signal is that it produces a slight carrier offset in the baseband waveform. Typically, small carrier offsets in the baseband waveform can be removed through signal processing algorithms. Thus, this characteristic is often tested during the design validation phase by applying a slight carrier offset to the test stimulus. If not removed appropriately, frequency offset will prevent the receiver from achieving carrier lock with the transmit signal.

DC Offset

DC offset is most problematic at the baseband I and Q outputs of a ZigBee transmitter. This impairment can significantly affect the quality of a modulated signal by causing carrier leakage. This increases a receiver’s EVM as well as the likelihood of a bit error. To ensure that a receiver is capable of handling DC offset appropriately, this impairment is often applied during the design validation phase.

I/Q gain imbalance

I/Q gain imbalance is a type of baseband impairment that affects the quality of a modulated signal. Visually, we can observe gain imbalance on a constellation plot. As we observe in the figure below, I/Q gain imbalance stretches the constellation plot in either a vertical or horizontal manner.

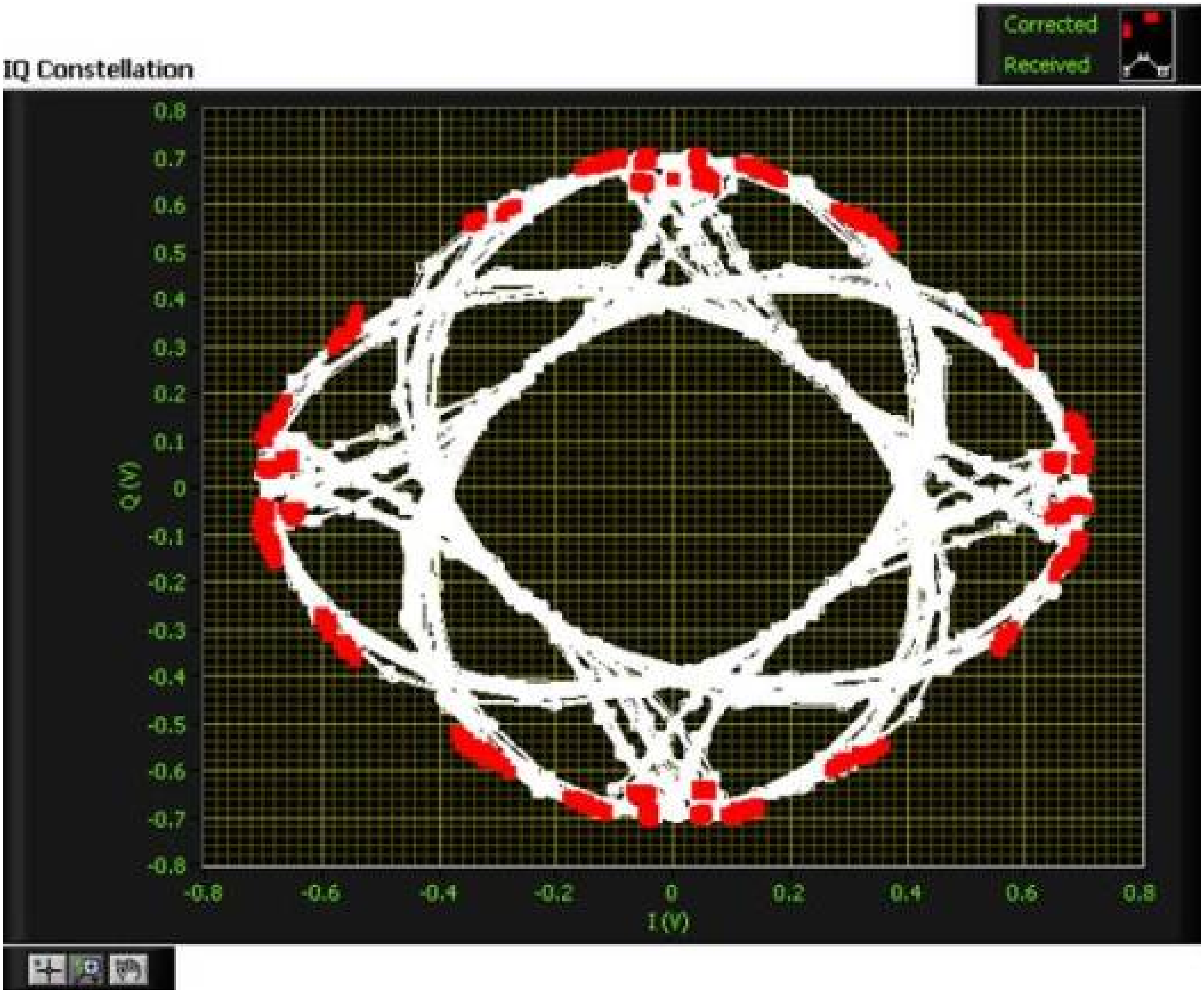

Figure 11. Constellation plot with 6 dB periodic gain imbalance.

As the figure above illustrates, gain imbalance has been added in a periodic manner, which periodically stretches the constellation plot in both the horizontal and vertical axis. In figure 11, the gain has been configured to vary by as much as 6 dB over time. Gain imbalance can be problematic in systems implementing direct upconversion to RF. It is caused by amplitude disparity between I and Q outputs of the baseband subsystem and increases the EVM observed by the receiver.

Quadrature skew

Quadrature skew is caused by non-exact of the quadrature-phase LO. In an ideal direct upconversion system, the in-phase and quadrature-phase LO components are exactly 90 degrees out of phase. However, slight deviations from the ideal value can affect the phase and amplitude of demodulated baseband waveforms. This affect is best illustrated in Figure 6 with a constellation plot. As the plot illustrates, returned symbols are slightly skewed their ideal positions, resulting in an increased EVM.

Phase noise

Phase noise is another impairment caused by imperfections of the local oscillator. At a high level, we can think of phase noise as instantaneous jitter of a sinusoid. In the frequency domain, this jitter causes a "spreading" of the carrier and produces power at frequencies that are offset from the desired center frequency. This is illustrated in the figure below.

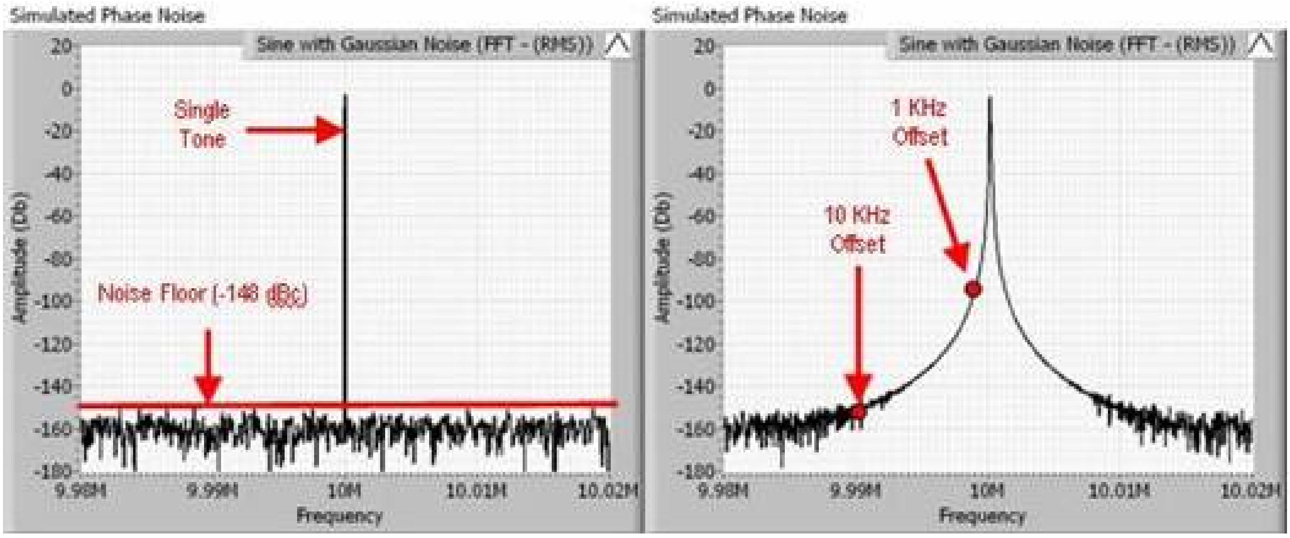

Figure 12. Phase noise spreads the power of a LO across adjacent frequencies

As figure 12 illustrates, phase noise is typically measured by the level of power at various frequency offset from the carrier. While phase noise can be specified at a variety of frequency offsets, the 10 KHz offset is the most common metric of comparison between components.

By introducing jitter to the time domain of a modulated signal, phase noise introduces slight phase uncertainty to a demodulated baseband waveform. On a constellation plot, phase noise can be observed by noticing the spreading of symbols along the parameter of the constellation plot.

ZigBee Automated Compliance Testing

So far, we have discussed individual measurements and impairments that can be used to characterize the performance of the transmit or receive chain of a ZigBee device. However, ZigBee devices are capable of both transmit and receive (transceiver) functionality. Thus production test of ZigBee transceivers requires testing of both capabilities in parallel. Seasolve's Automated Compliance Testing provides a sequence of Tx and Rx tests to quickly characterize a DUT's compliance and performance in accordance with the IEEE

802.15.4 standard. This software executes many of tests described above and produces a detailed report of the test results.

The tests provided are optimized for speed to reduce test time and are verified for their accuracy with various RF Chipsets from leading manufacturers. While we will not describe each test in detail in this section, the common test parameters include each of the following:

- PLL Frequency Test
- TX Gain Test
- Spurious Emission Test
- Phase Noise Test
- IQ Measurements
- Power Spectral Density
- Carrier Suppression Test
- LO Leakage
- PER and BER Tests
- Adjacent/Alternate Channel Rejections
- Maximum Input Power Test

Conclusion

While the ZigBee standard provides an excellent mechanism for low-power communications in mesh and ad hoc networks, it also produces significant test challenges. Fortunately, Seasolve's WiPAN LVSA, LVSG, and ACT software combined with PXI instrumentation provides a highly flexible solution to this challenge. With the appropriate software and hardware, a variety of Tx and Rx measurements can be made to ensure that ZigBee devices are fully complicate with the IEEE 802.15.4 standard and interoperable with other devices.