AN1440: SiWx917 Gain Offset Calibration

This application note covers the TX output power offset calibration procedure for SiWx917 Single Chip Wireless Solutions.

KEY POINTS

- SiWx917 gain offset calibration procedure
- WiSeConnect SDK gain offset calibration APIs
- Manufacturing utility gain offset calibration commands
- Wi-Fi TX power measurement

1. Introduction

Gain offset is the difference between the actual power delivered to the load (antenna) and the configured TX power. It is affected by all parts of the RF chain, including the SiWx917 PA, the RF matching network and the antenna feed line. During the production of SiWx917 parts, a baseline calibration is performed which assumes a typical ~2 dB front-end loss and results around ±1 dB TX power accuracy.

For more accurate power control, an additional calibration is needed which compensates the actual losses (or gains) in the RF front-end circuitry and (if performed individually on each manufactured device) minimizes the part-to-part variation. The total loss/gain in the RF front-end circuitry depends on the components used and the PCB layout & stack-up and as such, is specific to the application board. As a result, this application specific gain offset (referred simply by gain offset from now on) must be calibrated on the custom application board by the end-product manufacturer.

Notes:

- The maximum Wi-Fi TX power level can have up to ±2 dB part-to-part variation. The maximum TX power limit is calibrated during production to ensure compliance to 802.11 specifications like EVM and spectral mask, and also depends on the protocol and channel being used. The limit is defined at the SiWx917 RF pins and is not affected by the gain offset calibration. For regional RF regulatory compliance, it may be necessary to apply further TX power limitations which can be done using the Gain Tables as documented in AN1437: SiWx917 RF Regulatory Testing.
- The crystal frequency offset must be also calibrated. Guidelines on how to perform the crystal frequency offset calibration are provided in the AN1436: SiWx917 QMS Crystal Calibration Application Note.

The gain offset calibration is performed by adjusting the associated compensation values so that the gain offset is minimized. To measure the gain offset, transmit a modulated test signal with a specific Power Index and measure the actual TX power with a spectrum analyzer or Wi-Fi signal analyzer. The gain offset compensation values are integer values that correspond to approximately 0.5 dB resolution in output power and can be evaluated as the following:

```
Gain offset = ceil[(Power level reported by test equipment [dBm] + Cable loss [dB] – Power Index) x 2]
```

Because the gain offset may vary with the TX frequency, separate compensation parameters are available for low-, mid-, and high-band channels and (optionally) for Wi-Fi channel 14.

The gain offset compensation parameters can be calibrated at a single channel for each sub-band (e.g. Wi-Fi channel 1 for low-band, Wi-Fi channel 6 for mid-band and Wi-Fi channel 11 for high band). Alternatively, for better overall accuracy, the gain offset calibration can be also performed by testing the TX power offset across all channels and optimizing the gain offset compensation values to minimize e.g. the worst-case or RMS TX power offset across the band.

Notes:

- For best overall accuracy, perform the calibration with Power Index = 16 and 802.11g – 6 Mbps test signal.
- The gain offset calibration needs to be performed at room temperature.
- To update the gain offset calibration data of SiWx917 parts having no internal flash memory, the gain offset calibration data source must be set to the flash memory (instead of the eFuse memory). The gain offset calibration data source can be set to the flash memory by writing the EVM offset (e.g., zeroes, which have no effect on the EVM offset).

Table 1.1. Gain Offset Channel Mapping

Gain offset	Associated Wi-Fi channels	Associated BLE channels
Low-band	1,2,3	0-11
Mid-band	4,5,6,7,8	12-25
High-band	9,10,11,12,13, 14*	26-44
Ch14	14*	—
Note: If *Ch14* is written, then it will be used as gain offset for Wi-Fi channel 14. If Ch14 is not written, then the *High-band* gain offset will be used for Wi-Fi channel 14.		

After evaluating the gain offset error, update the compensation parameters, and verify that the gain offset is minimized. In some cases, the calibration may need to be repeated to fine-tune the results.

The gain offset calibration values are stored in the flash memory and can be updated either from the SoC or NCP host application with the WiSeConect APIs listed in 2.1 WiSeConnect APIs or using the Manufacturing Utility commands listed in section 3. Manufacturing Utility.

Because the gain offset can be adjusted in 0.5 dB steps, 0–0.5 dB residual gain offset error is expected. Furthermore, in order to avoid exceeding RF regulatory limits, it is recommended to tune the actual TX power slightly below the configured TX power (i.e., negative residual gain offset).

To achieve the highest possible TX power compliant with regulatory limits and best TX power accuracy, perform the gain offset calibration for each product individually. In this case, the maximum compliant TX power levels obtained during the end-product RF regulatory testing can be used directly in the regulatory power table (a.k.a. Gain Table).

A common gain offset compensaton also can be used, however in this case, the common gain offset calibration values should be evaluated on a sufficiently large sample size and the RF regulatory testing still should be performed with an individually calibrated device. Furthermore, if no individual gain offset calibration is performed, then it is recommended to decrease the Regulatory Power Table values by 1-2 dB compared to the maximum compliant TX power level obtained during the RF regulatory testing.

2. WiSeConnect APIs and Example Applications

2.1 WiSeConnect APIs

Use the WiSeConnect API functions listed in the table below to generate the test signals and update/read the Gain Offset calibration values.

Table 2.1. Recommended API Functions for Gain Offset Calibration

API Function	Description
`sl_si91x_transmit_test_start`	Enable test mode infinite Wi-Fi transmission with specified settings. The SiWx917 must be initialized in Transmit Test mode before calling this API.
`sl_si91x_transmit_test_stop`	Disable infinite Wi-Fi transmission.
`sl_si91x_calibration_read`	Read the frequency and gain offset calibration data.
`sl_si91x_calibration_write`	Update the frequency and gain offset calibration data.

Note: The SiWx917 should be initialized in Wi-Fi Transmit Test operation mode (`SL_SI91X_TRANSMIT_TEST_MODE`) for the tests.

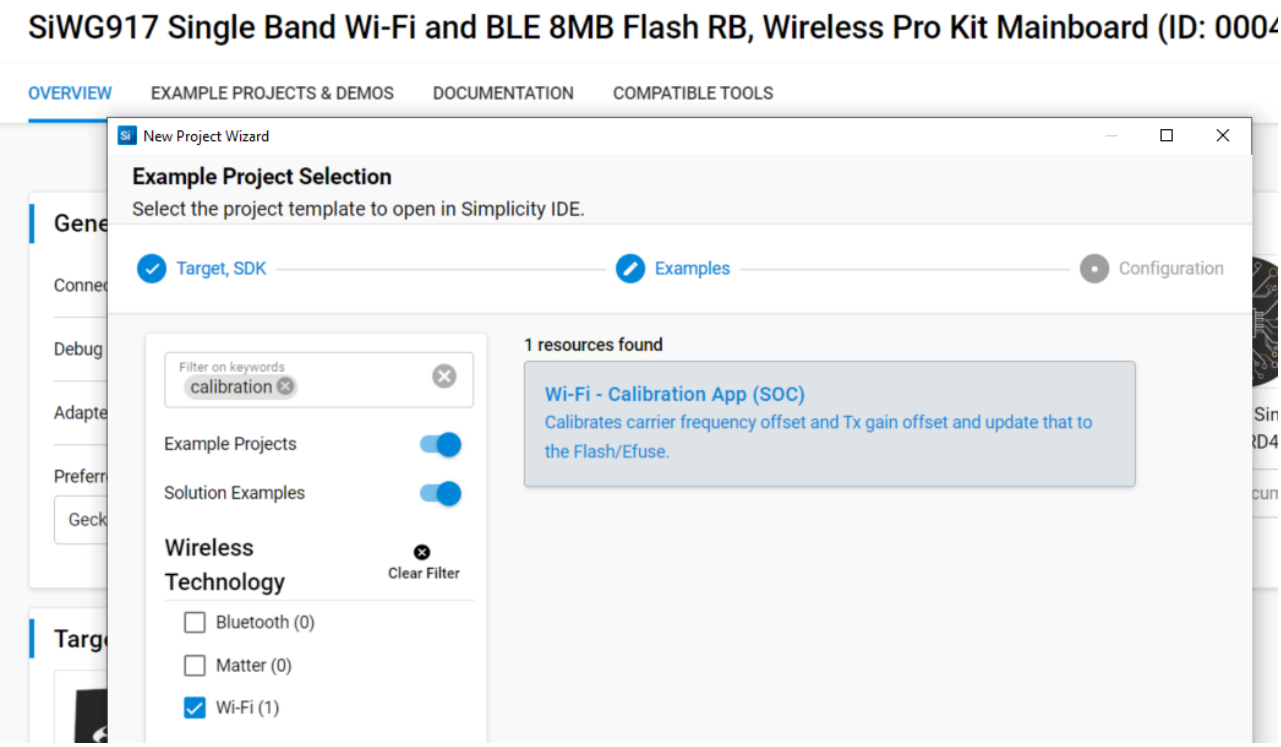
An example application, called Calibration App, is also provided by the WiSeConnect SDK which can be used to perform the Gain Offset calibration via a serial command line interface. Guidelines on how to use the Calibration App example are provided in 2.2 Wi-Fi Calibration App.

2.2 Wi-Fi Calibration App

2.2.1 Setup

The Wi-Fi Calibration App example project provides an easy-to-use serial command line interface for performing the SiWx917 Gain Offset calibration.

To create a Wi-Fi Calibration (SoC or NCP) application, open the new project wizard in Simplicity studio and choose the Wi-Fi Calibration App application.



Once the project is created, follow the guidelines provided in the project readme.md file to get started.

The TX test signal properties can be configured by modifying `tx_test_info` structure definition in the *app.c* file:

Member	Description	Recommended value
power	Test signal Power Index	16
rate	Data rate id, as specified in sl_wifi_data_rate_t	SL_WIFI_DATA_RATE_6 (→ 802.11g / 6 Mbps)
mode	Transmit Mode	Either 0 → BURST_MODE (for burst packets mode) or 1 → CONTINUOUS_MODE (for continuously modulated stream mode)
length	Length of the transmitted packet in bytes	1000 in burst packets mode or 260 in continuously modulated stream mode
channel	WLAN channel	1, 6, and 11 (for quick calibration) or all (for high accuracy calibration)

2.2.2 Usage

After startup, the application automatically starts Test Mode Wi-Fi transmission with the given configuration.

The gain offset (and frequency offset) calibration values can be updated with the `sl_calib_write` CLI command. The syntax of the command is as follows:

```
sl_calib_write=<target>,<flags>,<gain_offset_low>,<gain_offset_mid>,<gain_offset_high>,<xo_ctune>,<gain_offset_ch14
```

The parameters for the `wifi_transmit_test_start` command are shown in the table below.

Parameter	Description
target	Target memory. Must be set to 1 (Flash)
flags	Bit 0: Reserved for future use Bit 1: Write current XO calibration value (tuned with `sl_freq_offset command` to target) Bit 2: Write XO calibration value provided as argument `xo_ctune` to target Bit 3: N/A Bit 4: Add argument `gain_offset_low` to current low-band gain offset calibration value and write to target Bit 5: Add argument `gain_offset_mid` to current mid-band gain offset calibration value and write to target Bit 6: Add argument `gain_offset_high` to current high-band gain offset calibration value and write to target Bit 8: Collect DPD coefficients data Bit 9: Burn DPD coefficients data Bit 10: Add argument `gain_offset_ch14` to current ch14 gain offset calibration value and write to target Bit 31-11: Reserved for future use
gain_offset_low	Low-band (Wi-Fi channel 1-3, BLE channel 0-11) gain offset correction value
gain_offset_mid	Mid-band (Wi-Fi channel 4-8, BLE channel 12-25) gain offset correction value
gain_offset_high	High-band (Wi-Fi channel 9-14, BLE channel 26-44) gain offset correction value
xo_ctune	XO Ctune calibration value [0…255]
gain_offset_ch14	Wi-Fi channel 14 gain offset correction (0.5 dB steps)

For example, to increase the low-band TX power by 1 dB, issue the `sl_calib_write=1,16,-2,0,0,0,0` command, whereas to decrease the high-band TX power by 0.5 dB, issue `sl_calib_write=1,64,0,0,1,0,0`.

Note:

1. The SiWx917 must be reset to apply the updated gain offset calibration parameters.
2. If gain_offset_ch14 is written, then it will be used as gain offset for Wi-Fi channel 14. If gain_offset_ch14 is not written, then gain_offset_high will be used for Wi-Fi channel 14.

3. Manufacturing Utility

The Manufacturing Utility is a set of commands built into the Simplicity Commander CLI supporting various production tasks, including performing the gain offset calibration.

Table 3.1. Manufacturing Utility Commands Used for Gain Offset Calibration

Command	Description
`commander manufacturing radio`	Enable/disable test mode infinite Wi-Fi transmission with specified settings
`commander manufacturing gain`	Update the gain offset calibration data (incremental, i.e., adds specified value to the compensation value)
`commander manufacturing evmoffset`	Update the EVM offset calibration data. Also used for setting the flash memory as the gain offset calibration data source when the SiWx917 production calibration data is stored in the eFuse memory.

Example usage (SoC mode):

0. Start test mode infinite burst packet Wi-Fi transmission with power index = 16 and 802.11g / 6 Mbps protocol:

```
commander manufacturing radio --start --power 16 --phy 6MBPS --channel 1 -d SiWG917M111MGTBA
```

1. Increase low-band gain offset by 2 (decreases TX power by ~ 1 dB) and store:

```
commander manufacturing gain --ch1 2 --skipload -d SiWG917M111MGTBA
```

2. Stop transmission:

```
commander manufacturing radio --stop --skipload -d SiWG917M111MGTBA
```

3. Enable loading the gain offset calibration data from the flash memory instead of the eFuse memory by writing the EVM offset calibration data. (Writing all zeroes will not change the EVM offset calibration.) Only required to perform once and **only for SiWx917 parts having no internal flash memory.**

```
commander manufacturing evmoffset --off0 0 --off1 0 --off2 0 --off3 0 --off4 0 –store
```

For the full set of command options, refer to the help information of the specific command (invoked with the `--help` option).

Additional guidelines on how to use the Manufacturing Utility are provided in UG574: SiWx917 SoC Manufacturing Utility User Guide and UG575: SiWx917 NCP Manufacturing Utility User's Guide.

4. TX Power Measurement and Gain Offset Calibration Procedure

The TX power can be measured in two ways: Either with continuously modulated stream test signal and a spectrum analyzer configured in channel power integration mode, or with burst packets and a Wi-Fi signal analyzer configured in TX analysis mode.

The recommended test signal parameters for the gain offset calibration are as follows:

- Modulation: 802.11g – 6 Mbps[1]
- Channels: 1, 6, and 11 (for quick calibration) or all (for high accuracy calibration)[2]
- Power setting: Power Index = 16
- Mode: Burst packets or continuously modulated stream
- Packet/stream length: 1000 byte for burst packets/260 byte for continuous stream
- Region: Worldwide

Note:

1. Unmodulated continuous wave transmission should not be used for this calibration as the output power of unmodulated tones may differ from the output power of modulated signals.
2. For high-accuracy calibration, measure the TX power offset at all channels and evaluate an optimum low-, mid-, and high-band gain offset compensation values to minimize the worst-case or RMS TX power offset across the band.

4.1 Measurement with Spectrum Analyzer

1. Configure the device to transmit a 16 dBm, continuous stream mode, 802.11g / 6 Mbps test signal (e.g., at channel 1,6, and 11).

   If using the Wi-Fi Calibration App, then modify the tx_test_info definition as below for calibrating channel 1:

```
sl_si91x_request_tx_test_info_t tx_test_info = {
  .enable      = 1,
  .power       = 16,
  .rate        = SL_WIFI_DATA_RATE_6, // -> 802.11g - 6 Mbps
  .length      = 260,
  .mode        = 1,                   // CONTINUOUS_MODE
  .channel     = 6,                   // 1/6/11
...
};
```

2. Connect the RF port of the device to the spectrum analyzer. If the test setup includes any cables or adapters, then the results should be compensated with the RF attenuation of these.
3. Configure the spectrum analyzer to calculate the integrated channel power. See the table below for the recommended settings.

Table 4.1. Spectrum Analyzer Settings For TX Power Measurement

Setting	Value
Reference level	At least 8 dB higher than Wi-Fi TX power level (e.g. 24 dBm for 16 dBm TX power)
Center frequency	Center of active channel (e.g., 2412 MHz for channel 0, 2437 MHz for channel 6, 2462 MHz for channel 11)
Detector	RMS
RBW	<1 MHz
Sweep time	Period to guarantee accurate measurement
Measurement	Channel Power
Integration Bandwidth	20 MHz

4. Observe the TX power and calculate the gain offset. An example is shown on the figure below, where Power Index = 16 was programmed, the adapter attenuation is ~0.3 dB and the power level at the spectrum analyzer is 14.8 dBm, which means the gain offset is 14.8 dBm-16 +0.3 dB≈ -0.9 dB .

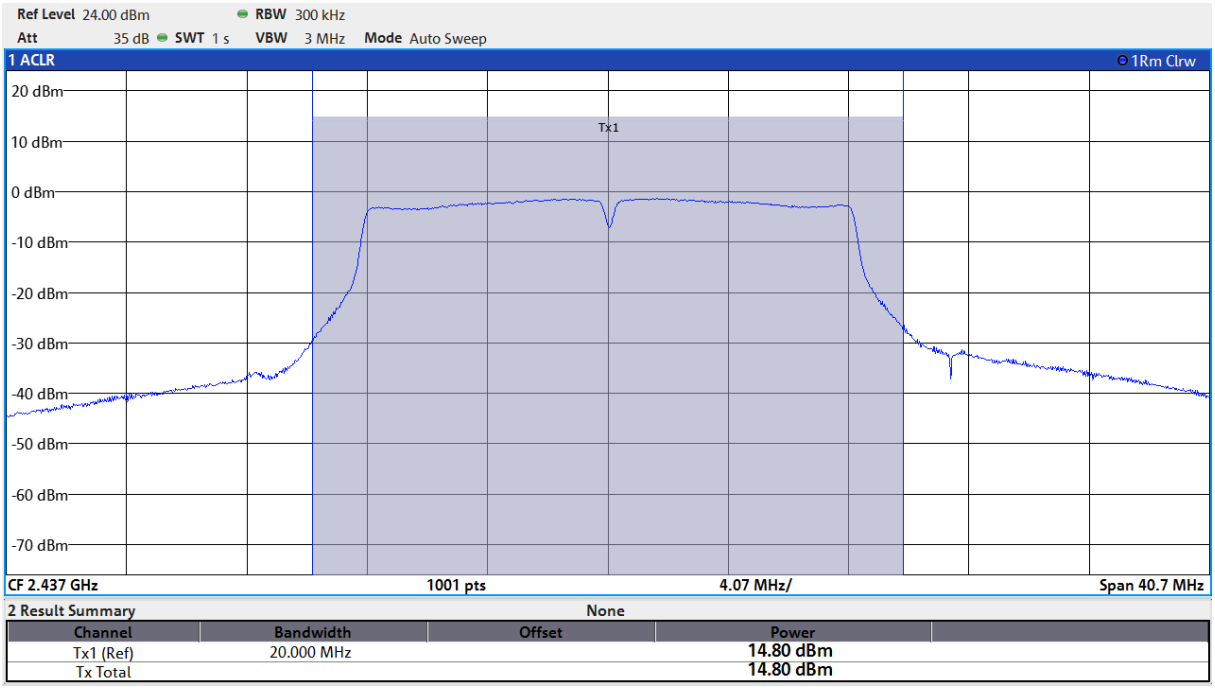


Figure 4.1. Power Measured with Spectrum Analyzer Before Gain Offset Calibration

5. Update the gain offset calibration value to eliminate the offset. In the example provided, the mid-band gain offset compensation should be increased by ~1 dB. If using the Wi-Fi Calibration App, then issuing `sl_calib_write=1,32,0,-2,0,0,0` will increase the mid-band gain offset by 1.0 dB.

   Note: The SiWx917 must be reset to apply the updated gain offset calibration parameters.

6. Verify the gain offset with the updated calibration and, if necessary, repeat step 4 and 5 until it is reduced to -0.5~0 dB.

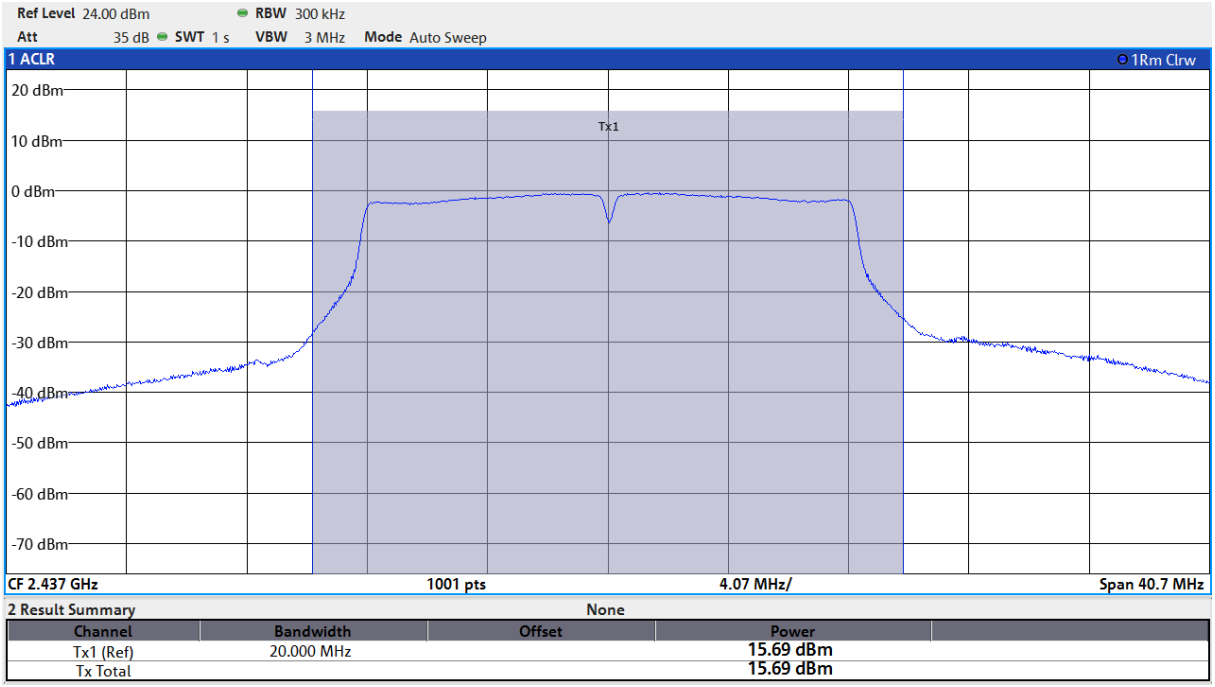


Figure 4.2. TX Power Measured with Spectrum Analyzer After Gain Offset Calibration

4.2 Measurement with Wi-Fi Signal Analyzer

1. Configure the device to transmit 16 dBm burst packets with 802.11g – 6 Mbps rate in transmit test mode.

   If using the Wi-Fi Calibration App, then update the tx_test_info definition as below for calibrating channel 1:

```
sl_si91x_request_tx_test_info_t tx_test_info = {
  .enable      = 1,
  .power       = 16,
  .rate        = SL_WIFI_DATA_RATE_6, // -> 802.11g - 6 Mbps
  .length      = 1000,
  .mode        = 0,                   // BURST_MODE
  .channel     = 6,                   // 1/6/11
...
};
```

2. Connect the RF port of the signal analyzer. If the test setup includes any cables or adapters, then the results should be compensated with the RF attenuation of these.
3. Configure the signal analyzer to Wi-Fi 802.11g TX analysis mode.
4. Observe the TX power and calculate the gain offset error. An example is shown in the figure below, where Power Index = 16 was programmed, the adapter attenuation is ~0.3 dB and the power level at the signal analyzer is 14.84 dBm, which means the gain offset is 14.84 dBm-16 +0.3 dB≈ -0.9 dB.

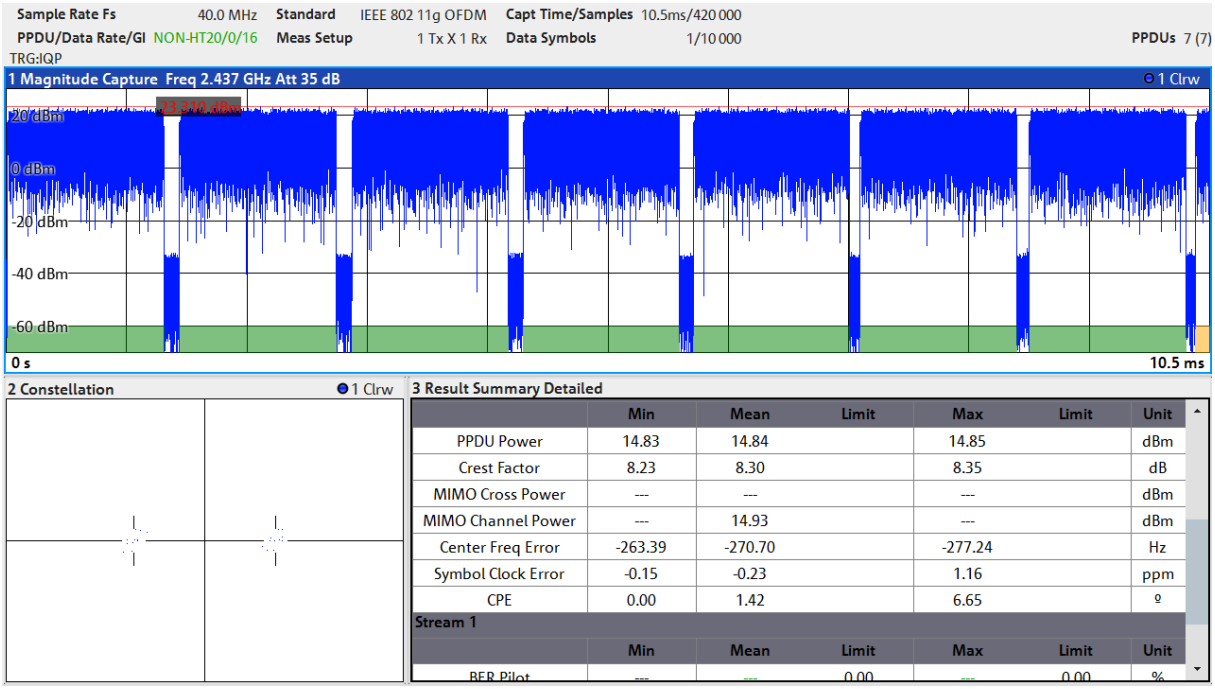


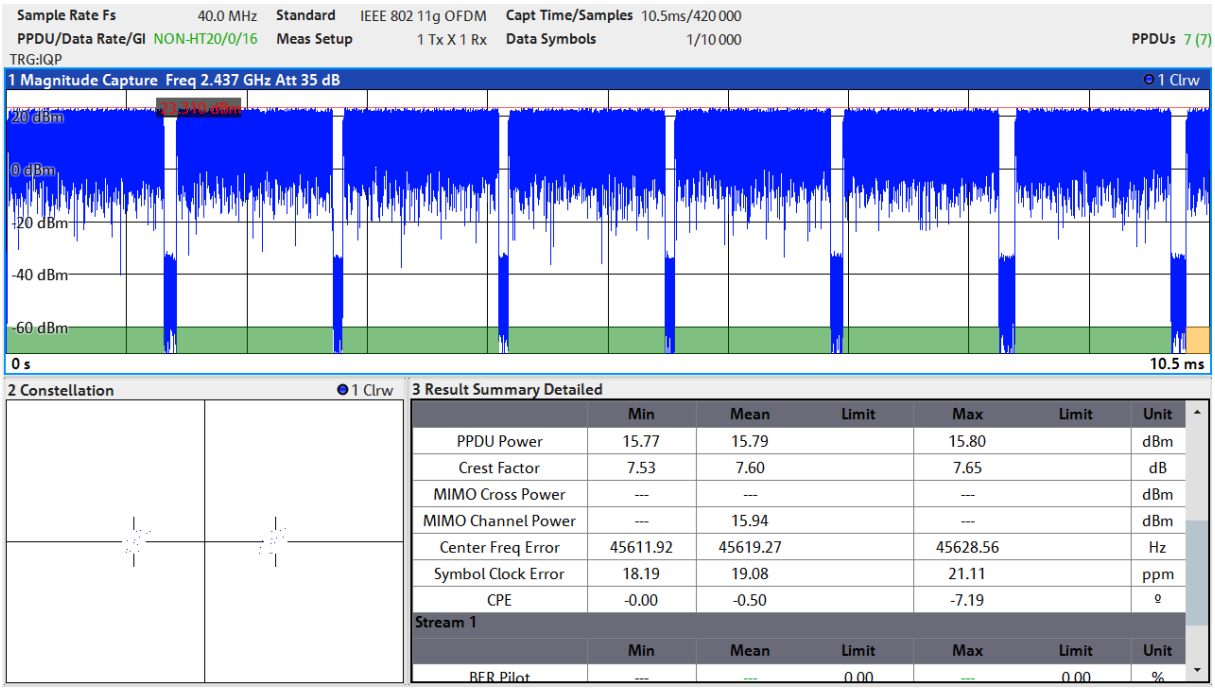
Figure 4.3. TX Power Measured with Wi-Fi Signal Analyzer Before Gain Offset Calibration

5. Update the gain offset calibration value to eliminate the offset. In the example provided, the mid-band gain offset should be increased by ~1 dB.

   If using the Wi-Fi Calibration App, then issuing `sl_calib_write=1,32,0,-2,0,0,0` will increase the mid-band gain offset by 1.0 dB.

   Note: The SiWx917 must be reset to apply the updated gain offset calibration parameters.

6. Verify the gain offset with the updated calibration and, if necessary, repeat step 4 and 5 until it is reduced to -0.5~0 dB.



	Min	Mean	Limit	Max	Limit	Unit
PPDU Power	15.77	15.79		15.80		dBm
Crest Factor	7.53	7.60		7.65		dB
MIMO Cross Power	---	---		---		dBm
MIMO Channel Power	---	15.94		---		dBm
Center Freq Error	45611.92	45619.27		45628.56		Hz
Symbol Clock Error	18.19	19.08		21.11		ppm
CPE	-0.00	-0.50		-7.19		º
Stream 1						
	Min	**Mean**	**Limit**	**Max**	**Limit**	**Unit**
BER Pilot	---	---	0.00	---	0.00	%

Figure 4.4. TX Power Measured with Wi-Fi Signal Analyzer After Gain Offset Calibration

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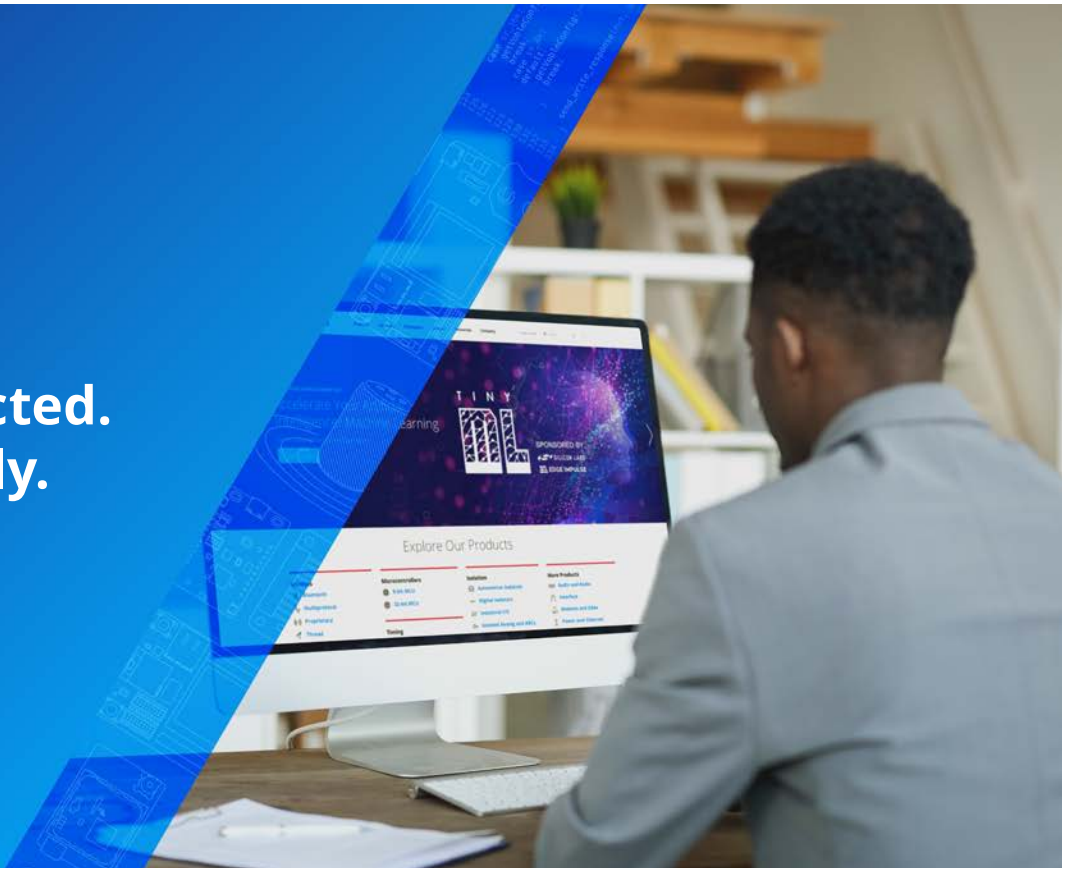

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