AN700.0: Manufacturing Test Guidelines for the EM35x

Most customers have standard product manufacturing test flows, but some do not incorporate RF testing. Document *AN718: Manufacturing Test Overview* provides a high-level overview of the product tests flow and phases – prototype testing, characterization testing, low-volume manufacturing, and high-volume manufacturing. This document's goal is to provide the finer details of these test phases and Silicon Labs' recommended best practices for manufacturing test. It is intended for Silicon Labs customers developing for the EM35x and who are moving from the early prototype development stage to the manufacturing production environment.

This application note applies to stack releases EmberZNet PRO 4.0 and later. It does not apply to the EFR32™ portfolio. See *AN700.1: Manufacturing Test Guidelines for the EFR32* for more information about those products.

KEY POINTS

- Test flow
- Test definitions
- Test recommendations
- Test architecture and equipment
- Embedded software tools
- Appendices with test specifics

1. Introduction

Most customers have standard product manufacturing test flows, but some do not incorporate RF testing. This document details the different options for integrating RF testing and characterization into your standard test flows. Document *AN718: Manufacturing Test Overview*, provides a high-level overview of the product tests flow and phases – prototype testing, characterization testing, low-volume manufacturing, and high-volume manufacturing. This document's goal is to provide the finer details of these test phases and Silicon Labs' recommended best practices for manufacturing test. Due to the various options available during prototype testing, this document focuses on the characterization and manufacturing test phases.

Device programming is not discussed in this application note. For information on the programming options available for EM35x devices, refer to document *AN717: Programming Options for EM35x*.

If after reading this document you have questions or require assistance with the procedures described, contact a support representative at www.silabs.com/zigbee-support.

2. Test Definitions

To communicate with the device under test (DUT) and control various device test modes by automated test software, Silicon Labs provides embedded software applications to allow for both serial communication as well as Over the Air (OTA) communication to automated test software. Both of these interfaces enable configuring an Ember device for receive or transmit modes, turning on peripherals (if applicable), reading Analog to Digital Conversion (ADC) pins on the micro (if applicable), putting the radio and/or microprocessor to sleep, and similar control functions. See section 5. Embedded Software Tools for a description of the NodeTest standalone test application, referred to throughout this document.

The tests can be divided into different types of tests— RF testing, DC testing, and peripheral testing.

- RF testing is any test specific to the operation and functionality of the radio (for example, transmitting and receiving ZigBee packets).
- DC testing is any test related to the voltage and current characteristics of the device or board (for example, active and sleep currents).
- Peripheral testing is any test not specific to RF or DC, like a sensor or an external crystal.

The following sections describe the tests that make up the potential suite of DUT testing.

2.1 Serial Communication Test

The Serial Communication Test verifies valid serial communication with the DUT before testing. This is a basic check that the device has been programmed correctly. If no communication is present, the DUT fails this test and does not proceed with further testing. This test is important because if there is no serial communication with the DUT, there is no way to interface with the DUT to put the device into test mode.

2.2 Channel Calibration Test

When a device is powered up for the first time and selects a channel, a calibration is automatically run to properly configure the device for operation. This calibration occurs the first time each channel is selected, as well as any time there is a change in temperature large enough to trigger recalibration.

Note: The HAL in the embedded software controls the calibration.

Silicon Labs recommends that customers select each channel so that the calibration is guaranteed to run before any functional testing. Silicon Labs also recommends that the calibration data values be stored in a data log or compared against a known range of valid values as a way of initially determining if there are any problems with the device or board. A check for valid calibration data can be a good initial test that the device is soldered down properly before any other functional checks.

The channel calibration data is stored within the token system as CAL_DATA (, 0xd245 for the EM35x as of EmberZNet PRO 4.5, 0xd243 for earlier releases). The calibration token is 64 bytes long, 4 bytes per channel.

Note: The channel calibration data storage has changed over time and is therefore different when comparing EmberZNet PRO stack releases. Please see 7. Appendix A – Channel Calibration Data Storage Information for byte configurations and acceptable value ranges for various EmberZNet PRO stack releases.

The byte configuration for EM35x devices for stack releases of EmberZNet PRO 4.5 and later is as follows:

- byte 0: LNA Temperature at Calibration time; Reset=0x7f, Minimum=0xd8 (-40ºC), Maximum=0x55 (+85ºC) (8-bit signed)
- byte 1: Modulation DAC; Reset=0x80, Minimum=0, Maximum=0x7f (7 bit)
- byte 2: Modulation DAC Temperature at Calibration Time; Reset=0x7f, Minimum=0xd8 (-40ºC), Maximum=0x55 (+85ºC) (8-bit signed)
- byte 3: Low Noise Amp; Reset=0x80, Minimum=0, Maximum=0x3e (6 bit, LSB always 0)

For example, for the Modulation DAC (byte 1) anything above 0x7f for EM35x is invalid with the exception of 0x80, which indicates that the channel has not yet been calibrated.

Any values equal to 0 or greater than or equal to the maximum value indicate a problem, so the acceptable ranges are as follows:

EM35x for stack releases of EmberZNet PRO 4.5 and later:

- bytes 0,4,8,...,60: values 0xd8-0x55 are good, 0x7f is uncalibrated
- bytes 1,5,9,...,61: values 0x01-0x7e are good, 0x80 is uncalibrated
- bytes 2,6,10,...,62: values 0xd8-0x55 are good, 0x7f is uncalibrated
- bytes 3,7,11,...,63: values 0x01-0x3d are good, 0x80 is uncalibrated

8. Appendix B – Example Test Data presents an example of expected calibration data distribution across a sample of boards. The data was collected for the now-obsolete EM2xx devices, but is equally applicable to the EM35x.

Note: When programming a device for test or retest of a DUT, use the --erase option to ensure that all previous calibration data is erased. Silicon Labs recommends erasing the flash contents of a device before testing to ensure the calibration is executed at the time the device is tested.

2.3 Supply Current Test

The Supply Current Test verifies that current consumption is valid for each mode of operation for the DUT. The modes of operation are set through the serial interface and include transmit mode (multiple power levels, normal mode, and boost mode), receive mode (normal mode and boost mode), and sleep modes (radio sleep and deep sleep). If there is excessive current draw, the DUT fails this test and does not proceed with further testing. This test is especially important for devices that will be used in battery-operated applications, as these measurements are an effective predictor of battery life.

For measuring sleep mode current draw, a multi-meter is required with the ability to measure less than 1 μA.

2.4 Quick Verify of Transmit and Receive Test

The Quick Verify of Transmit and Receive Test quickly verifies that the DUT transmits valid packets to the Reference Node and receives valid packets from the signal generator. This can be tested on any single channel in the available frequency band. If either of these checks fails, the DUT fails this test and does not proceed with further testing. This test identifies hardware that does not require full characterization testing due to a major manufacturing defect.

2.5 Transmit Power Test

The Transmit Power Test verifies that the power level of the transmitter is at the appropriate level and within a specified range. The power output is measured with the power meter at multiple power levels and in both normal and boost modes to confirm power output accuracy at various coded settings. The serial command interface can include a function that enables continuous waveform (CW) or unmodulated tone to be transmitted for ease of measuring these power levels. Silicon Labs recommends that this test be performed over a subset of the frequency band to record trends in power output versus frequency.

The transmit power output can be measured with a spectrum analyzer or a power meter.

2.6 Transmit Frequency Test

The Transmit Frequency Test verifies the crystal accuracy and valid transmission frequency of the DUT. The CW tone is again used for this transmission. Silicon Labs recommends that this test be performed over a subset of the frequency band to record trends versus frequency.

The transmit frequency can be measured with a spectrum analyzer or a frequency counter. The measured frequency will differ depending on the channel selected. When measuring frequency offset versus channel, a saw-tooth pattern is observed, such that the frequency of every 3rd channel is repeated. This is due to the 11.71 kHz resolution of the synthesizer. 11.71 kHz correlates to 4.9 ppm, which means errors of up to ±2.4 pmm will occur from the synthesizer setting. Silicon Labs recommends measuring the true frequency error by selecting channels 0xD (2415 MHz), 0x10 (2430 MHz), 0x13 (2445 MHz), 0x16 (2460MHz), and/or 0x19 (2475 MHz), where the frequency error due to the resolution of the synth is 0.

As of EmberZNet PRO 4.6 GA, Silicon Labs released a feature to use a synthesizer frequency offset to adjust the 24 MHz oscillator frequency to accurately center IEEE-802.15.4 channels. Using NodeTest command setSynOffset, an offset is applied to the radio synthesizer frequency and is used to compensate for variations in 24 MHz crystals. The MFG_SYNTH_FREQ_OFFSET token is used to permanently store this offset value. The NodeTest command does not set the token, it only adjusts the synthesizer offset in RAM, so changes only have effect until the next reset. The token must be written through a separate API call or em3xx_load. The manufacturing library also contains this functionality. For more information on this token and feature, refer to in this document and the Manufacturing Token section of AN710, *Bringing Up Custom Devices: For the EM35x SoC Platform*.

2.7 Transmit Error Vector Magnitude Test

The Transmit Error Vector Magnitude (EVM) test verifies that the device’s EVM is within specified limits. The EVM is measured with a spectrum analyzer. Either a transmit packet or transmit stream command is used for this transmission, as the spectrum itself is analyzed. Silicon Labs recommends that this test be performed over a subset of the frequency band to record trends versus frequency.

Some spectrum analyzers are able to measure EVM as a standalone instrument, while other spectrum analyzers require a PC software tool to provide EVM measurement details.

2.8 Transmit Sweep Test

The Transmit Sweep Test verifies transmission of valid packets from the DUT to the Reference Node at all channels or a subset of channels across the frequency band. The Reference Node is put into receive mode while the DUT transmits 100 packets to the Reference Node for each channel, with an attenuation between nodes that translates to a strong signal, approximately 60 dB attenuation between devices. Please refer to the specific radio chip data sheet for more information.

Packet success rate is measured at each channel. The packet success rate percentage is defined as the number of packets received divided by the number of packets transmitted and then multiplied by 100. For the Transmit Sweep Test, anything below 100% packet success rate is flagged as a failure, as this test is conducted at a signal level where all packets should be received. This test confirms that there are no frequency-dependent issues with transmit mode.

2.9 Receive Sweep Test

The Receive Sweep Test is similar to the Transmit Sweep Test. It verifies reception of valid packets at the DUT from the signal generator at all channels or a subset of channels across the frequency band and at two receiver input power levels (a strong signal level, approximately -50 dBm, and a level closer to the edge of sensitivity performance, approximately -90 dBm).

The DUT is put into receive mode while the signal generator transmits 100 packets for each channel. Packet success rate is measured at each channel/receive input level. Any packets missed at the strong signal level are considered a failure, while the failure threshold at the lower input level can be at a lower percentage, depending on the expected sensitivity of the radio. Please refer to the data sheet of the radio chip for details related to receive sensitivity. This test should be performed over the full operating band to record trends versus frequency.

Silicon Labs recommends using a signal generator to transmit packets to a DUT, as the signal generator allows for easily configuring the receive input power level at the DUT.

2.10 Receive Sensitivity Test

The Receive Sensitivity Test determines the receiver sensitivity of the DUT. The DUT is placed in receive mode with 1,000 valid packets being sent from the signal generator for each channel. The power level should begin at some level before the 1% Packet Error Rate (PER) threshold. Please refer to the data sheet for the specific radio chip for more information on the sensitivity. The PER is measured until the receiver input power level corresponding to 1% PER is determined. This test should be performed over a subset of the operating band to record trends versus frequency. During the characterization testing phase Silicon Labs recommends that the actual sensitivity level be determined, while at high volumes the receive sensitivity specification can be set as the low limit and be used as a single power level for ease of testing.

Silicon Labs recommends using a signal generator to transmit packets to a DUT, as the signal generator allows for easily configuring the receive input power level at the DUT.

2.11 Receive Waterfall Test

The Receive Waterfall Test determines the receiver sensitivity of the DUT by collecting data to determine the receiver roll-off curve. The DUT is placed in receive mode with 100 valid packets being sent from the signal generator for each channel. The power level should begin at some level before the 1% PER threshold. Please refer to the data sheet for the specific radio chip for more information on the sensitivity. The packet success rate is measured for all input powers selected for testing. Silicon Labs recommends that enough input power levels are selected to ensure that the data collected includes both 100% and 0% packets received. This allows for a complete roll-off curve to be observed. This test should be performed over a subset of the operating band to record trends versus frequency. Silicon Labs recommends this test for characterization testing so that the roll-off is quantified and understood but can be omitted at higher volumes.

Silicon Labs recommends using a signal generator to transmit packets to a DUT, as the signal generator allows for easily configuring the receive input power level at the DUT.

2.12 Receive Signal Strength Indicator (RSSI) Test

The RSSI Test measures the RSSI value for a single channel and known receiver input power level. The RSSI is determined by receiving a valid packet from the signal generator and reading the RSSI value through the serial command interface. The DUT is placed into receive mode while the signal generator transmits a single packet and the RSSI measurement is averaged to determine RSSI value. This single data point is measured to verify that the RSSI pin for the radio chip is connected and that RSSI is reporting a valid level. The RSSI operation of the chip itself is validated at the chip testing level and is not tested here.

Silicon Labs recommends using a signal generator to transmit packets to a DUT, as the signal generator allows for easily configuring the receive input power level at the DUT.

2.13 External 32 kHz Crystal Test

The operation of the external 32 kHz crystal (if applicable) should be verified. NodeTest includes the command `rtc`, which verifies that the crystal is operating and running properly.

2.14 Peripherals Test

Various peripherals, if applicable, can be tested through the serial port. These include anything that may be accessed through the ADC or GPIO (general purpose I/O) on the micro. For example, an LED is often tied to a GPIO pin for some status to be alerted. The state of the LED can be modified by changing the level of the GPIO pin. Another example is reading an ADC pin for a particular voltage level that corresponds to the status of a peripheral such as a temperature sensor or an accelerometer. Any peripheral accessible through GPIO or the ADC should be tested to ensure valid functionality.

3. Test Recommendations

This section outlines the various tests that can be run on the hardware product, which tests Silicon Labs recommends to be run, and the channel and power mode selection for each test in each phase.

3.1 Characterization Testing

Characterization testing is recommended for early production stages. In this phase of testing, the hardware is characterized on all 16 ZigBee channels or a subset of these channels, as well as at various transmit output power levels or receiver input power levels. This phase fully characterizes the hardware that is being developed, determines the tests to be executed in manufacturing test, determines the test limits of these tests, and flushes out any manufacturing or process issues that might be present.

Silicon Labs recommends that the tests outlined in the following table be conducted in the characterization phase of testing. This table, and the similar tables that follow in subsequent sections of this document, list the various tests that could be run on these devices, which tests Silicon Labs recommends be run, and the channel and power mode selection for each test in each phase.

Note: An X in these tables represents a test that is recommended for this phase of testing.

Table 3.1. Characterization Test Recommendations

		Channel				Power Mode	
Test	Run?	Mid	Low-Mid-High	Subset	All	Normal	Boost
Serial Communication	X						
Channel Calibration	X				X		
Supply Current	X	X				X	X
Transmit/Receive Verify	X	X				X	
Transmit Power	X		X			X	X
Transmit Frequency	X		X			X	X
Transmit EVM	X		X			X	X
Transmit Sweep	X				X	X	
Receive Sweep	X				X	X	
Receive Sensitivity	X		X			X	X
Receive Waterfall	X		X			X	X
RSSI	X	X				X	
External 32kHz Crystal	X						
Peripherals	X						

3.2 Low Volume Manufacturing Test

Low-volume manufacturing test is usually a subset of the characterization testing. A subset of the 16 ZigBee channels or transmit output power levels can be tested to reduce the test time without compromising test coverage. For example, one channel/power level combination (likely mid-band at max power) can be measured for transmit power and frequency. Also, receive waterfall can be omitted and receive sensitivity can be run in its place, where a certain packet-success rate is expected at mid-band for a given input power level.

The results from the characterization phase of testing help determine not only what should be tested in the manufacturing phase but also the test limits to be applied to certain tests. For example, if a particular test does not fail at all during the characterization phase, it can be omitted from the manufacturing phase altogether. Also, if it is determined that a particular test will fail all channels if it fails at all, testing can be reduced from all channels to a single channel, most likely mid-band.

3.2.1 Test Recommendations

The following table lists the tests Silicon Labs recommends be conducted in the low-volume manufacturing phase of testing.

Table 3.2. Low Volume Manufacturing Test Recommendations

		Channel				Power Mode	
Test	Run?	Mid	Low-Mid-High	Subset	All	Normal	Boost
Serial Communication	X						
Channel Calibration	X				X		
Supply Current	X	X				X	X
Transmit/Receive Verify	X	X				X	
Transmit Power	X	X				X	
Transmit Frequency	X	X				X	
Transmit EVM							
Transmit Sweep	X			X		X	
Receive Sweep	X			X		X	
Receive Sensitivity	X	X				X	
Receive Waterfall							
RSSI	X	X				X	
External 32kHz Crystal	X						
Peripherals	X						

3.2.2 Test Times

The typical test time that can be achieved in the low-volume manufacturing test phase is three minutes per board. If the devices are preprogrammed, the overall test time can be reduced to less than three minutes. Program times vary depending on the flash memory size of the microprocessor. Note that programming may be included at both the front end (test application) and back end (final application) of the process. If you do not want to perform multiple programming steps during this phase of testing, Silicon Labs recommends that you include the manufacturing library in the final application.

3.2.3 Setting Test Limits

The results of the characterization phase of testing help determine how the limits are set for low-volume manufacturing test. Other factors in setting limits are customer application and manufacturing variation. For example, if an application specifies only a certain amount of dynamic range, perhaps limits will be relaxed to allow for this. Manufacturing variation can also be a factor in setting limits. For example, if the performance of the board is sensitive to particular components, it is important to account for any performance variation that may be seen with these particular components.

3.2.4 Full Characterization Sampling

It is important to continue to fully characterize samples from each production run to ensure that nothing in the process has shifted, causing a difference in the overall performance of a production run compared to a previous run. The size of this sample can be determined by the manufacturer, but Silicon Labs recommends this full characterization sampling for additional test coverage and process control at volume testing.

3.3 High-Volume Manufacturing Test

High-volume manufacturing testing is much simpler than characterization testing or low- volume manufacturing testing. The hardware design and manufacturing process have already been proven, so the product now just requires a quick “go/no go” functional test to verify operation.

3.3.1 Test Recommendations

Silicon Labs recommends that the tests in the following table be conducted in the high-volume phase of testing.

Table 3.3. High-Volume Test Recommendations

		Channel				Power Mode	
Test	Run?	Mid	Low-Mid-High	Subset	All	Normal	Boost
Serial Communication	X						
Channel Calibration	X				X		
Supply Current	X	X				X	X
Transmit/Receive Verify	X	X				X	
Transmit Power							
Transmit Frequency							
Transmit EVM							
Transmit Sweep							
Receive Sweep							
Receive Sensitivity	X	X				X	
Receive Waterfall							
RSSI							
External 32kHz Crystal	X						
Peripherals	X						

3.3.2 Test Times

The typical test time that can be achieved in the high-volume manufacturing test phase is less than one minute per board. This assumes that devices are preprogrammed with the customer application and that the customer application uses the manufacturing library for invoking test modes.

3.3.3 Setting Test Limits

Since the test environment in the high-volume manufacturing phase is different from the test environment in the low-volume phase, setting the limits is also done differently. The test limits for the basic transmit and receive tests are dependent on the fixed attenuation between the Golden Node and the DUT, as well as the variation in over-the-air results. Silicon Labs recommends that customers run a sample size of boards through testing to determine these test limits.

3.3.4 Full Characterization Sampling

Even in high-volume testing, it makes sense to fully characterize samples from each production run to ensure that the process has not shifted in any way. The size of this sample can be determined by the manufacturer, but this full characterization sampling is recommended for additional test coverage at high volumes.

4. Test Architecture and Equipment

The following sections detail the recommended test architecture and equipment for each phase of testing, discuss test results and their dependence on test setup, and describe the typical manufacturing faults detected in manufacturing test.

4.1 Characterization Testing

The architecture and test equipment used in the characterization stage of testing is more comprehensive than that of the volume manufacturing stages.

4.1.1 Test Architecture

The following figure shows an example of the interfaces of the test equipment to the DUT. The test equipment can be controlled by test software through the General Purpose Interface Bus (GPIB) or Recommended Standard 232 (RS-232). The DUT may be controlled through either RS-232 or Virtual UART from a telnet connection to a Debug Adapter (ISA or ISA3). Any number of DUTs may be tested at once, but this number is dependent on serial ports available and will affect the selection of the power splitter and matrix switch hardware described in the following figure.

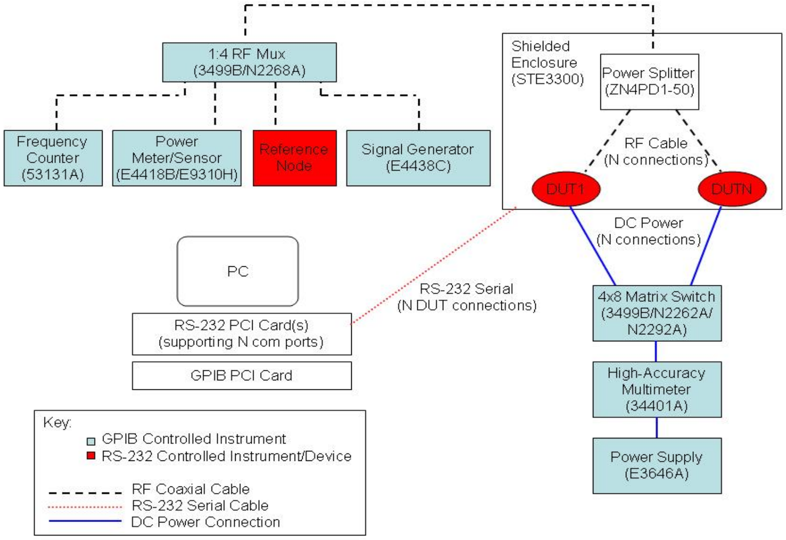

1:4 RF Mux
(3499B/N2268A)
Frequency Counter (53131A)
Power Meter/Sensor (E4418B/E9310H)
Reference Node
Signal Generator (E4438C)
Shielded Enclosure (STE3300)
Power Splitter (ZN4PD1-50)
RF Cable
(N connections)
DUT1
DUTN
DC Power
(N connections)
PC
RS-232 PCI Card(s)
(supporting N com ports)
GPIB PCI Card
RS-232 Serial
(N DUT connections)
4x8 Matrix Switch (3499B/N2262A/ N2292A)
High-Accuracy Multimeter (34401A)
Power Supply (E3646A)
Key:
GPIB Controlled Instrument
RS-232 Controlled Instrument/Device
RF Coaxial Cable
RS-232 Serial Cable
DC Power Connection

Figure 4.1. Architecture Example of the Characterization Test

Note: When using Virtual UART instead of RS-232, there is no need for RS-232 PCI cards in the test PC. Instead, some number of Debug Adapters (one per DUT) is required to drive the Virtual UART functionality and therefore Power over Ethernet (PoE) network hubs may be required. Please refer to the Debug Adapter technical specifications (TS1 for EM2xx and TS7 for EM35x) for more information on interfacing to the Debug Adapters.

4.1.2 Recommended Equipment

The recommended characterization test setup uses Agilent test equipment for the basic radio frequency (RF) measurements and current measurements, as well as for supplying power to the DUT and switching the RF connections from the DUT to various types of measurement equipment. A Reference Node, as mentioned in the characterization stage of testing, is any Ember radio communication module (RCM) configured with the same radio chip as the DUT that can be used to verify transmission of packets from the DUT.

The following table lists the basic set of test equipment Silicon Labs has used for characterization testing. Note that some of these test equipment models are no longer available or supported by the manufacturer. Please consult the equipment manufacturer for acceptable alternative or replacement models for these particular instruments.

Table 4.1. Recommended Characterization Test Equipment

Manufacturer	Part Number	Description	Purpose
Agilent	E4418B	Power Meter	Used with power sensor to measure transmit power of the DUT
Agilent	E9301H	Power Sensor	Used with power meter to measure transmit power of the DUT
Agilent	53131A	Universal Counter	Measures the transmission frequency accuracy of the DUT
Agilent	53131A-030	3GHz Option	53131A universal counter option for 3GHz to measure the transmission frequency accuracy of the DUT
Agilent	E4402B	Spectrum Analyzer	Used to verify transmit power, transmit frequency accuracy, and EVM of the DUT
Agilent	89601A	Spectrum Analyzer VSA Software	Software option for the E4402B that allows for measuring EVM
Agilent	E4438C-504	Signal Generator – 250kHz to 4GHz	Verifies reception of valid packets at the DUT
Agilent	E4438C-1E5	Time Base Option	Improves frequency accuracy of E4438C
Agilent	E4438C-602	Baseband Generator	Internal baseband generator, 64MSa memory with digital bus capability
Agilent	E4438C-005	Hard Drive Option	6GB hard drive for E4438C (optional for storage beyond the 2.8MSa provided by E4438C-602)
Agilent	E3646A	Dual Output Power Supply	Powers the DUT and Reference Node
Agilent	34401A	Digital Multimeter	Verifies current consumption of the DUT in various modes of operation
Agilent	3499B	Data Acquisition Switch Unit	Supplies power to the DUT and switches RF connection
Agilent	N2262A	4x8 Matrix Module	3499B module; supplies power to the DUT
Agilent	N2268A	3.5GHz 1:4 RF Mux Module	3499B module; switches RF connection from the DUT to the Reference Node, frequency counter, power meter, or signal generator
Agilent	N2292A	Screw Terminal Block	Terminal block accessory for N2262A 3499B module
Mini-Circuits	ZN4PD1-50	1:4 Multiplexer Splitter	Splits power from test equipment to a maximum of 4 DUTs; alternative parts can be used for more or fewer DUTs
Ramsey Electronics	STE3300	Shielded RF Enclosure	Provides RF isolation for the DUT during testing
Silicon Labs	N/A	Reference Node	Known good radio module that is used as a receiver reference node in DUT transmit tests; manufacturer can be Silicon Labs, a Silicon Labs customer, or a Silicon Labs module partner

Note: Silicon Labs recommends the spectrum analyzer (E4402B or similar model number) and VSA software option (89601A or similar model number) for EVM testing and for general hardware debug. The spectrum analyzer may also be used in place of a power meter and frequency counter in characterization testing to measure transmit power and transmit frequency offset. In volume manufacturing test, however, the power meter and frequency counter are a much more cost-effective method of measuring transmit power and transmit frequency offset than the spectrum analyzer.

4.1.3 Configuring Equipment

Some test equipment needs to be configured specifically for 802.15.4 radio communications. For the signal generator, for instance, the specific packet needs to be configured. See 9. Appendix C – Signal Generator Data Files and Configuration for more information on downloading waveform files to the signal generator and configuring the signal generator for valid 802.15.4 packets.

There are various options for triggering the signal generator to transmit packets to the device. The configuration noted in 9. Appendix C – Signal Generator Data Files and Configuration expects a single trigger for each packet. The signal generator data file can also be configured to transmit some number of packets for each trigger event. Please consult the equipment manufacturer for more information on creating these data files and the various triggering options.

One example of triggering the signal generator is to provide a TTL-level trigger signal at the Pattern Trigger Input port on the back of the E4432B/E4438C unit. In some of Silicon Labs' test set-ups, the Transmit pin of a PC's RS-232 port serves as the trigger signal. The PC's RS-232 port is connected to a TTL-to-RS-232 converter, whose transmit pin (and ground pin) is connected to the Pattern Trigger Input port of the signal generator. The automated test sends characters (for example, the letter 'p', which in ASCII is 0x70) to provide a single pulse on the serial port. Configuring the baud rate appropriately, this serial port can be used to send characters to trigger the signal generator at various rates for testing.

4.1.4 Low-Cost Alternative to Signal Generator (Golden Node)

For some customers, adding a signal generator to manufacturing test is not desired or not possible due to cost concerns. In this case, Silicon Labs recommends using a Golden Node (a known good device that can be used in test for repeatable measurements) with TCXO (temperature controlled/compensated crystal oscillator). The TCXO allows for frequency accuracy when using the Golden Node as a known good transmitter source for DUT receive tests. Using a Golden Node without TCXO would present issues with test accuracy, as the crystal would drift over time and temperature. The Golden Node will have known transmitter performance (0 dBm +/- 0.5 dBm) across voltage and temperature, allowing for test repeatability.

4.1.5 RF Test Interface Examples

The type of interface to the DUT and the RF shielded test enclosure selected for testing can determine the accuracy and repeatability of the measurements. The Ramsey STE3300 test enclosure listed in Table 4.1 Recommended Characterization Test Equipment on page 11 is recommended.

It is important to pay special attention to the RF test interface to the DUT because of the sensitivity of these signals. For example, a product with a 50-Ohm terminated Subminiature Type A (SMA) connector populated on the board can be connected directly to a coaxial cable with a known loss. Repeatability in this scenario is very good.

Another example is a product with an embedded antenna that was designed with test points for RF and ground can be connected with a pogo-pin style RF probe. The path loss from the RF test point to the cabled connections of the setup can be calibrated to determine accurate performance. The repeatability of this setup is dependent on the board layout, in the sense that the RF and ground signals should have test points in close proximity to one another. The repeatability is also more dependent on the shielded enclosure in this case, because the RF signal is exposed at the test point rather than enclosed within an SMA connector as in the first example.

As a final example, a product with an embedded antenna can be tested over the air within an enclosure. A reference antenna would be used within the enclosure to feed back the RF signal to the RF Mux. The path loss over the air from the reference antenna to the DUT antenna can be calibrated to determine accurate performance. Fixed position of the DUT and position of the DUT and reference antennas are crucial to getting repeatable results.

4.2 Low-Volume Manufacturing Testing

The architecture and test equipment used in the characterization stage of testing is more comprehensive than that of the volume manufacturing stages.

4.2.1 Test Architecture

The test architecture in the low-volume phase of testing is very similar to that of the characterization phase.

4.2.2 Recommended Equipment

The equipment Silicon Labs recommends for the low-volume manufacturing phase of testing is very similar to that for the characterization phase. Some of the equipment may be removed depending on the tests selected for this phase.

4.2.3 Interference

There are many RF devices in a test environment, such as wireless networks, microwave ovens, and mobile phones. For this reason, it is important to maintain RF isolation of the DUT from these sources of interference. It is also important to maintain RF isolation between multiple stations. For example, the equipment for test station A should be able to communicate only with a DUT from test station A and not with a DUT from test station B. Likewise, the equipment for test station B should be able to communicate only with a DUT from test station B and not a DUT from test station A. If these stations are not isolated from each other, the DUT will not be uniquely configured and multiple boards could share unique configuration information.

4.3 High-volume Manufacturing Testing

The architecture and test equipment used in the characterization stage of testing is more comprehensive than that of the volume manufacturing phases.

4.3.1 Test Architecture

The test architecture in the high-volume phase of testing can be structured any number of ways depending on customer preference. One approach is to develop this test with a Golden Node programmed with an application that allows the DUT to obtain unique configuration information from the Golden Node through packets transmitted and received. This test may be limited to configuring one DUT at a time. The Golden Node initiates communication with the unconfigured DUT and sends unique configuration information to the DUT. The Golden Node can then interface with the PC application to configure the DUT uniquely. Then the DUT can reboot itself and be ready for testing or application operation. A basic transmit/receive test can then be run. The test architecture for this phase of testing is shown in the following figure.

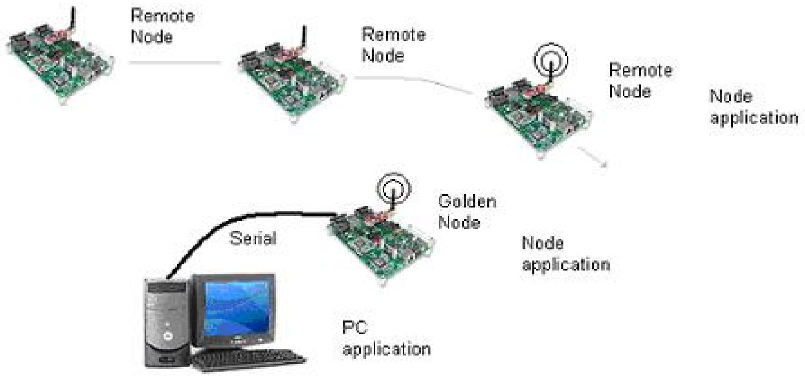


Figure 4.2. Architecture Example of a High-Volume Manufacturing Test

Another approach is to develop a test with a serial interface to both the Golden Node and the DUT. This may be more straightforward to develop but requires a more extensive set up and use of a UART (either serial or virtual UART through a Debug Adapter (ISA or ISA3)).

4.3.2 Recommended Equipment

The equipment is based on the tests selected for this phase of testing, as well as the preference of the customer. No matter the approach, it is important that, at the very least, the Golden Node (and in some cases the DUT) have an interface to a PC or server so that it can log test information like calibration data, serial numbers, EUI, test results, and so on.

4.3.3 Interference

A facility running multiple test stations maintains RF isolation among the stations, as previously detailed. In this test phase, the only interface to the DUT is power, as all communication between the Golden Node and the DUT is done through the radio. All of the test equipment used in the characterization testing can be removed from the process, unless a customer decides to continue to test certain functionality on the board that requires test equipment.

5. Embedded Software Tools

Silicon Labs supports two different embedded software tools for manufacturing test: a standalone test application called NodeTest, and a manufacturing test library that is used as a test mode within the customer application. The following sections describe these two embedded software tools.

5.1 Standalone Test Application - NodeTest

The characterization stage typically utilizes a standalone test application. NodeTest is a standalone test application that Silicon Labs recommends for any test stage in which the customer's application is not yet mature enough to include a test mode. NodeTest provides a serial command line interface to the Silicon Labs device. For information on using NodeTest for basic device testing see *AN1019: Using the NodeTest Application*.

5.2 Manufacturing Library

Silicon Labs recommends that customers use the manufacturing library in mature applications, regardless of the testing phase. Customers without mature applications can build a simple Zigbee sample application with the manufacturing library enabled to access this functionality. The manufacturing library provides access to a test mode within the application and removes the need for multiple application bootloads or multiple programming steps within the manufacturing process. The manufacturing library is available as a configurable plugin in the EmberZNet SDK. The guidelines for enabling the manufacturing library plugin and using the manufacturing library CLI commands for manufacturing tests are provided in *AN1162: Using the Manufacturing Library for EmberZNet*.

6. Conclusions and Summary

As you can see from the descriptions of each test phase within this document, the recommended tests and test flow are different when comparing characterization testing with manufacturing testing.

The following table lists the test recommendations by phase and Table 6.2 Comparison of Test Phases on page 15 compares the test phases.

Note: In the following table, C denotes tests recommended for characterization testing, L denotes tests recommended for low-volume manufacturing testing, and H denotes tests recommended for high-volume manufacturing.

Table 6.1. Test Recommendations by Phase

		Channel				Power Mode	
Test	Run?	Mid	Low-Mid-High	Subset	All	Normal	Boost
Serial Communication	CLH						
Channel Calibration	CLH				CLH		
Supply Current	CLH	CLH				CLH	CLH
Transmit/Receive Verify	CLH	CLH				CLH	
Transmit Power	CL	L	C			CL	C
Transmit Frequency	CL	L	C			CL	C
Transmit EVM	C		C			C	C
Transmit Sweep	CL			L	C	CL	
Receive Sweep	CL			L	C	CL	
Receive Sensitivity	CLH	LH	C			CLH	C
Receive Waterfall	C		C			C	C
RSSI	CL	CL				CL	
External 32kHz Crystal	CLH						
Peripherals	CLH						

Table 6.2. Comparison of Test Phases

Step	Characterization	Manufacturing Low-Volume	Manufacturing High-Volume
Program bootloader (if applicable)	Functional Test	Functional Test or Preconfigured	Preconfigured
Program/load test application	Functional Test	Functional Test or Preconfigured	Manufacturing library within final application
Load stack information	Functional Test	Functional Test or Preconfigured	Preconfigured
Load manufacturing Information	Functional Test	Functional Test	Golden Node application
Load application information	Functional Test	Functional Test	Preconfigured
Verify DUT operation	Functional Test	Functional Test	Golden Node application
Program/load production application	Functional Test	Functional Test	Preconfigured

In the characterization phase of testing, all programming and configuration steps can be automated to occur within the test itself. In the low-volume manufacturing phase, some of these steps can be done before actual manufacturing. For example, the device can be pre-configured with the appropriate bootloader and/or test application. In the case of high-volume manufacturing, the test functions can be included in the production application as a test mode, as previously mentioned with the manufacturing library. The Golden Node application can be developed by the customer to configure the appropriate unique manufacturing information for each DUT.

7. Appendix A – Channel Calibration Data Storage Information

Over time, Silicon Labs has worked to improve channel calibration for the Ember EM35x devices. With these improvements, the channel calibration data storage has changed at times and therefore there are differences in this data storage when comparing Ember stack releases and/or devices. This appendix provides some details regarding these differences.

EmberZNet PRO 4.2.0

- Token Creator: D243
- Channel Calibration Byte Configuration
  - byte 0: VCO at LNA cal; Reset=0xff, Minimum=0, Maximum=0x3f (6 bit)
  - byte 1: Modulation DAC; Reset=0x80, Minimum=0, Maximum=0x7f (7 bit)
  - byte 2: Modulation DAC Temperature at Calibration Time; Reset=0x7f, Minimum=0xd8 (-40ºC), Maximum=0x55 (+85ºC) (8-bit signed)
  - byte 3: Low Noise Amp; Reset=0x80, Minimum=0, Maximum=0x3e (6 bit, LSB always 0)
- Channel Calibration Valid Range of Values
  - bytes 0,4,8,...,60: values 0x01-0x3e are good, 0xff is uncalibrated
  - bytes 1,5,9,...,61: values 0x01-0x7e are good, 0x80 is uncalibrated
  - bytes 2,6,10,...,62: values 0xd8-0x55 are good, 0x7f is uncalibrated
  - bytes 3,7,11,...,63: values 0x01-0x3d are good, 0x80 is uncalibrated
- Notable changes compared to previous releases
  - Byte 2 now used to store Modulation DAC Temperature at Calibration Time
  - Reset value for byte 2 changed from 0x80 to 0x7f

EmberZNet PRO 4.5.0 and Later

- Token Creator: D245
- Channel Calibration Byte Configuration
  - byte 0: LNA Temperature at Calibration Time; Reset=0x7f, Minimum=0xd8 (-40ºC), Maximum=0x55 (+85ºC) (8-bit signed)
  - byte 1: Modulation DAC; Reset=0x80, Minimum=0, Maximum=0x7f (7 bit)
  - byte 2: Modulation DAC Temperature at Calibration Time; Reset=0x7f, Minimum=0xd8 (-40ºC), Maximum=0x55 (+85ºC) (8-bit signed)
  - byte 3: Low Noise Amp; Reset=0x80, Minimum=0, Maximum=0x3e (6 bit, LSB always 0)
- Channel Calibration Valid Range of Values
  - bytes 0,4,8,...,60: values 0xd8-0x55 are good, 0x7f is uncalibrated
  - bytes 1,5,9,...,61: values 0x01-0x7e are good, 0x80 is uncalibrated
  - bytes 2,6,10,...,62: values 0xd8-0x55 are good, 0x7f is uncalibrated
  - bytes 3,7,11,...,63: values 0x01-0x3d are good, 0x80 is uncalibrated
- Notable changes compared to previous releases
  - Token creator changed from D243 to D245
  - Low Noise Amp Temperature at Calibration Time is tracked rather than VCO at LNA
  - Temperature at Calibration Time algorithms updated to use data from IC production test

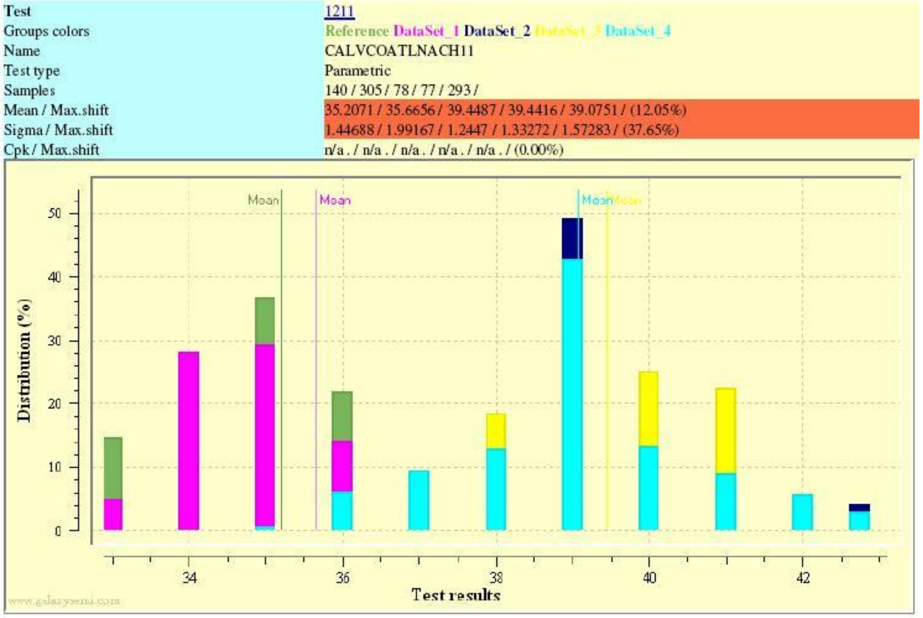
Items of Note

- EM35x Modulation DAC calibration data is 7 bits (0x7F max)

8. Appendix B – Example Test Data

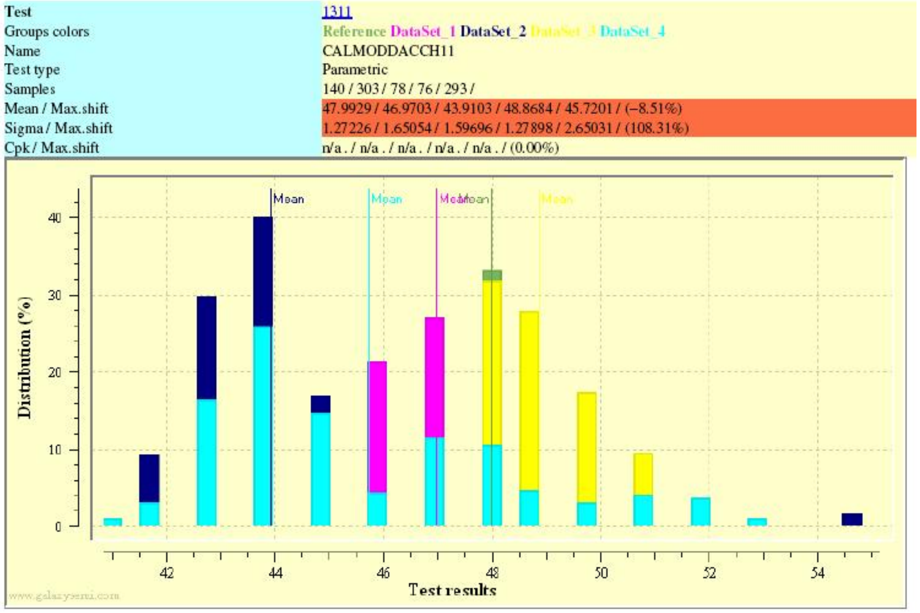
This collection of histograms presents the typical distribution of test results for a given sample of EM35x IC devices. Collecting data in this manner will help determine acceptable test limits in manufacturing test. This test data was collected from the now-obsolete Ember EM250 radio communication modules (130-0452-000 Revision B0), but the result distribution is equally applicable to the EM35x. The data presented was collected on boards tested using the Ember development kit module manufacturing test program.

The histograms were created using Galaxy Examinator (www.galaxysemi.com).



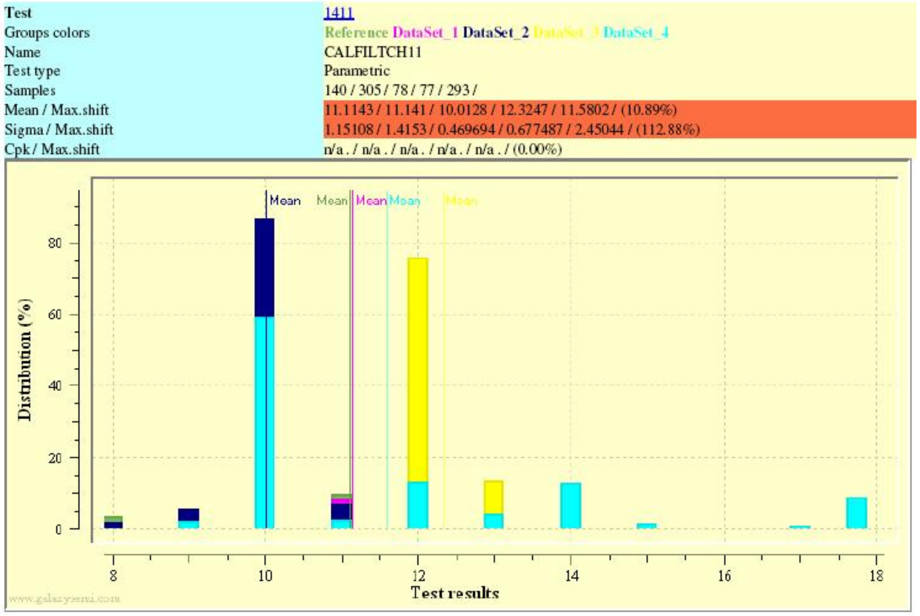
Test	1211
Groups colors	Reference DataSet_1 DataSet_2 DataSet_3 DataSet_4
Name	CALVCOATLNACH11
Test type	Parametric
Samples	140 / 305 / 78 / 77 / 293 /
Mean / Max.shift	35.2071 / 35.6656 / 39.4487 / 39.4416 / 39.0751 / (12.05%)
Sigma / Max.shift	1.44688 / 1.99167 / 1.2447 / 1.33272 / 1.57283 / (37.65%)
Cpk / Max.shift	n/a . / n/a . / n/a . / n/a . / n/a . / (0.00%)

Figure 8.1. Comparison Histogram for VCO at LNA Calibration Channel 11, 5 Board Builds



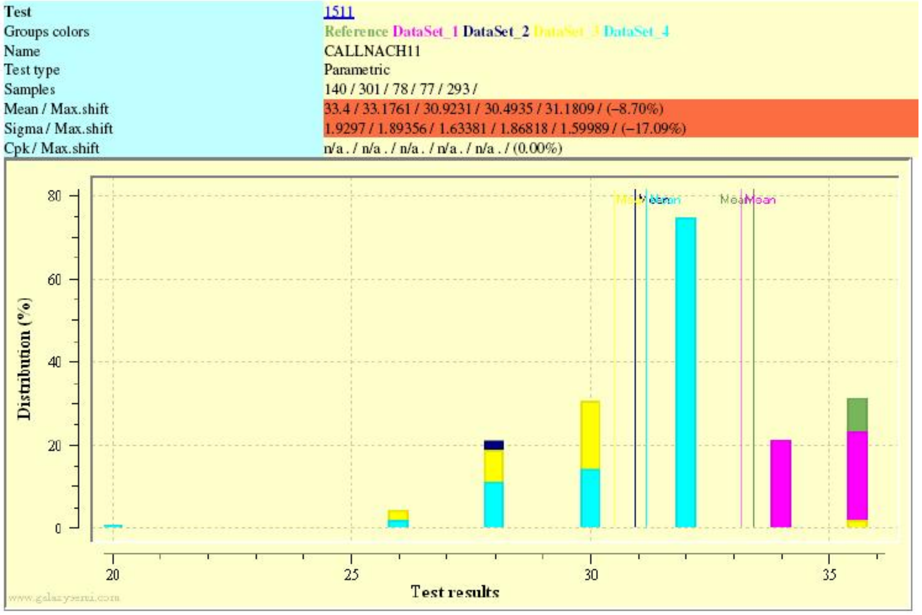
Test	1311
Groups colors	Reference DataSet_1 DataSet_2 DataSet_3 DataSet_4
Name	CALMODDACCH11
Test type	Parametric
Samples	140 / 303 / 78 / 76 / 293 /
Mean / Max.shift	47.9929 / 46.9703 / 43.9103 / 48.8684 / 45.7201 / (–8.51%)
Sigma / Max.shift	1.27226 / 1.65054 / 1.59696 / 1.27898 / 2.65031 / (108.31%)
Cpk / Max.shift	n/a . / n/a . / n/a . / n/a . / n/a . / (0.00%)

Figure 8.2. Comparison Histogram for Mod Dac Calibration Channel 11, 5 Board Builds



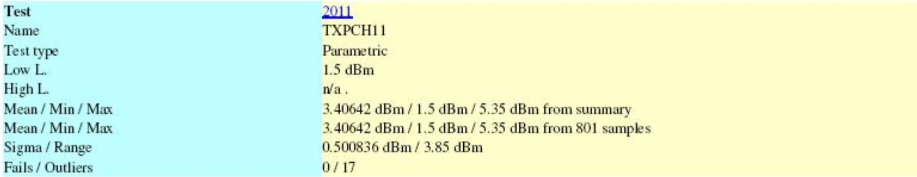
Test	1411
Groups colors	Reference DataSet_1 DataSet_2 DataSet_3 DataSet_4
Name	CALFILTCH11
Test type	Parametric
Samples	140 / 305 / 78 / 77 / 293 /
Mean / Max.shift	11.1143 / 11.141 / 10.0128 / 12.3247 / 11.5802 / (10.89%)
Sigma / Max.shift	1.15108 / 1.4153 / 0.469694 / 0.677487 / 2.45044 / (112.88%)
Cpk / Max.shift	n/a . / n/a . / n/a . / n/a . / n/a . / (0.00%)

Figure 8.3. Comparison Histogram for Filter Calibration Channel 11, 5 Board Builds



Test	1511
Groups colors	Reference DataSet_1 DataSet_2 DataSet_3 DataSet_4
Name	CALLNACH11
Test type	Parametric
Samples	140 / 301 / 78 / 77 / 293 /
Mean / Max.shift	33.4 / 33.1761 / 30.9231 / 30.4935 / 31.1809 / (–8.70%)
Sigma / Max.shift	1.9297 / 1.89356 / 1.63381 / 1.86818 / 1.59989 / (–17.09%)
Cpk / Max.shift	n/a . / n/a . / n/a . / n/a . / n/a . / (0.00%)

Figure 8.4. Comparison Histogram for LNA Calibration Channel 11, 5 Board Builds



Test	2011
Name	TXPCH11
Test type	Parametric
Low L.	1.5 dBm
High L.	n/a .
Mean / Min / Max	3.40642 dBm / 1.5 dBm / 5.35 dBm from summary
Mean / Min / Max	3.40642 dBm / 1.5 dBm / 5.35 dBm from 801 samples
Sigma / Range	0.500836 dBm / 3.85 dBm
Fails / Outliers	0 / 17

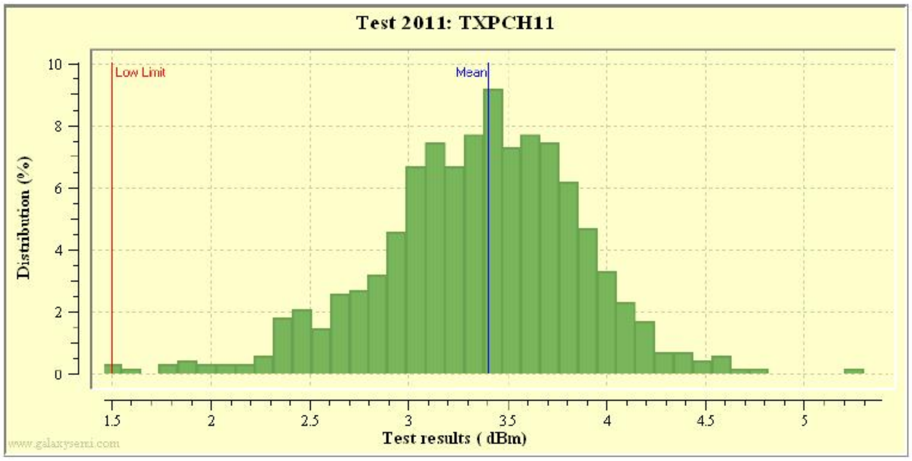
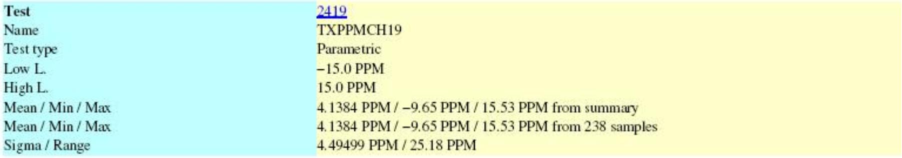


Figure 8.5. Histogram for Transmit Power Test Channel 11, Sample of 801 Boards



Test	2419
Name	TXPPMCH19
Test type	Parametric
Low L.	−15.0 PPM
High L.	15.0 PPM
Mean / Min / Max	4.1384 PPM / −9.65 PPM / 15.53 PPM from summary
Mean / Min / Max	4.1384 PPM / −9.65 PPM / 15.53 PPM from 238 samples
Sigma / Range	4.49499 PPM / 25.18 PPM

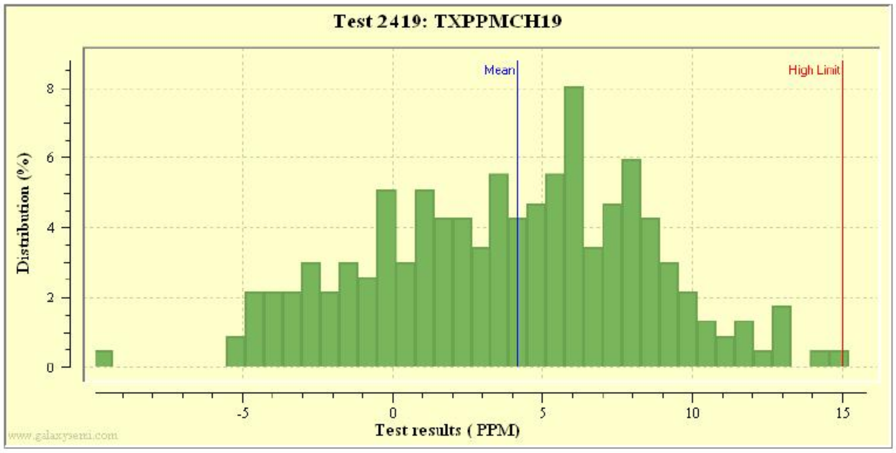
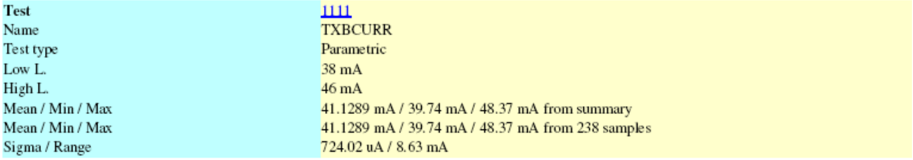


Figure 8.6. Histogram for Transmit Frequency Offset PPM Channel 19, Sample of 238 Boards



Test	1111
Name	TXBCURR
Test type	Parametric
Low L.	38 mA
High L.	46 mA
Mean / Min / Max	41.1289 mA / 39.74 mA / 48.37 mA from summary
Mean / Min / Max	41.1289 mA / 39.74 mA / 48.37 mA from 238 samples
Sigma / Range	724.02 uA / 8.63 mA

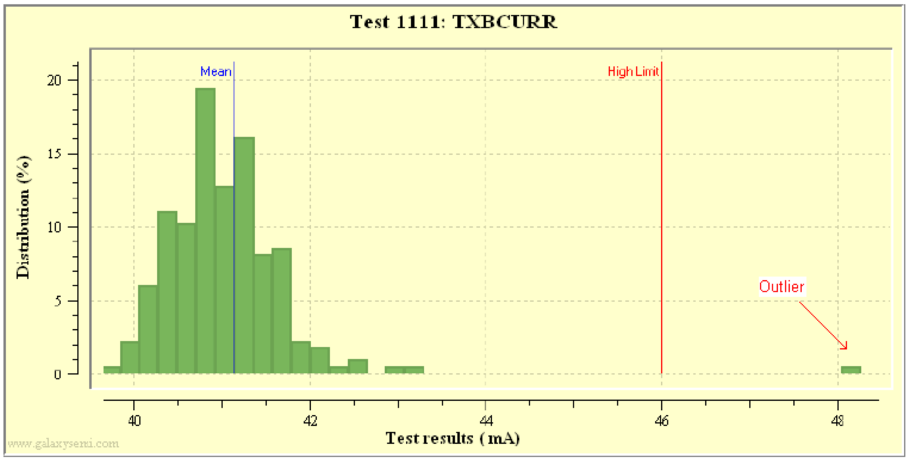


Figure 8.7. Histogram for Boost Mode Transmit Current, Sample of 238 Boards

9. Appendix C – Signal Generator Data Files and Configuration

The signal generator arbitrary waveform generator requires I and Q data files defining the waveform to be transmitted. The E4432B uses 14-bit files, while the E4438C uses 16-bit files. These data files can be downloaded from www.silabs.com/zigbee-support.

9.1 Downloading the 802.15.4 2.4 GHz arbitrary waveform files to the signal generator

The signal generator requires specific waveform files for generating the IEEE 802.15.4 type packets. This procedure describes how to download the arbitrary waveform file from the PC to the test equipment.

1. Connect the signal generator through GPIB to the PC.
2. Download and install IntuiLink from the Agilent website (www.agilent.com/). Search for IntuiLink for PSG.
3. Select the download link IntuiLink for PSG/ESG Signal Generators at the bottom of the page. This is an Excel toolbar, so make sure Microsoft Excel is also installed on the PC. Follow the instructions on the web page. This link will install the toolbar that lets you download the I/Q data files to the signal generator.
4. Click Download Arb Waveform on the toolbar.
5. Select the I waveform file. Select the Auto find Q file name check box to automatically find the Q file
6. Select type Waveform and File Type ASCII if not already set.
7. Markers should be set as Marker Start 0 and Length 4. User Marker File should not be checked.
8. Select the Auto find marker – file name check box.
9. Uncheck the Auto Name check box and name the file EM250_20BYTE.
10. Set the Scale Factor to 70.
11. If using the E4438C, under Markers set Start to 0 and set Length to 4.
12. Select Download, and the signal generator should download the file appropriately.

9.2 Configuring the arbitrary waveform generator for use in test – E4432B Series

After you have downloaded the I/Q data files to waveform memory, you need to configure the signal generator with the settings detailed in the next sections: 9.2 Configuring the arbitrary waveform generator for use in test – E4432B Series or 9.3 Configuring the arbitrary waveform generator for use in test – E4438C Series.

Before starting this procedure, make sure the I-Q waveform file has been downloaded to the signal generator (see the section 9.1 Downloading the 802.15.4 2.4 GHz arbitrary waveform files to the signal generator).

1. On the signal generator keypad, press the Mode button and then select Arb Waveform Generator | Dual Arb.
2. Choose Select Waveform and use the wheel to highlight the desired waveform file (it should be EM250_20BYTE if you followed the 9.1 Downloading the 802.15.4 2.4 GHz arbitrary waveform files to the signal generator procedure above.
3. Choose Select Waveform again and then press Return.
4. Select Waveform Segments and use the wheel to highlight the desired waveform file EM250_20BYTE.
5. Select Store, then Store Segment to NVARB Memory and then press Return.
6. Select Arb Setup, and under Arb Sample Clock type in 16MHz with the keypad and then Enter. Press the Return button.
7. Set the following:

Set:	To:
Arb Reference	Int
Recon Filter	8MHz
Marker Pol	Neg
Mkr2 to RF Blank	On and then press the Return button.

8. Select Trigger | Single.
9. Select Trigger Set-up and set the following:

Set:	To:
Trigger Source	Ext
Ext Pol	Neg
Ext Delay	Off

10. Verify that the displayed menu in the middle of the screen shows the following before continuing:
    - Sample Clock 16 MHZ
    - Reconstruction 8 MHz
    - Ref Freq 10 MHz (Int)
    - Trig Type Single
    - Trig Source Ext
    - Polarity Neg
    - Retrigger Off
    - Delay Off
11. Turn Arb to On.
12. Press Save to save this current state so it can easily be recalled for future use. Name this state EM250_20BYTE if desired.

9.3 Configuring the arbitrary waveform generator for use in test – E4438C Series

Before starting this procedure, make sure the I-Q waveform file has been downloaded to the signal generator (see the section 9.1 Downloading the 802.15.4 2.4 GHz arbitrary waveform files to the signal generator).

1. On the signal generator keypad, press the Mode button and select Arb Waveform Generator | Dual Arb.
2. Choose Select Waveform and use the wheel to highlight the desired waveform file (it should be EM250_20BYTE if you followed the preceding 9.1 Downloading the 802.15.4 2.4 GHz arbitrary waveform files to the signal generator procedure.
3. Choose Select Waveform again and then press Return.
4. Select Waveform Segments and use the wheel to highlight the desired waveform file EM250_20BYTE.
5. Select Store, then Store Segment to NVWFM Memory and then press Return twice.
6. Select Arb Setup, and under Arb Sample Clock type in 16 MHz with the keypad and then Enter. Press the Return button.
7. Set Arb Reference to Int.
8. Select Waveform Utilities and set Scale Waveform Data to 100%.
9. Select Clipping, and then set the following:

Set:	To:
Clipping Type	(|I+jQ|)
Clip |I+jQ|	100%

10. Select Return twice.
11. Choose Marker Utilities | Marker Polarity and then set the following:

Set:	To:
Marker 1 Polarity	Pos
Marker 2 Polarity	Neg
Marker 3 Polarity	Pos
Marker 4 Polarity	Pos

12. Select Return and then Marker Routing and then set the following:

Set:	To:
Pulse/RF Blank	Marker 2
ALC Hold	None
Alternate Amplitude	None

13. Press Return twice, select More, and then set the following options:

Set:	To:
Waveform Runtime Scaling	70%
I/Q Mod Filter (40.0MHz)	Auto
I/Q Output Filter (40.0MHz)	Auto
Modulator Atten (10.0dB)	Auto
High Crest Mode	Off

14. To check that all of the arbitrary waveform settings are correct, choose Arb Setup | Header Utilities and verify the following settings are displayed:

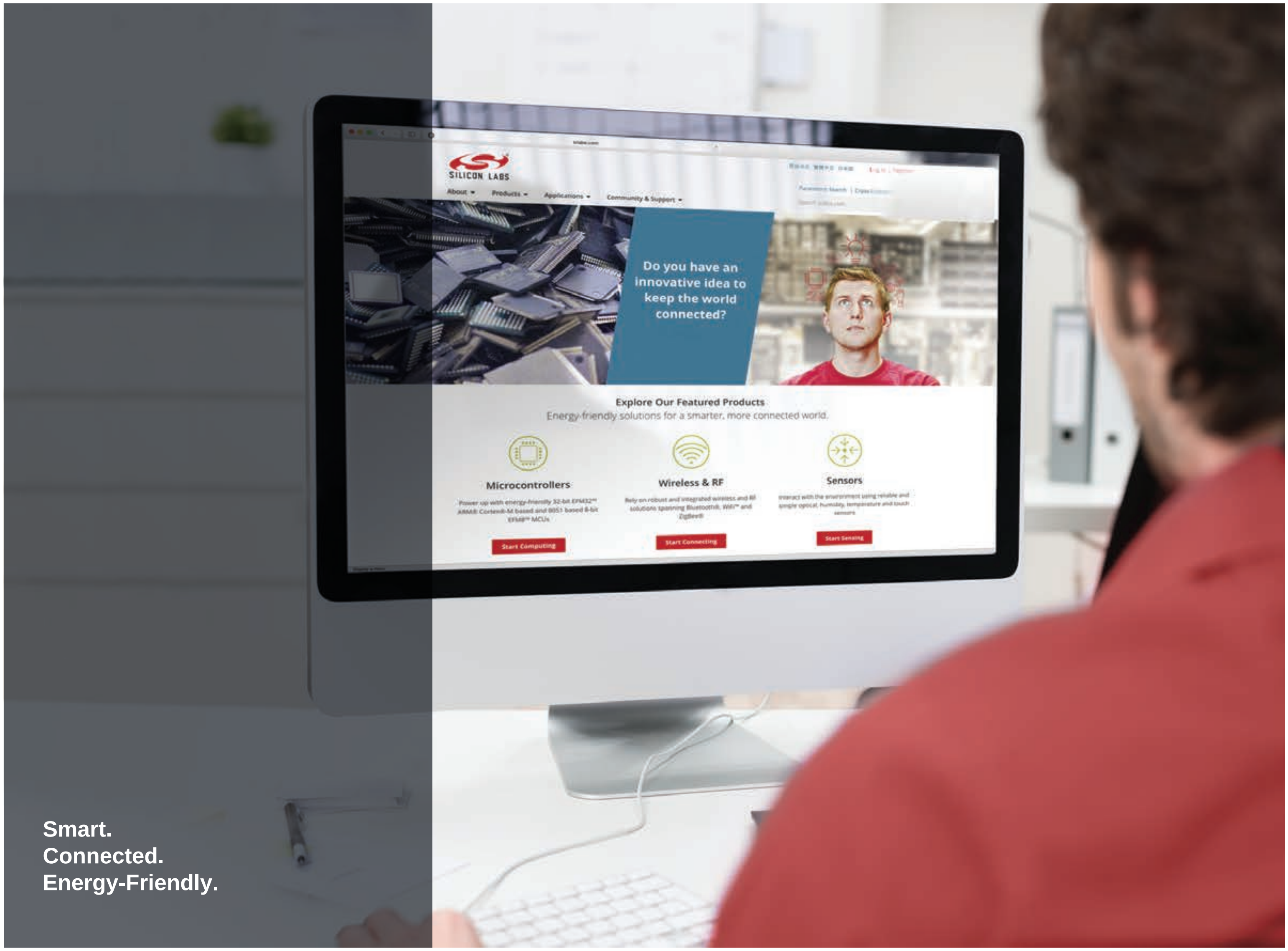
This Setting:	Is Set To:
Sample Rate	16MHz
Runtime Sampling	70%
Marker 1 Polarity	Pos

This Setting:	Is Set To:
Marker 2 Polarity	Neg
Marker 3 Polarity	Pos
Marker 4 Polarity	Pos
ALC Hold Routing	None
Alt Ampl. Routing	None
RF Blank Routing	Marker 2
High Crest Mode	Off
Mod Attenuation	Auto
I/Q Mod Filter	Auto
I/Q Output Filter	Auto

15. Select Return twice.
16. Select Trigger | Single.
17. Select Trigger Set-up and set the following:

Set:	To:
Trigger Source	Ext
Ext Pol	Neg
Ext Delay	Off

18. Verify that the displayed menu in the middle of the screen shows the following before continuing:
    - Sample Clock 16 MHZ
    - IQ Mod Filter 40 MHz
    - Ref Freq 10 MHz (Int)
    - Trig Type Single
    - Trig Source Ext
    - Polarity Neg
    - Retrigger Off
    - Delay Off
19. Turn Arb to On.
20. Press Save to save this current state so it can easily be recalled for future use. Name this state EM250_20BYTE if desired.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