Si446x and FCC Part 15.247 Digital Transmission System Compliance at 902-928 MHz

1. Introduction

This application note demonstrates the compliance of Si446x RFICs with the regulatory requirements of FCC Part 15.247 for Digital Transmission Systems (DTS) operating in the unlicensed 902-928 MHz band. Within this frequency band, the FCC allows a transmit power level of up to 1 watt if certain operational conditions are met. The primary intent of these restrictions is to minimize interference to other operators in the band through “spreading” of the signal energy. This spreading may be accomplished in both the frequency and time domains through use of a Frequency Hopping Spread Spectrum (FHSS) system, or only in the frequency domain through use of a Wideband Digital Transmission System. In a DTS device, the signal energy may be spread across a wide bandwidth by use of digital modulation with a combination of a high data rate and/or high frequency deviation. As a result, a high level of transmit power level may be used while maintaining a relatively low power spectral density (PSD) at any point in the modulation spectrum.

The FCC previously required a DTS device to spread the signal energy through a modulation technique known as Direct Sequence Spread Spectrum (DSSS). In a DSSS system, the binary data of the transmit data stream is multiplied with a higher-rate pseudo-random chip sequence. The resulting data stream takes on the rate of the chip sequence and thus the bandwidth of the modulated signal on the air interface increases accordingly. The reverse process is performed on the receive side of the link; the received signal is again multiplied with a local copy of the pseudo-random chip sequence to “collapse” the signal down to its original bandwidth.

The FCC has recently eliminated the requirement that DTS devices must use DSSS techniques and now allows ***any*** form of wideband digital modulation to be used, as long as the resulting 6 dB bandwidth is above a minimum value (500 kHz) and the PSD is below a maximum level (+8 dBm / 3 kHz). Part 15.247 does not require use of a specific type of modulation (e.g., OOK, FSK, BPSK, QPSK, QAM, etc.)

This application note is concerned only with DTS devices, and does not discuss or demonstrate operation as a FHSS device. As will be shown, compliance is readily obtained when the high-power members of the Si446x family (e.g., Si4463/Si4464) are configured for their maximum transmit power level of +20 dBm. As a result, any of the chips within the Si446x family (including lower-power members such as Si4460 and Si4461) may also be used to achieve compliance. The measurements presented within this document were taken with a Si4463-B1 RFIC mounted on a 4463-PCE20C915-EK RFSW Pico RF Test Card (see section "5. Reference Design Schematic" on page 28).

The Si4463 chip was configured to transmit at its maximum power level by setting the PA_PWR_LVL property = 0x7F. Various data rates and deviations were chosen in order to comply with the required minimum 6 dB bandwidth and required maximum power spectral density. The tests were performed at room temperature with a supply voltage of V_{DD}=3.3 V.

1.1. Reference Documents

It is expected that readers will familiarize themselves with the following documents:

- Code of Federal Regulations (CFR) Title 47, Part 15 (with emphasis on Sections 15.247, 15.35, 15.205, 15.209, and 15.109)
- FCC Office of Engineering and Technology (Laboratory Division), “Guidance for Performing Compliance Measurements on Digital Transmission Systems (DTS) Operating Under Section 15.247”, June 5, 2014.

Part 15.247 contains the required levels of performance but does not provide details of the test methodology recommended to verify the performance (i.e., spectrum analyzer settings). The document from the Office of Engineering and Technology (hereafter, referred to as the “Compliance Measurements Guide”) discusses the recommended test methodology in detail; this test methodology was followed meticulously in development of this application note.

1.2. Summary of Measured Results

A summary of measured results is provided in Table 1.

Table 1. Summary of Measured Results

Spec Par	Parameter	Condition	Limit	Measured	Margin
15.247(b)(3)	Maximum Conducted Power	RBW > DTS BW Method (Peak)	+30 dBm	+20.59 dBm	9.41 dB
		AVGSA-1 Method	+30 dBm	+20.59 dBm	9.41 dB
15.247(a)(2)	6 dB Bandwidth	2GFSK DR=150 K Dev=200 K	500 kHz (min)	557.4 kHz	57.4 kHz
		2GFSK DR=4.8 K Dev=190 K	500 kHz (min)	512.6 kHz	12.6 kHz
15.247(e)	Power Spectral Density	AVGPSD-1 Method 2GFSK DR=150K Dev=200K Pout = +20.59 dBm	+8 dBm/3 kHz	+4.19 dBm/3kHz	3.81 dB
		AVGPSD-1 Method 2GFSK DR=500K Dev=175K Pout = +20.59 dBm	+8 dBm/3kHz	-0.36 dBm/3kHz	8.36 dB
		PKPSD Method 2GFSK DR=150 K Dev=200 K Pout = +20.59 dBm	+8 dBm/3 kHz	+15.06 dBm/ 3 kHz	-7.06 dB
15.247(d)	Spurious Emissions	Non-Restricted Bands	-30 dBc	-70.96 dBc	40.96 dB
		Restricted Bands	-43.2 dBm	-50.64 dBm	7.44 dB
		Unintentional Radiation (RX Mode)	-43.2 dBm	-87.05 dBm	43.85 dB

2. Summary of FCC Part 15.247 Requirements in the 902-928 Band

The main requirements of FCC Part 15.247 for Digital Transmission Systems operating in the 902-928 MHz band are summarized in this section. Part 15.247 is concerned only with performance of the transmitter, and contains no requirements on receiver performance. However, any RF device operating in the FCC 902-928 MHz band must also comply with the requirements of Part 15.209 “Radiated Emission Limits from Intentional Radiators” and Part 15.109 “Radiated Emission Limits from Unintentional Radiators”. Part 15.209 provides a limit on spurious emissions (including harmonics) while actively transmitting, and Part 15.109 provides a limit on spurious emissions in any non-transmit mode of operation (including RX mode, STANDBY mode, or SLEEP mode). This application note demonstrates compliance with these sections as well, for the sake of completeness.

2.1. FCC Part 15.247 (b) (3) Maximum Conducted Power

The maximum allowable conducted power is specified in Part 15.247(b)(3) as 1 watt. The standard provides for two different methods of measuring the conducted power. One method measures the peak conducted power, while the other method measures the average conducted power (summed across all antennas and all symbols in the signaling alphabet, and excluding any time interval when the device is not transmitting). Either method of measurement is acceptable to the FCC; however, the method used to verify maximum conducted power must also be used to verify the power spectral density (see section “3.3. FCC Part 15.247(e) Power Spectral Density”).

This maximum conducted power limit is based on the use of antennas with directional gains that do not exceed 6 dBi (dB relative to an isotropic antenna). If transmitting antennas of directional gain greater than 6 dBi are used, the conducted output power from the intentional radiator shall be reduced by the amount in dB that the directional gain of the antenna exceeds 6 dBi. This application note assumes use of antenna whose gain does not exceed 6 dBi.

2.2. FCC Part 15.247 (a) (2) 6 dB Bandwidth

The standard requires the 6 dB bandwidth of the DTS signal to be a minimum of 500 kHz. The Compliance Measurements Guide details two different acceptable methods of configuring a spectrum analyzer to verify compliance with this bandwidth requirement; both methods are demonstrated in this application note.

2.3. FCC Part 15.247 (e) Power Spectral Density

The standard requires the energy of the DTS signal to be sufficiently spread such that the power spectral density shall not exceed +8 dBm in any 3 kHz bandwidth. The FCC requires that this measurement be made during any interval of continuous transmission (i.e., the user cannot average over short transmission bursts with gaps between bursts, thus artificially reducing the average power spectral density). The FCC allows the power spectral density to be measured using either peak or average measurement techniques; however, the method used must match that used to verify Part 15.247(b)(3) Maximum Conducted Power.

2.4. FCC Part 15.247(d) Spurious Emissions

The FCC does not place any restrictions on spurious emissions that fall within the 902-928 MHz band (e.g., specifications on Adjacent Channel Power). However, the standard requires that emissions measured in any 100 kHz bandwidth ***outside*** of the 902-928 MHz band shall be at least 20 dB below the level measured in the 100 kHz bandwidth ***within*** the 902-928 MHz band that contains the highest level of desired power. If compliance with Part 15.247(b)(3) Maximum Conducted Power was demonstrated using RMS averaging, then the required level of attenuation is increased to 30 dB.

This general requirement on spurious emissions of -20 dBc (or -30 dBc) is relatively simple to meet. However, there are some frequency bands (known as restricted bands) in which tighter limits on radiated emissions apply. These restricted frequency bands are specified in Part 15.205, while the radiated emission limits within these bands are specified in Part 15.209. These emission limits are in terms of ***radiated*** field strengths. However, the Equivalent Isotropic Radiated Power (EIRP) may be calculated if the gain of the transmit antenna is known. If an isotropic antenna is assumed, the EIRP limits may be calculated as -49.2 dBm (from 216-960 MHz) and -41.2 dBm (above 960 MHz). The Compliance Measurements Guide requires the user to assume a minimum antenna gain of 2 dBi, thus effectively tightening these limits to -51.2 dBm and -43.2 dBm, respectively. Verification of compliance with these EIRP limits using a conducted measurement technique thus provides a first-order approximation of

compliance with the actual radiated emission limits. This conducted measurement technique is used within this application note.

2.4.1. FCC Part 15.205 Restricted Frequency Bands

For the sake of completeness, the list of Restricted Frequency Bands from Part 15.205 is shown below. The reader should note that when operating in the 902-928 MHz frequency band, the 3rd, 4th, 5th, 8th, 9th, and 10th harmonics (potentially) fall in a restricted band.

MHz	MHz	MHz	GHz
0.090–0.110	16.42–16.423	399.9–410	4.5–5.15
[1] 0.495–0.505	16.69475–16.69525	608–614	5.35–5.46
2.1735–2.1905	16.80425–16.80475	960–1240	7.25–7.75
4.125–4.128	25.5–25.67	1300–1427	8.025–8.5
4.17725–4.17775	37.5–38.25	1435–1626.5	9.0–9.2
4.20725–4.20775	73–74.6	1645.5–1646.5	9.3–9.5
6.215–6.218	74.8–75.2	1660–1710	10.6–12.7
6.26775–6.26825	108–121.94	1718.8–1722.2	13.25–13.4
6.31175–6.31225	123–138	2200–2300	14.47–14.5
8.291–8.294	149.9–150.05	2310–2390	15.35–16.2
8.362–8.366	156.52475–156.52525	2483.5–2500	17.7–21.4
8.37625–8.38675	156.7–156.9	2690–2900	22.01–23.12
8.41425–8.41475	162.0125–167.17	3260–3267	23.6–24.0
12.29–12.293	167.72–173.2	3332–3339	31.2–31.8
12.51975–12.52025	240–285	3345.8–3358	36.43–36.5
12.57675–12.57725	322–335.4	3600–4400	([2])
13.36–13.41.			

Figure 1. Restricted Frequency Bands

2.4.2. FCC Part 15.209 General Limits on Radiated Emissions

For the sake of completeness, the General Limits on Radiated Emissions from Part 15.209 are also shown below.

Frequency (MHz)	Field strength (microvolts/meter)	Measurement distance (meters)
0.009–0.490	2400/F(kHz)	300
0.490–1.705	24000/F(kHz)	30
1.705–30.0	30	30
30–88	100 **	3
88–216	150 **	3
216–960	200 **	3
Above 960	500	3

Figure 2. General Limits on Radiated Emissions

3. Measurement Results

All measurements were taken with an Anritsu MS2692A signal analyzer. The analyzer settings used for each measurement are noted within each measurement section. The WDS scripts used to configure the RFIC are shown in shown in section “4. Wireless Development Suite (WDS) Script Files” .

All measurements within this section were taken with the RFIC configured for an output power level of +20 dBm. Unless otherwise noted, the RFIC was configured for 2GFSK modulation (BT=0.5) by a PN15 sequence with DR=150 kbps and Dev=200 kHz.

3.1. FCC Part 15.247(b)(3) Maximum Conducted Power

The allowed maximum conducted transmitter power is specified in FCC Part 15.247(b)(3) as 1 watt. The standard provides for two acceptable methods of measuring the conducted power. One method measures the peak conducted power, while the other method measures the average conducted power. The Compliance Measurements Guide discusses several different techniques for each of these measurement methods. Compliance with the requirement for Maximum Conducted Power is demonstrated using two of these techniques, one for the peak conducted power method and the other for the average conducted power method.

3.1.1. Maximum Peak Conducted Output Power (RBW>DTS BW Method)

In this test method, the peak conducted power is measured by configuring the spectrum analyzer to use a peak detector, a resolution bandwidth that is greater than the bandwidth of the DTS signal, and trace mode = max hold. The spectrum analyzer configuration provided in the Compliance Measurements Guide is as follows:

- Set the RBW ≥ DTS signal bandwidth
- Set the VBW ≥ 3 x RBW
- Set the Frequency Span ≥ 3 x RBW
- Set the Sweep Time = Auto Couple
- Set the Detector type = Peak Detector
- Set Trace Mode = Max Hold
- Allow the resulting trace to fully stabilize
- Use the Peak Marker function to determine the peak amplitude level

The peak conducted output power measured by this method is shown in Figure 3. The Si446x family of chips complies with the requirements of FCC Part 15.247(b)(3) for Maximum Peak Conducted Power.

- Limit: 1 W = +30 dBm (max)
- Measured: +20.59 Bm
- Margin: 9.41 dB (PASS)

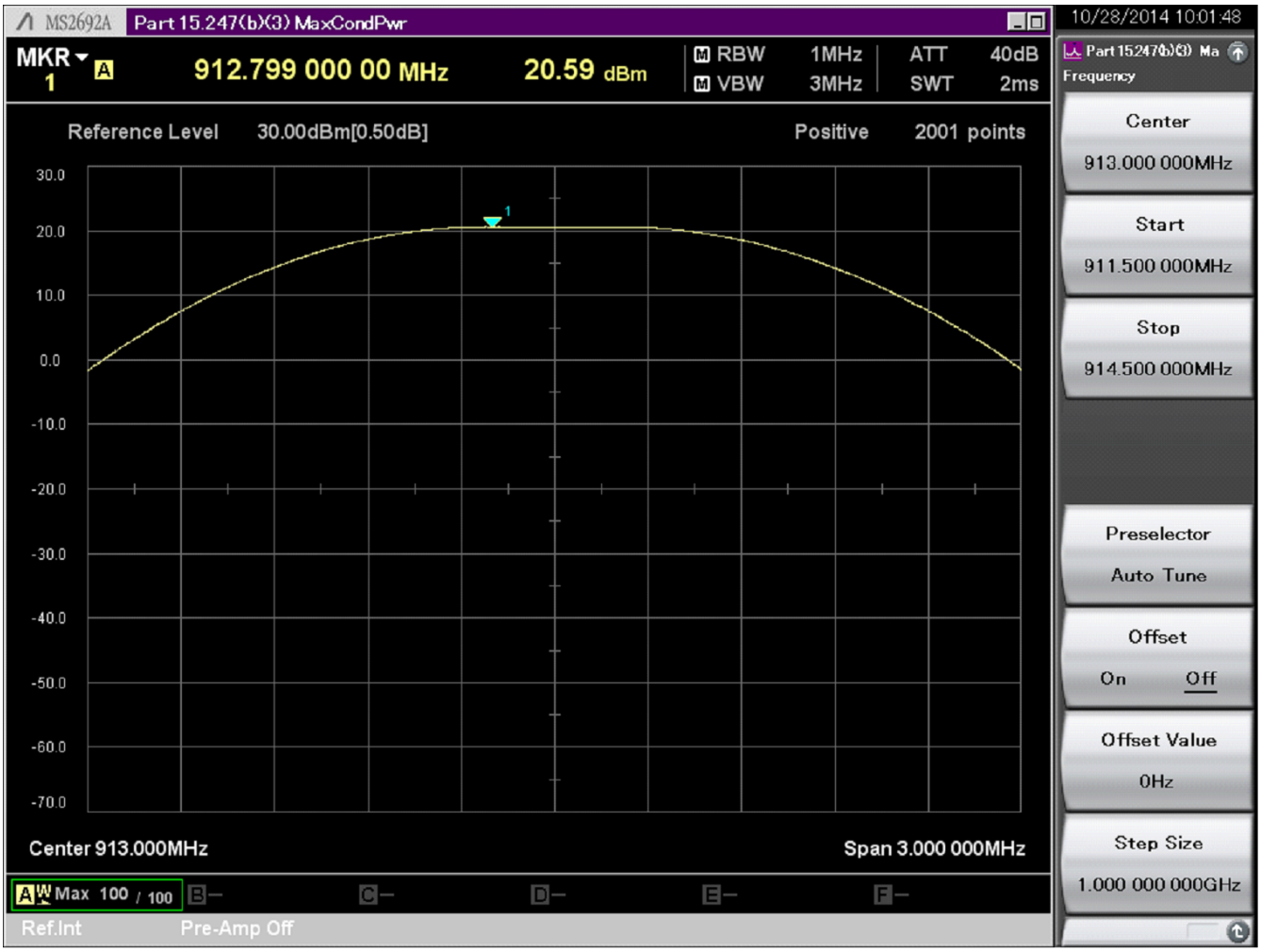


Figure 3. Peak Conducted Output Power

3.1.2. Maximum Average Conducted Output Power (AVGSA-1 Method)

In this test method, the average conducted power is measured by configuring the spectrum analyzer to use an RMS detector, a resolution bandwidth that is 1% to 5% of the occupied bandwidth of the DTS signal, trace mode = averaging, and integrating the power across the occupied bandwidth of the signal. (Many spectrum analyzers have such a band power function as a built-in feature.) The spectrum analyzer configuration provided in the Compliance Measurements Guide is as follows:

- Set the Frequency Span ≥ 1.5 x OCBW
- Set the RBW = 1% to 5% of the OCBW (but not to exceed 1 MHz)
- Set the VBW ≥ 3 x RBW
- Set the Sweep Time = Auto Couple
- Set the Number of Points in Sweep ≥ 2 * FreqSpan / RBW
- Set the Detector type = RMS Detector
- Set Trace Mode = Averaging (minimum of 100 sweeps)
- Compute the power by integrating the spectrum across the OCBW using the Band Power function of the spectrum analyzer

The average conducted output power measured by this method is shown in Figure 4. The Si446x family of chips complies with the requirements of FCC Part 15.247(b)(3) for Maximum Average Conducted Power.

- Limit: 1 W = +30 dBm (max)

- Measured: +20.59 dBm
- Margin: 9.41 dB (PASS)

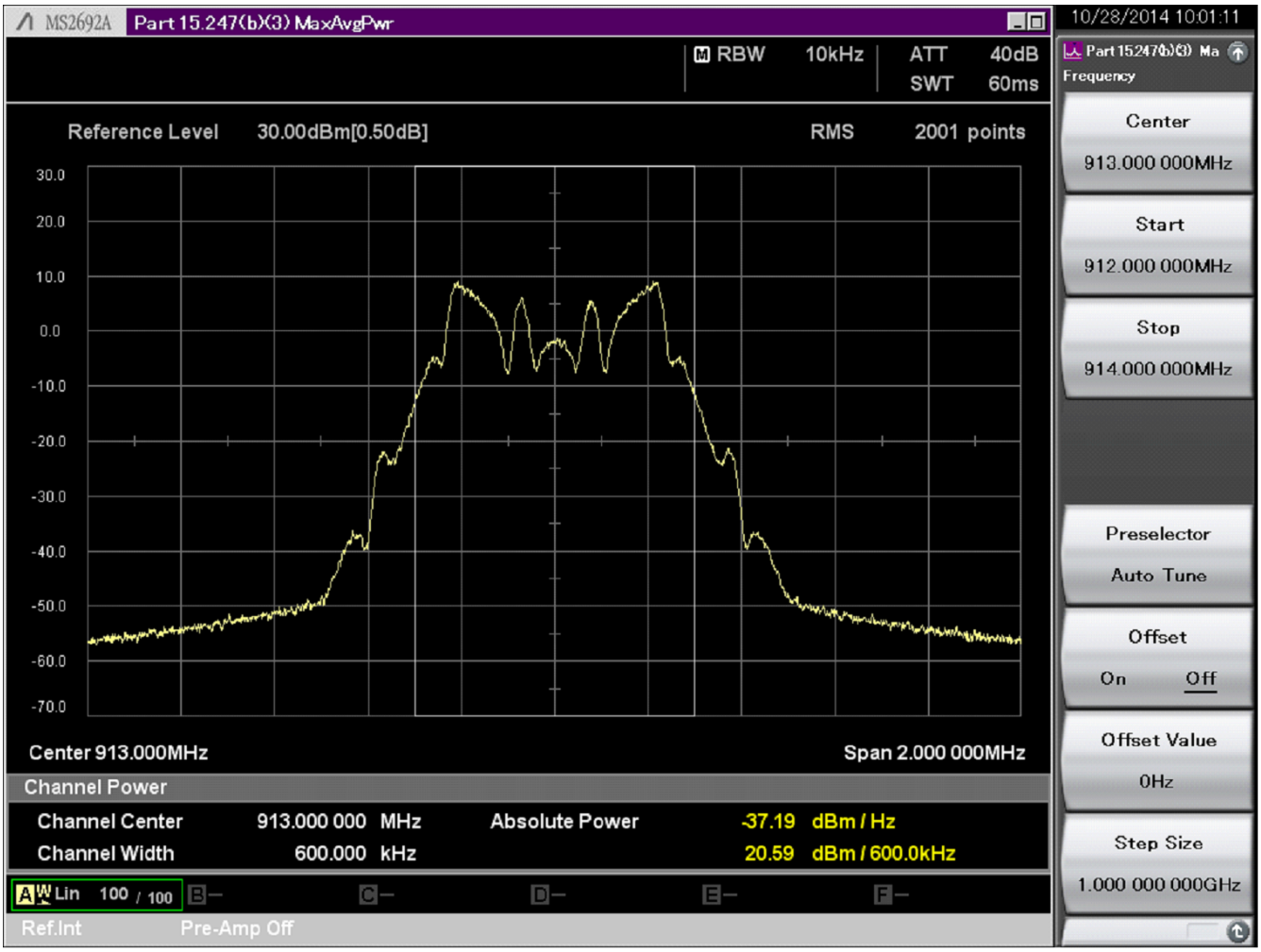


Figure 4. Average Conducted Power (Band Power Method)

As the modulation protocol selected for this test (i.e., 2GFSK) was a constant envelope type of modulation, the values of output power measured by the peak and average methods are essentially identical. Selection of a modulation protocol with non-constant envelope will likely result in different output power levels when measured by these two methods.

3.2. FCC Part 15.247(a)(2) 6 dB Bandwidth

FCC Part 15.247(a)(2) requires the 6 dB bandwidth of the DTS signal to be at least 500 kHz.

It is self-evident that any desired value of modulation bandwidth may be obtained by the appropriate selection of data rate and/or deviation. Compliance with the minimum 6 dB bandwidth requirement may thus be achieved with a wide range of data rates and deviations. The plots shown here demonstrate regulatory compliance for a variety of selected modulation protocols, but they should not be construed as the ***only*** possible modulation protocols that achieve compliance with the 6 dB bandwidth requirement. However, the selection of modulation protocol also has a significant effect on power spectral density, and thus two different modulation protocols that are both compliant with the 6 dB bandwidth requirement may be limited to greatly different power levels under Part 15.247(e) Power Spectral Density. (See section “3.3.3. Effect of Modulation Index on Power Spectral Density and Max Transmit Power” .) It is ultimately the responsibility of the user to select the data rate and deviation so as to maintain compliance with ***all*** regulatory requirements.

The Compliance Measurements Guide provides for two acceptable methods of measuring the modulation bandwidth of the DTS signal. Both methods share the same basic spectrum analyzer settings; one method manually adjusts markers to the 6 dB down points, while the second method takes advantage of automatic bandwidth measurement functionality of the spectrum analyzer. Compliance with the requirement for 6 dB bandwidth is here demonstrated using both of these techniques.

3.2.1. 6 dB Bandwidth (Option 1)

In this test method, the modulated bandwidth of the DTS signal is measured by configuring the spectrum analyzer to use a peak detector, a resolution bandwidth of 100 kHz, and trace mode = max hold. The spectrum analyzer configuration provided in the Compliance Measurements Guide is as follows:

- Set the RBW = 100 kHz
- Set the VBW ≥ 3 x RBW
- Set the Sweep Time = Auto Couple
- Set the Detector type = Peak Detector
- Set Trace Mode = Max Hold
- Allow the resulting trace to fully stabilize
- Measure the width between the two outermost frequency points whose amplitudes are attenuated by 6 dB, relative to the maximum level measured in the fundamental emission

The measured 6 dB bandwidth for a modulation protocol of 2GFSK, BT=0.5, DR=150 kbps, Deviation=200 kHz is shown in Figure 5. The Si446x family of chips complies with the requirements of FCC Part 15.247(a)(2) for minimum 6 dB Bandwidth for this selected modulation protocol.

- Limit: 500 kHz (min)
- Measured: 557.4 kHz
- Margin: 57.4 kHz (PASS)

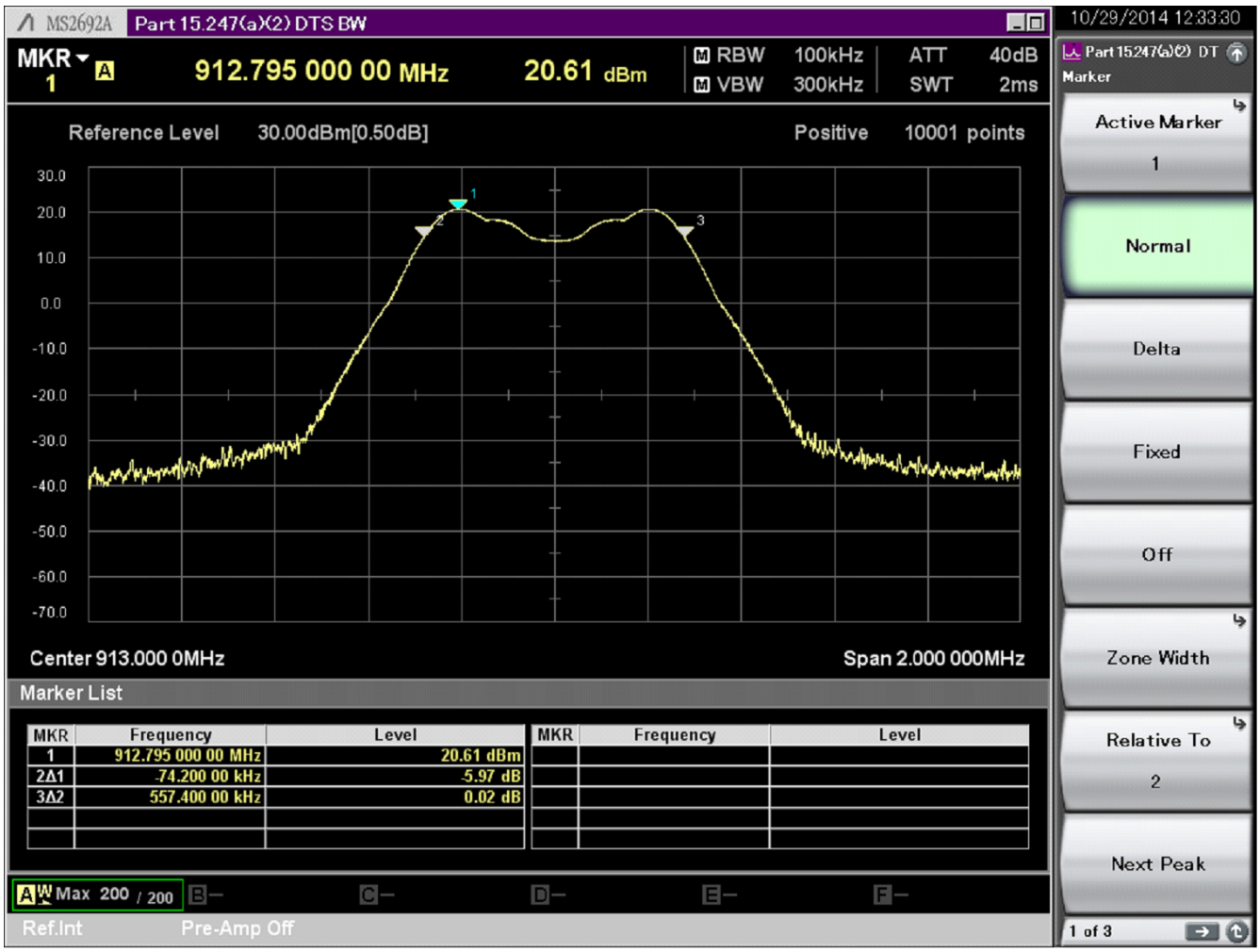


Figure 5. 6 dB Bandwidth (2GFSK DR=150 kbps Dev=200 kHz)

3.2.2. 6 dB Bandwidth (Option 2)

In this test method, the spectrum analyzer is configured in exactly the same fashion as for Option 1, but the automatic Occupied Bandwidth (X dB) function of the spectrum analyzer is used. The spectrum analyzer configuration provided in the Compliance Measurements Guide is as follows:

- Set the RBW = 100 kHz
- Set the VBW ≥ 3 x RBW
- Set the Sweep Time = Auto Couple
- Set the Detector type = Peak Detector
- Set Trace Mode = Max Hold
- Allow the resulting trace to fully stabilize
- Use the automatic Occupied Bandwidth (X dB) function of the spectrum analyzer, with ‘X’ = 6 dB

Care shall be taken so that the automatic bandwidth measurement is not influenced by any intermediate power nulls in the fundamental emission that might be ≥ 6 dB. In such a case, the analyzer may report the bandwidth between ***any*** two frequency points whose amplitudes are attenuated by 6 dB relative to the maximum level measured in the fundamental emission, instead of the outermost frequency points.

The measured 6 dB bandwidth for a modulation protocol of 2GFSK, BT=0.5, DR=4.8 kbps, Deviation=190 kHz is shown in Figure 6. The Si446x family of chips complies with the requirements of FCC Part 15.247(a)(2) for minimum 6 dB Bandwidth for this selected modulation protocol.

- Limit: 500 kHz (min)
- Measured: 512.6 kHz
- Margin: 12.6 kHz (PASS)

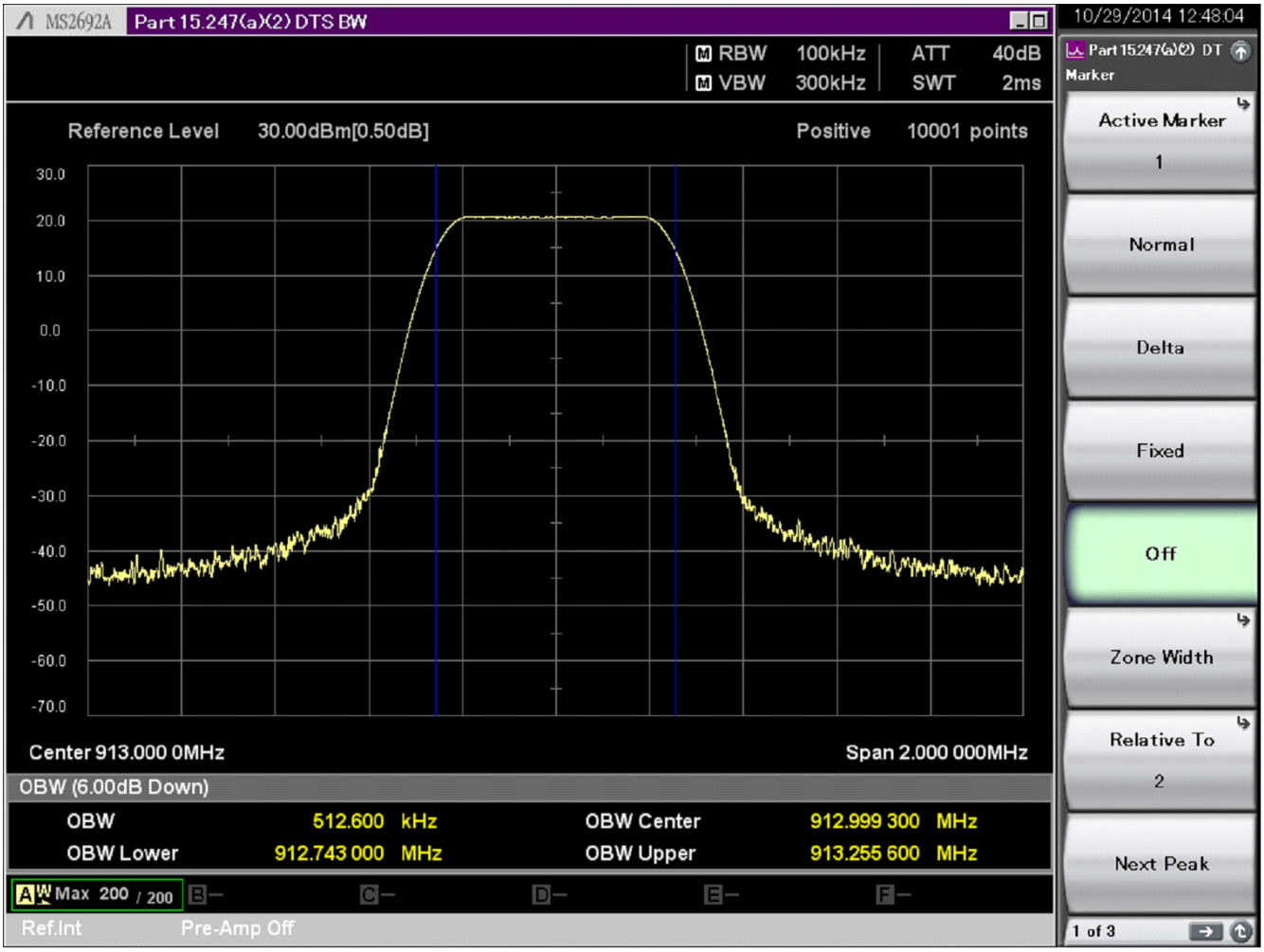


Figure 6. 6 dB Bandwidth (2GFSK DR=4.8 kbps Dev=190 kHz)

3.3. FCC Part 15.247(e) Power Spectral Density

The FCC requires the energy of the DTS signal to be sufficiently spread such that the power spectral density shall not exceed +8 dBm in any 3 kHz bandwidth during any interval of continuous transmission. The FCC allows the power spectral density to be measured using either peak or average measurement techniques; however, the method used must match that used to verify Part 15.247(b)(3) Maximum Conducted Power. The average measurement technique generally returns a lower measured value of power spectral density and thus allows use of a higher transmit output power level without exceeding the +8 dBm / 3 kHz limit.; it may thus prove advantageous to use the average measurement technique, where possible.

The Compliance Measurements Guide provides for several acceptable methods of measuring the power spectral density of the DTS signal. Compliance with the requirement for power spectral density is here demonstrated using two of these methods.

3.3.1. Average Power Spectral Density (AVGPSD-1 Method)

In this test method, the power spectral density of the DTS signal is measured by configuring the spectrum analyzer to use an RMS detector, a resolution bandwidth of between 3 kHz and 100 kHz, and trace mode = max hold. The spectrum analyzer configuration provided in the Compliance Measurements Guide is as follows:

- Set the Frequency Span = 1.5 x Occupied Bandwidth (e.g., 750 kHz for OCBW = 500 kHz)
- Set 3 kHz ≤ RBW ≤ 100 kHz
- Set the VBW ≥ 3 x RBW
- Set the Detector type = RMS Detector
- Set the Number of Points in Sweep ≥ 2 * FreqSpan / RBW
- Set the Sweep Time = Auto Couple
- Set Trace Mode = Averaging (minimum of 100 sweeps)
- Use the peak marker function to find the maximum amplitude level within the sweep
- If the measured value exceeds the limit, reduce the RBW (to no less than 3 kHz) and repeat

The measured power spectral density for a modulation protocol of 2GFSK, BT=0.5, DR=150 kbps, Deviation=200 kHz is shown in Figure 7. The Si446x family of chips complies with the requirements of FCC Part 15.247(e) Power Spectral Density for this selected modulation protocol and output power level (i.e., +20.59 dBm). It would be possible to increase the output power by 3.81 dB (i.e., to +24.4 dBm) and still maintain compliance with this PSD requirement.

- Limit: +8 dBm / 3 kHz (max)
- Measured: +4.19 dBm / 3 kHz
- Margin: 3.81 dB (PASS)

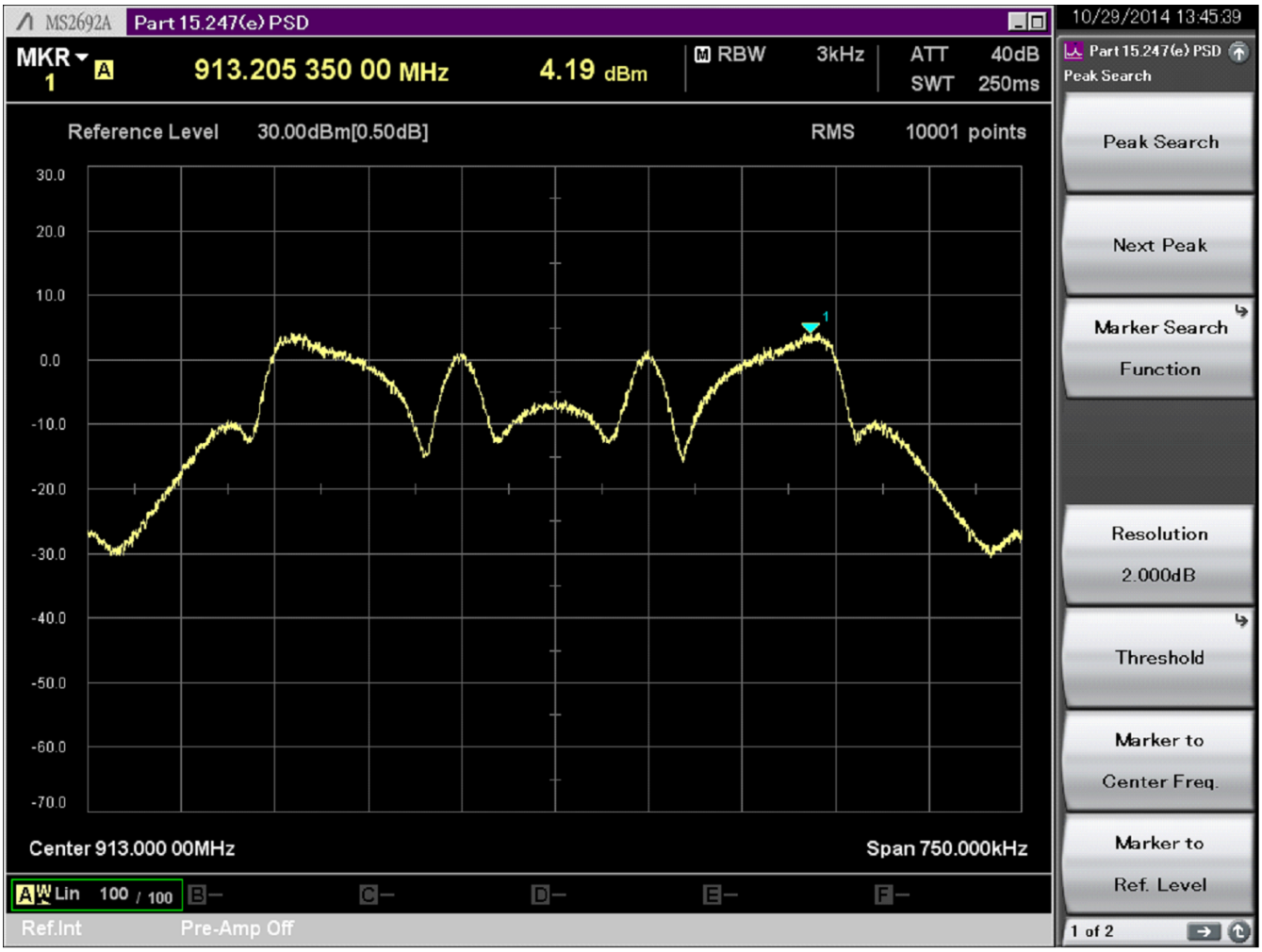


Figure 7. Average Power Spectral Density (Pout=+20 dBm, 2GFSK DR=150 kbps Dev=200 kHz)

3.3.2. Peak Power Spectral Density (PKPSD Method)

In this test method, the power spectral density of the DTS signal is measured by configuring the spectrum analyzer to use a peak detector, a resolution bandwidth of between 3 kHz and 100 kHz, and trace mode = max hold. The spectrum analyzer configuration provided in the Compliance Measurements Guide is as follows:

- Set the Frequency Span = 1.5 x DTS 6 dB bandwidth (e.g., 750 kHz for 6 dB BW = 500 kHz)
- Set 3 kHz ≤ RBW ≤ 100 kHz
- Set the VBW ≥ 3 x RBW
- Set the Detector type = Peak Detector
- Set the Sweep Time = Auto Couple
- Set Trace Mode = Max Hold
- Allow the resulting trace to fully stabilize
- Use the peak marker function to find the maximum amplitude level within the sweep
- If the measured value exceeds the limit, reduce the RBW (to no less than 3 kHz) and repeat

The measured power spectral density for a modulation protocol of 2GFSK, BT=0.5, DR=150 kbps, Deviation=200 kHz is shown in Figure 8. The Si446x family of chips fails to comply with the requirements of FCC Part 15.247(e) Power Spectral Density for this selected modulation protocol and output power level (i.e., +20.59 dBm). It would be necessary to reduce the output power by 7.06 dB (i.e., to +13.53 dBm) in order to gain compliance with this PSD requirement, when using this measurement method.

- Limit: +8 dBm / 3 kHz (max)
- Measured: +15.06 dBm / 3 kHz
- Margin: -7.06 dB (FAIL)

Figure 8. Peak Power Spectral Density (Pout=+20 dBm, 2GFSK DR=150 kbps Dev=200 kHz)

These measurements of the power spectral density illustrate the significant difference in performance that may be observed when using the different acceptable test methods (peak and average). Measurement of the power spectral density using the averaging technique will be used throughout the remainder of this application note.

3.3.3. Effect of Modulation Index on Power Spectral Density and Max Transmit Power

The selected modulation protocol affects not only the bandwidth of the modulated signal, but also the shape of its power spectral density. As the PSD must remain below the +8 dBm/3 kHz limit, the selected modulation protocol may significantly impact the maximum conducted output power that may be transmitted while remaining in compliance with this PSD limit.

The general shape of the PSD of a 2GFSK-modulated signal is determined by its modulation index ‘h’:

$$h = \frac{2 \times \text{Deviation}}{\text{DataRate}}$$

Equation 1.

Certain values of modulation index result in PSDs that do not appear as continuously-spread spectra but instead contain discrete tones. These values of modulation index should be avoided as it will be necessary to reduce the output power until these discrete tones fall under the +8 dBm/3 kHz limit. The most problematic values of modulation index are integer values, e.g., h = {1, 2, 3…}. The traces shown in Figure 9 illustrate this concept.

These spectra result from using the same data rate (DR=150 kbps) but with different modulation indices (h = 2.33, 2.67, and 3.0). It is apparent that the discrete tone appearing in the h=3 trace (green trace) would require the output power to be decreased by 4.7 dB in order to comply with the +8 dBm/3 kHz limit of Part 15.247(e), while the output power could be increased in the other two test cases (blue and purple traces) while still remaining compliant with this same limit.

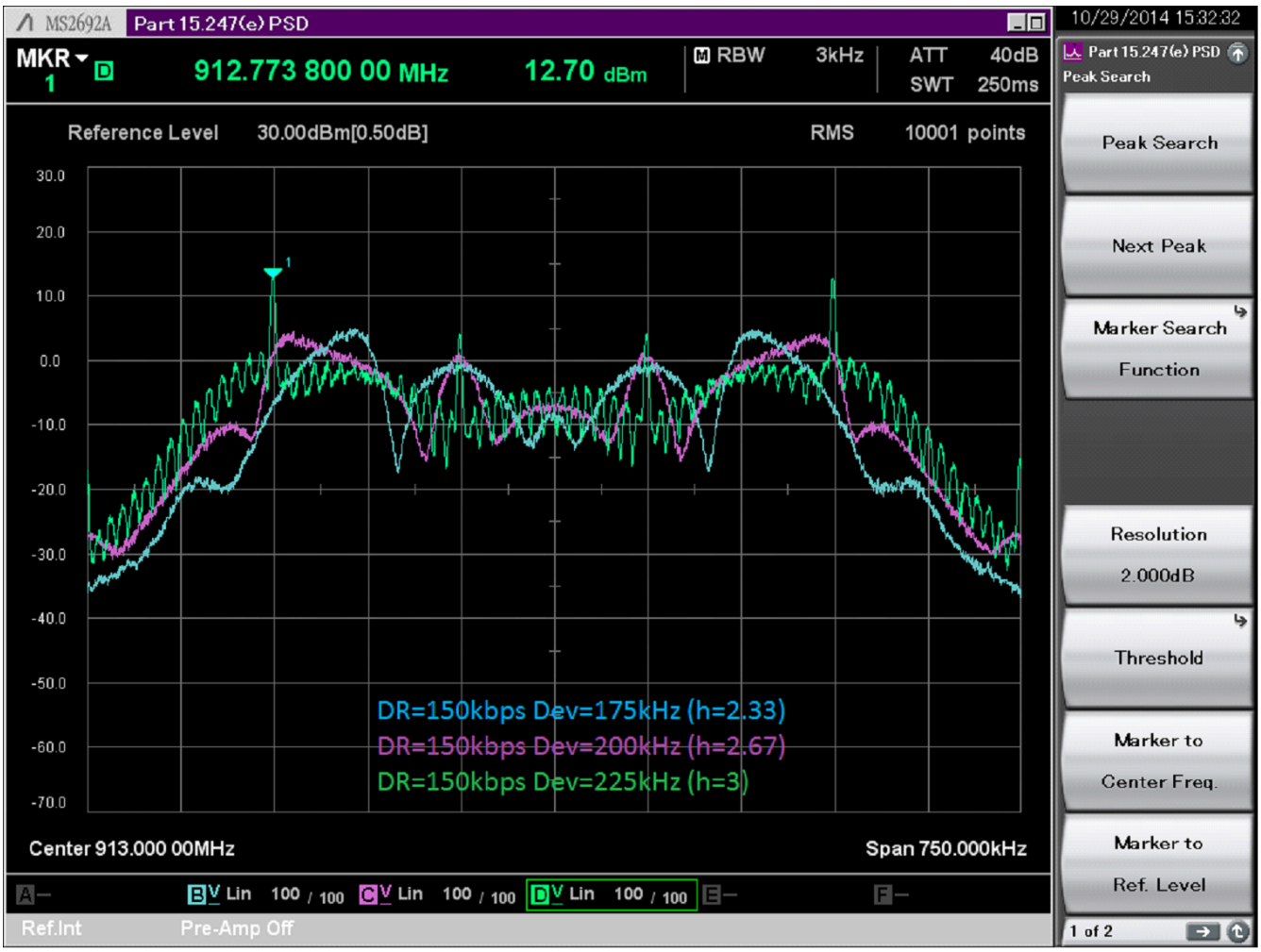


Figure 9. Power Spectral Density for Various Values of Modulation Index

As mentioned in section “3.2. FCC Part 15.247(a)(2) 6 dB Bandwidth” , it is possible to comply with the minimum 6 dB bandwidth requirement with a wide range of modulation protocols. While both data rate and deviation affect the resulting bandwidth, the deviation has the stronger influence. Thus it is possible to comply with the minimum 6 dB bandwidth limit with a low data rate but high deviation (e.g., for DR=4.8 kbps Dev=190 kHz). However, the PSD for such low-DR, high-Dev protocols will exhibit strong peaks or “horns” at the outer edges of their bandwidths, as shown in Figure 10. For this modulation protocol, it would again be necessary to reduce the output power in order to gain compliance with the +8 dBm/3 kHz limit of Part 15.247(e).

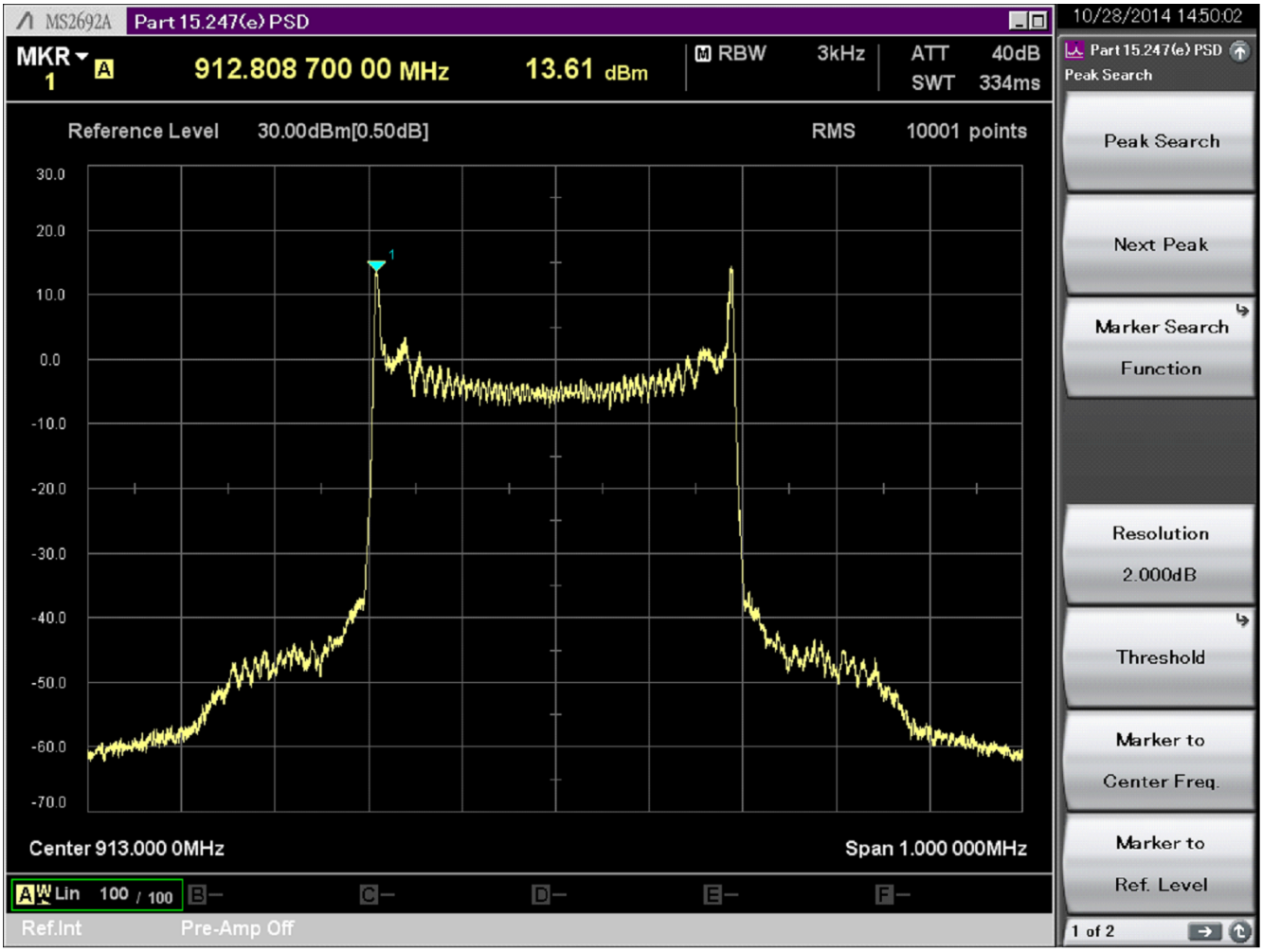


Figure 10. Average Power Spectral Density (Pout =+20 dBm, 2GFSK DR=4.8 kbps Dev=190 kHz)

Operation under Part 15.247 is generally motivated by the desire to transmit higher levels of output power, with a presumed improvement in link budget. The maximum conducted output power allowed under Part 15.247(b)(3) is 1 watt, but only if the 6 dB bandwidth and PSD requirements are simultaneously met. It is therefore useful to search for a modulation protocol whose PSD allows operation at an output power level of 1 watt, while simultaneously complying with the minimum 6 dB bandwidth limit.

One such modulation protocol is 2GFSK, BT=0.5, DR=500 kbps, Dev=175 kHz. This choice of modulation index (h=0.7) results in a very flat PSD, as shown in Figure 11. There are no “peaks” in the PSD that would require reducing the output power to remain compliant with the +8dBm/3kHz limit. In this test case, the output power could theoretically be increased by 8.36 dB (e.g., by addition of an external power amplifier) while remaining compliant with the PSD limit. As the actual measured transmit power level was previously shown to be +20.59 dBm (for this device and board, see Figure 4), this would imply compliant operation at an output power level of +28.95 dBm, quite close to the maximum-allowed limit of +30 dBm = 1 watt.

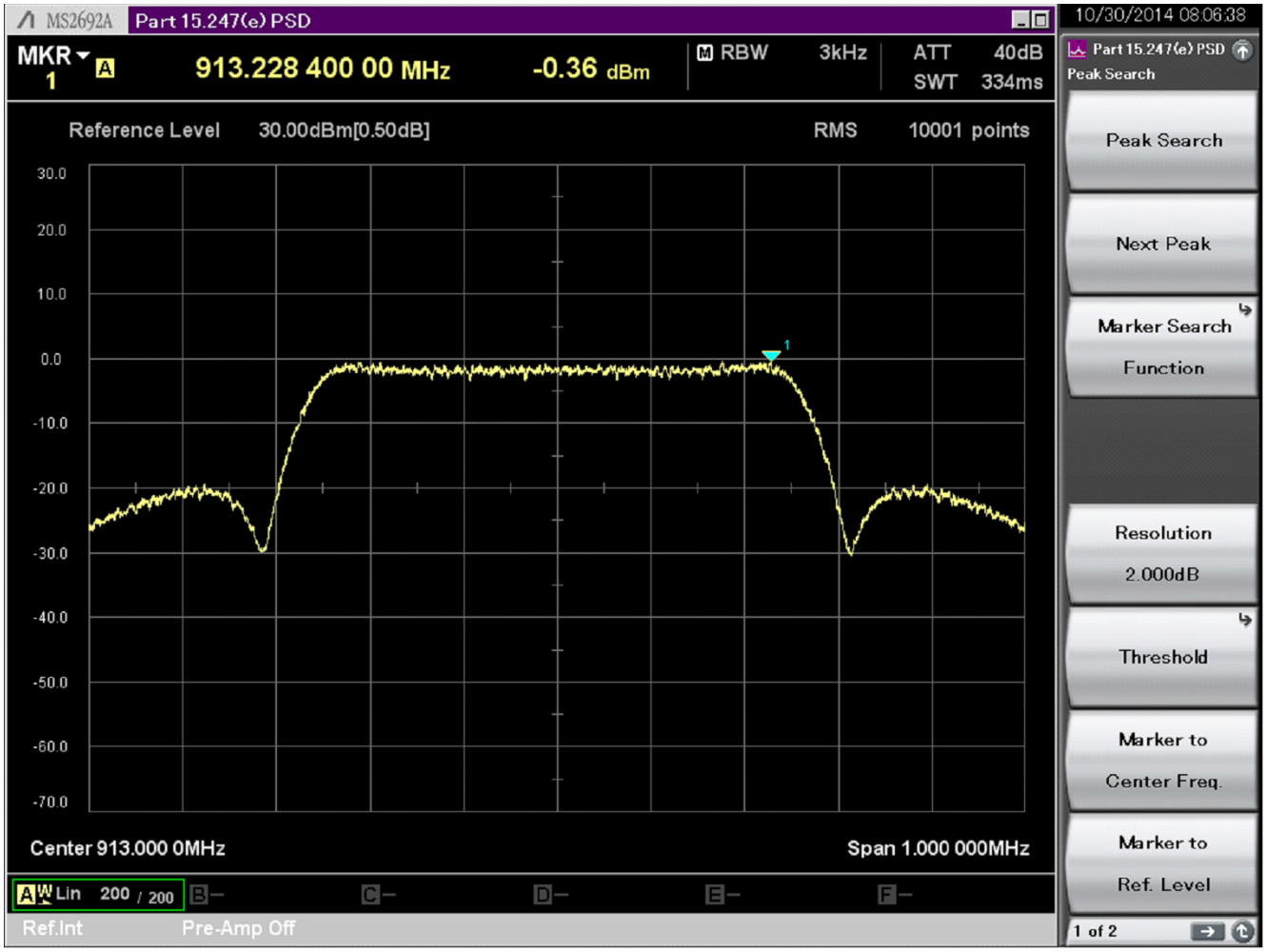


Figure 11. Average Power Spectral Density (Pout=+20 dBm, 2GFSK DR=500 kbps Dev=175 kHz)

The reader is reminded that all tests in this application note were performed with modulation by a PN15 data sequence, and thus represent a best-case condition of “white” or noise-like data content. A typical data transmission may contain fields with highly repetitive content (e.g., Preamble or Sync Word fields) that may give rise to higher discrete tones or peaks in the PSD, thus limiting the output power to lower values than demonstrated here.

3.4. FCC Part 15.247(d) Spurious Emissions

3.4.1. Spurious Emissions in Non-Restricted Frequency Bands

The FCC requires that peak spurious emissions in any 100 kHz bandwidth that fall outside the band of operation (i.e., 902-928 MHz) and in non-restricted frequency bands (see Part 15.205) shall be attenuated by a minimum of 20 dB relative to the maximum in-band power spectral density level in a 100 kHz bandwidth. This -20 dBc limit is applicable if compliance with Part 15.247(b)(3) Maximum Conducted Power was verified using a peak measurement procedure; the required amount of attenuation is increased to 30 dB if the Maximum Conducted Power was verified using an average measurement procedure. In either case, the measurement of the spurious emission itself is performed using a peak measurement technique.

The measurement consists of first establishing a reference level, followed by measurement of the actual spurious emission. The spectrum analyzer configuration provided in the Compliance Measurements Guide for establishing the reference level is as follows:

- Set the Center Frequency = DTS channel center frequency

- Set the Frequency Span = 1.5 x DTS 6dB bandwidth (e.g., 750 kHz for 6 dB BW = 500 kHz)
- Set the RBW = 100 kHz
- Set the VBW ≥ 3 x RBW
- Set the Detector type = Peak Detector
- Set the Sweep Time = Auto Couple
- Set Trace Mode = Max Hold
- Allow the resulting trace to fully stabilize
- Use the peak marker function to find the maximum PSD level within the sweep

The measurement of the actual spurious emission is performed with the same spectrum analyzer configuration, except tuning the center frequency and span to encompass the range of spurious emissions to be measured.

The reference level established by this procedure is shown in Figure 12. A plot of the measured spurious emissions falling within the ±17 MHz bands immediately adjacent to the 902-928 MHz band is shown in Figure 13. The Si446x family of chips complies with the requirements of FCC Part 15.247(d) for Spurious Emissions within the measured frequency span.

- Limit: -30 dBc (max)
- Measured: -70.96 dBc
- Margin: 40.96 dB (PASS)

Although measurement across only one example frequency span is demonstrated in this application note, it is strongly expected that the Si446x family of chips will comply with this spurious emission requirement in any non-harmonic frequency band. However, it is possible to position the channel center frequency so close to the edge of the authorized frequency band that the modulation spectrum itself falls outside the frequency band and thus (potentially) violates the spurious emission limit. It is the responsibility of the user to select the channel center frequency to avoid this situation.

Figure 12. Spurious Emission Reference Level (2GFSK DR=150 kbps Dev=200 kHz)

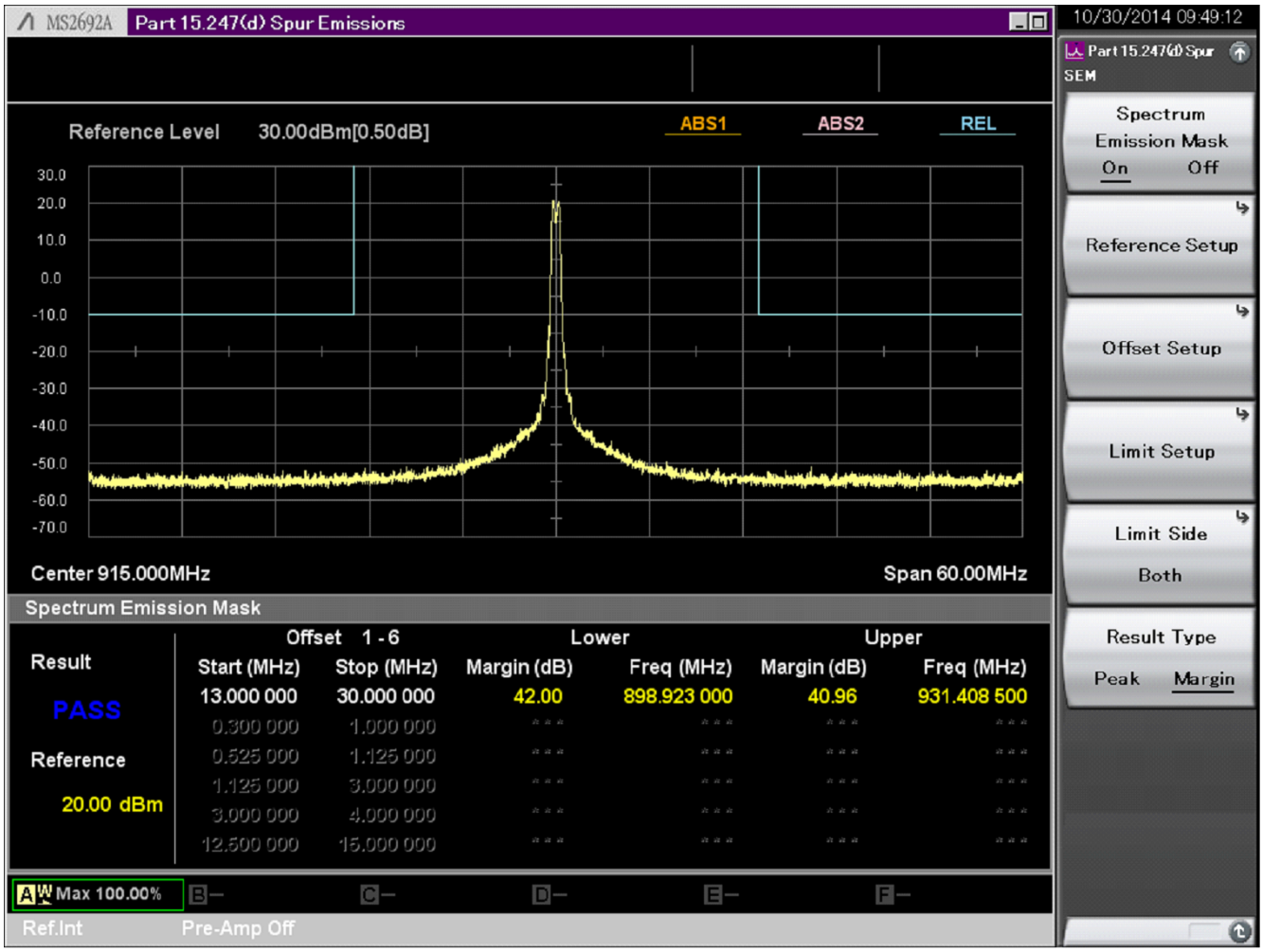


Figure 13. Spurious Emission Level (2GFSK DR=150 kbps Dev=200 kHz)

3.4.2. Spurious Emissions in Restricted Frequency Bands

Part 15.247(d) requires that any radiated emissions that fall in a restricted band (see section "2.4.1. FCC Part 15.205 Restricted Frequency Bands") must comply with the general limits on radiated emission limits (see section "2.4.2. FCC Part 15.209 General Limits on Radiated Emissions"). These emission limits are in terms of ***radiated*** field strengths; however, the Compliance Measurements Guide provides for use of a conducted measurement technique when the transmit antenna gain is known. The general limit on radiated emissions at frequencies above 960 MHz is 500 µV/meter at a distance of 3 meters (i.e.,54 dBµV/meter or -41.2 dBm).

Part 15.35 specifies the measurement bandwidth and type of detector function required for measurement of conducted or radiated emissions. A detector with a quasi-peak function is required for frequencies below 1 GHZ, while an average detector is required for frequencies above 1 GHz, using a minimum resolution bandwidth of 1 MHz. When operating within the 902-928 MHz band, all harmonics will necessarily fall above 1 GHz and thus the test method using an average detector is demonstrated in this section.

The spectrum analyzer configuration provided in the Compliance Measurements Guide is as follows:

- Set the RBW = 1 MHz
- Set the VBW ≥ 3 x RBW
- Set the Detector type = RMS
- Set the Number of Points in Sweep ≥ 2 * FreqSpan / RBW
- Set the Sweep Time = Auto Couple

- Set Trace Mode = Power Averaging (minimum of 100 sweeps)
- Allow the resulting trace to fully stabilize
- Record the conducted output power (in dBm) at those frequencies where spurious responses are observed
- Add the maximum transmit antenna gain (in dBi) to determine the EIRP level
- Convert EIRP to equivalent electric field strength 'E' at measurement distance 'D' using the relationship in Equation 2 below
- Compare the resultant electric field strength level to the applicable limit

$$E_{\frac{dBuV}{m}} = EIRP_{dBm} - 20 \times \log(D_{meters}) + 104.8dB$$

Equation 2.

The Compliance Measurements Guide discusses the difficulty of knowing (or determining) the gain of the transmit antenna at the out-of-band harmonic frequencies; the antenna gain at such frequencies is likely to be different than the gain at the desired in-band frequency. As a result, use of a conservative antenna gain value is necessary. The Compliance Measurements Guide requires use of an antenna gain value that is the maximum in-band gain of the antenna (across all operating bands), or 2 dBi, whichever is greater. This decreases the amount of conducted spurious power that may be transmitted while remaining in compliance with the emission limit, i.e., the spec is effectively tightened by 2 dB to -43.2 dBm EIRP.

A plot of the measured conducted spurious emissions (potentially) falling within restricted bands is shown in Figure 14. The Si446x family of chips complies with the requirements of FCC Part 15.247(d) for Spurious Emissions in Restricted Bands.

- Limit: -43.2 dBm EIRP (restricted bands), -30 dBc (non-restricted bands)

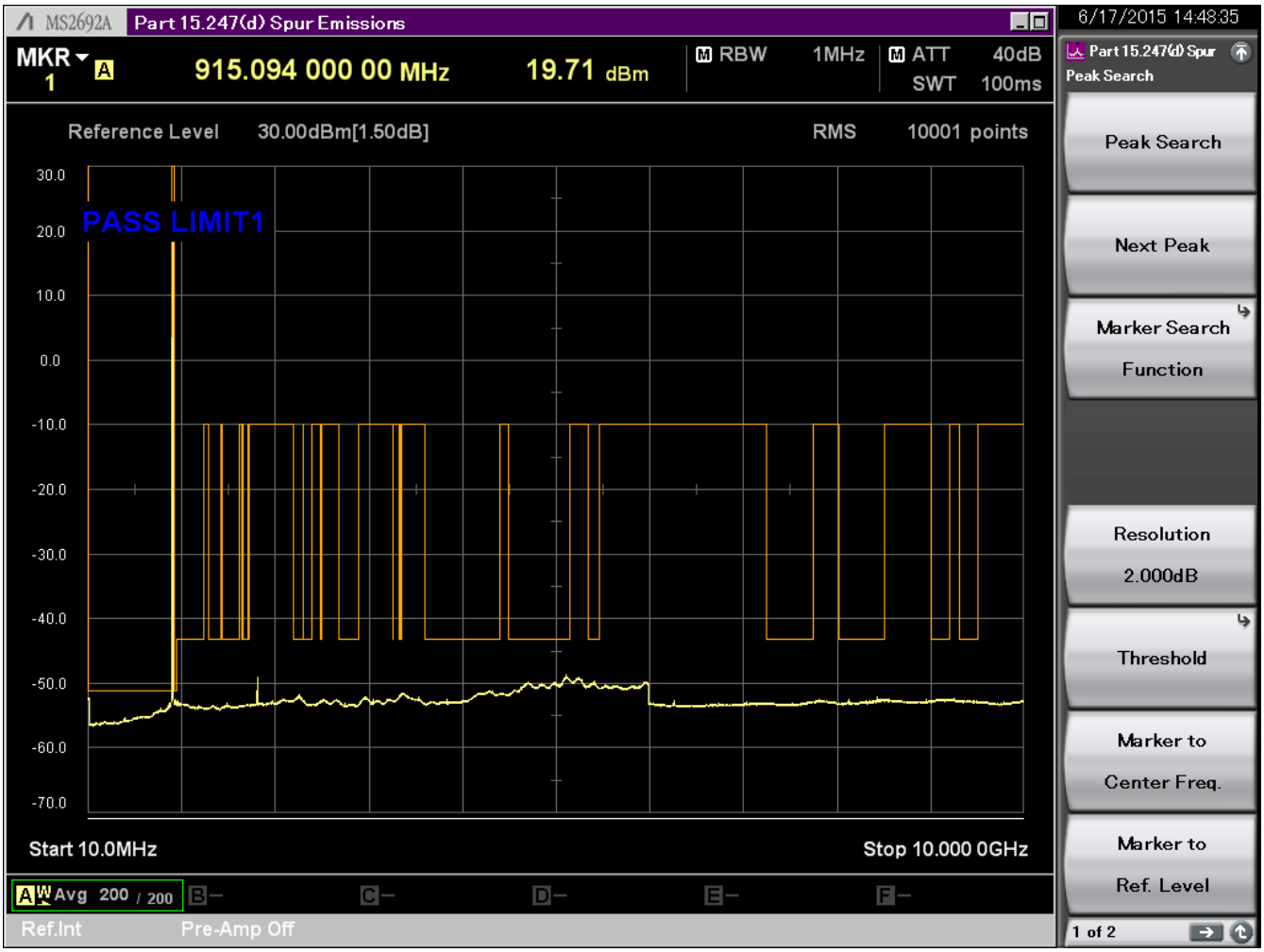


Figure 14. Spurious Emission Levels (with Restricted Band Mask)

3.4.3. FCC Part 15.109(a) Unintentional Radiation (i.e., in RX Mode)

Any RF device operating in the FCC 902-928 MHz band must also comply with the requirements of Part 15.109(a) “Radiated Emission Limits from Unintentional Radiators” which provides a limit on spurious emissions in any non-transmit mode of operation (including RX mode, STANDBY mode, or SLEEP mode). The spectrum analyzer configuration is the same as that used in section “3.4.2. Spurious Emissions in Restricted Frequency Bands” .

A plot of the measured conducted unintentional radiated emissions in RX mode is shown in Figure 15. The Si446x family of chips complies with the requirements of FCC Part 15.109(a) for Spurious Emissions in Restricted Bands.

- Limit: -43.2 dBm EIRP (max)
- Measured: -87.05 dBm
- Margin: 43.85 dB (PASS)

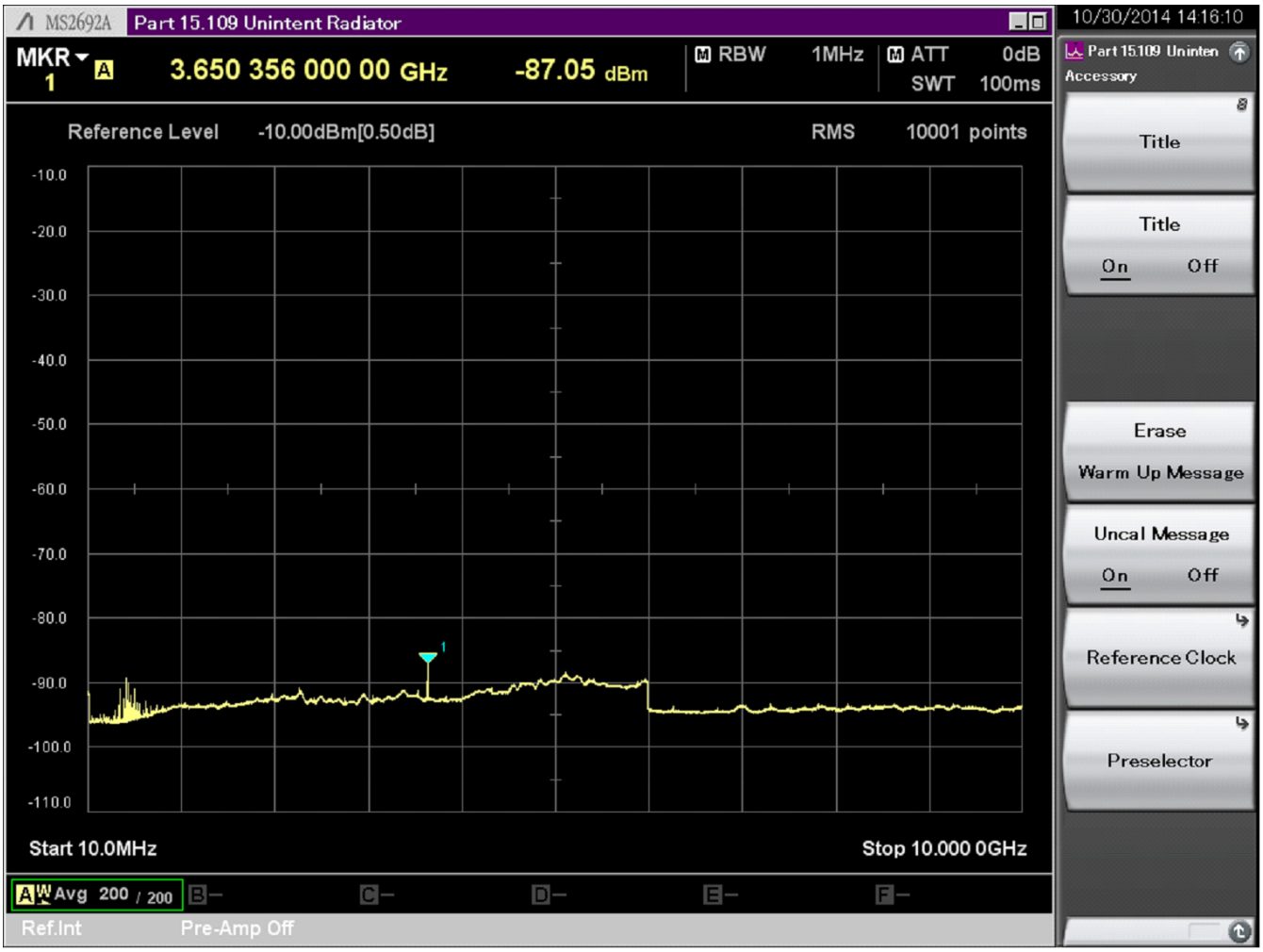


Figure 15. Unintentional Radiation in RX Mode

3.5. Link Budget vs. Modulation Protocol

It was previously shown that different modulation protocols may be limited to different transmit output power levels in order to remain compliant with the +8 dBm/3 kHz limit on their power spectral densities. It is also known that different modulation protocols may have different RX Sensitivity performance, even when comparing two protocols that have (approximately) the same modulation bandwidth. It is therefore useful to develop a table that estimates the achievable link budget as a function of various Part 15.247-compliant modulation protocols. Link budget is here defined as:

$$\mathrm{LinkBudget}_{dB} = \mathrm{TxPower}_{dBm} - \mathrm{RxSens}_{dBm}$$

Equation 3.

The “Peak PSD/3kHz” column in Table 2 represents the peak power spectral density measured with the value of average conducted output power shown in Figure 4 (~+20.5 dBm). The “Max TX Power” column then represents the calculated maximum conducted output power level that would remain in compliance with the PSD limit of Part 15.247(e). The “RX Sensitivity” column is the measured RF input level corresponding to BER = 0.1% (1E-3) for each modulation protocol; the “Link Budget” column is then calculated according to Equation 3. All TX measurements in Table 2 were taken with the same average conducted output power level (i.e., ~+20.5 dBm).

Table 2. Link Budget vs. Modulation Protocol

Data Rate	Deviation	6 dB BW	Peak PSD/3kHz	Max TX Power	RX Sensitivity	Link Budget
4.8 kbps	190 kHz	512.4 kHz	+13.6 dBm	+14.9 dBm	-110.2 dBm	125.1 dB
10 kbps	190 kHz	512.4 kHz	+12.7 dBm	+15.8 dBm	-108.8 dBm	124.6 dB
20 kbps	190 kHz	512.8 kHz	+11.8 dBm	+16.7 dBm	-107.1 dBm	123.8 dB
40 kbps	180 kHz	502.8 kHz	+11.9 dBm	+16.6 dBm	-106.5 dBm	123.1 dB
50 kbps	175 kHz	500.4 kHz	+12.4 dBm	+16.1 dBm	-105.9 dBm	122.0 dB
75 kbps	175 kHz	521.2 kHz	+7.0 dBm	+21.5 dBm	-104.5 dBm	126.0 dB
100 kbps	175 kHz	507.8 kHz	+5.7 dBm	+22.8 dBm	-103.4 dBm	126.2 dB
150 kbps	175 kHz	504.0 kHz	+5.1 dBm	+23.4 dBm	-101.8 dBm	125.2 dB
250 kbps	175 kHz	501.2 kHz	+3.3 dBm	+25.2 dBm	-99.8 dBm	125.0 dB
400 kbps	175 kHz	505.8 kHz	+7.9 dBm	+20.6 dBm	-99.4 dBm	120.0 dB
500 kbps	175 kHz	507.4 kHz	-0.3 dBm	+28.8 dBm	-98.1 dBm	126.9 dB

The values of deviation shown in Table 2 should be considered as the absolute minimum acceptable values for use. These values of deviation were deliberately chosen to just barely comply with the minimum 6 dB bandwidth requirement of 500 kHz. It is likely the user will desire to select a larger value of deviation to obtain a greater margin of compliance.

It is also apparent that operation near the maximum allowed output power of 1 watt will not be possible unless a very specific modulation protocol is selected. The +8 dBm/3 kHz limit on PSD forces a reduction in output power for most other modulation protocols.

Fortunately, the resulting limit on transmit power does not have an extreme effect on link budget. While there is some variation in link budget in the above table, the range of variation is not large; what is lost due to a required reduction in transmit output power is re-gained in an improvement in sensitivity (due to operation with a lower data rate).

4. Wireless Development Suite (WDS) Script Files

4.1. WDS Script for TX 913.0 MHz +20 dBm 2GFSK DR=150 K Dev=200 K Configuration

TX measurements at F=913.0 MHz with output power = +20 dBm with modulation of 2GFSK DR=150 kbps Dev=200 kHz used the following WDS script.

```
#BatchName TX 913.0 MHz ClassE +20dBm 2GFSK PN15
# DR=150kbps Dev=200kHz XO30M LoopBW=450kHz
# Revision Date:  10/28/2014, ModemCalc=1.1.0.2
# Start
RESET
'POWER_UP' 01 00 01 C9 C3 80
'PART_INFO'
'FUNC_INFO'
# Adjust Crystal Osc cap bank to center oscillator frequency
'SET_PROPERTY' 'GLOBAL_XO_TUNE' 4A
# Modem control group = 2GFSK Internal PN Seq
'SET_PROPERTY' 'MODEM_MOD_TYPE' 13
'SET_PROPERTY' 'MODEM_CLKGEN_BAND' 08
# PN polynomial = PN9 by default
#'SET_PROPERTY' 'PKT_WHT_POLY_15_8' 01
#'SET_PROPERTY' 'PKT_WHT_POLY_7_0' 08
# Set polynomial = PN11
#'SET_PROPERTY' 'PKT_WHT_POLY_15_8' 05
#'SET_PROPERTY' 'PKT_WHT_POLY_7_0' 00
# Set polynomial = PN13
#'SET_PROPERTY' 'PKT_WHT_POLY_15_8' 1B
#'SET_PROPERTY' 'PKT_WHT_POLY_7_0' 00
# Set polynomial = PN15
'SET_PROPERTY' 'PKT_WHT_POLY_15_8' 60
'SET_PROPERTY' 'PKT_WHT_POLY_7_0' 00
# Synth control group = 450 kHz Loop BW
'SET_PROPERTY' 'SYNTH_PFDCP_CPFF' 39
'SET_PROPERTY' 'SYNTH_PFDCP_CPINT' 04
'SET_PROPERTY' 'SYNTH_VCO_KV' 0B
'SET_PROPERTY' 'SYNTH_LPFILT3' 05
'SET_PROPERTY' 'SYNTH_LPFILT2' 04
'SET_PROPERTY' 'SYNTH_LPFILT1' 01
'SET_PROPERTY' 'SYNTH_LPFILT0' 03
# Freq control group = 913.0 MHz, XO=30M
'SET_PROPERTY' 'FREQ_CONTROL_INTE' 3B
'SET_PROPERTY' 'FREQ_CONTROL_FRAC_2' 0E
'SET_PROPERTY' 'FREQ_CONTROL_FRAC_1' EE
'SET_PROPERTY' 'FREQ_CONTROL_FRAC_0' EE
'SET_PROPERTY' 'FREQ_CONTROL_W_SIZE' 20
# PA control group = Class-E, +20 dBm
'SET_PROPERTY' 'PA_MODE' 08
'SET_PROPERTY' 'PA_PWR_LVL' 7F
'SET_PROPERTY' 'PA_BIAS_CLKDUTY' 00
```

```
# Tx parameters, DR=150kbps, Dev=200kHz
'SET_PROPERTY' 'MODEM_DATA_RATE_2' 2D
'SET_PROPERTY' 'MODEM_DATA_RATE_1' C6
'SET_PROPERTY' 'MODEM_DATA_RATE_0' C0
'SET_PROPERTY' 'MODEM_TX_NCO_MODE_3' 09
'SET_PROPERTY' 'MODEM_TX_NCO_MODE_2' C9
'SET_PROPERTY' 'MODEM_TX_NCO_MODE_1' C3
'SET_PROPERTY' 'MODEM_TX_NCO_MODE_0' 80
'SET_PROPERTY' 'MODEM_FREQ_DEV_2' 00
'SET_PROPERTY' 'MODEM_FREQ_DEV_1' 1B
'SET_PROPERTY' 'MODEM_FREQ_DEV_0' 4F
# GPIO configuration
# RX-State/NoChg/TX-State
'GPIO_PIN_CFG' 21 00 20 00 00 00
# Start transmitting
'START_TX' 00 00 00
```

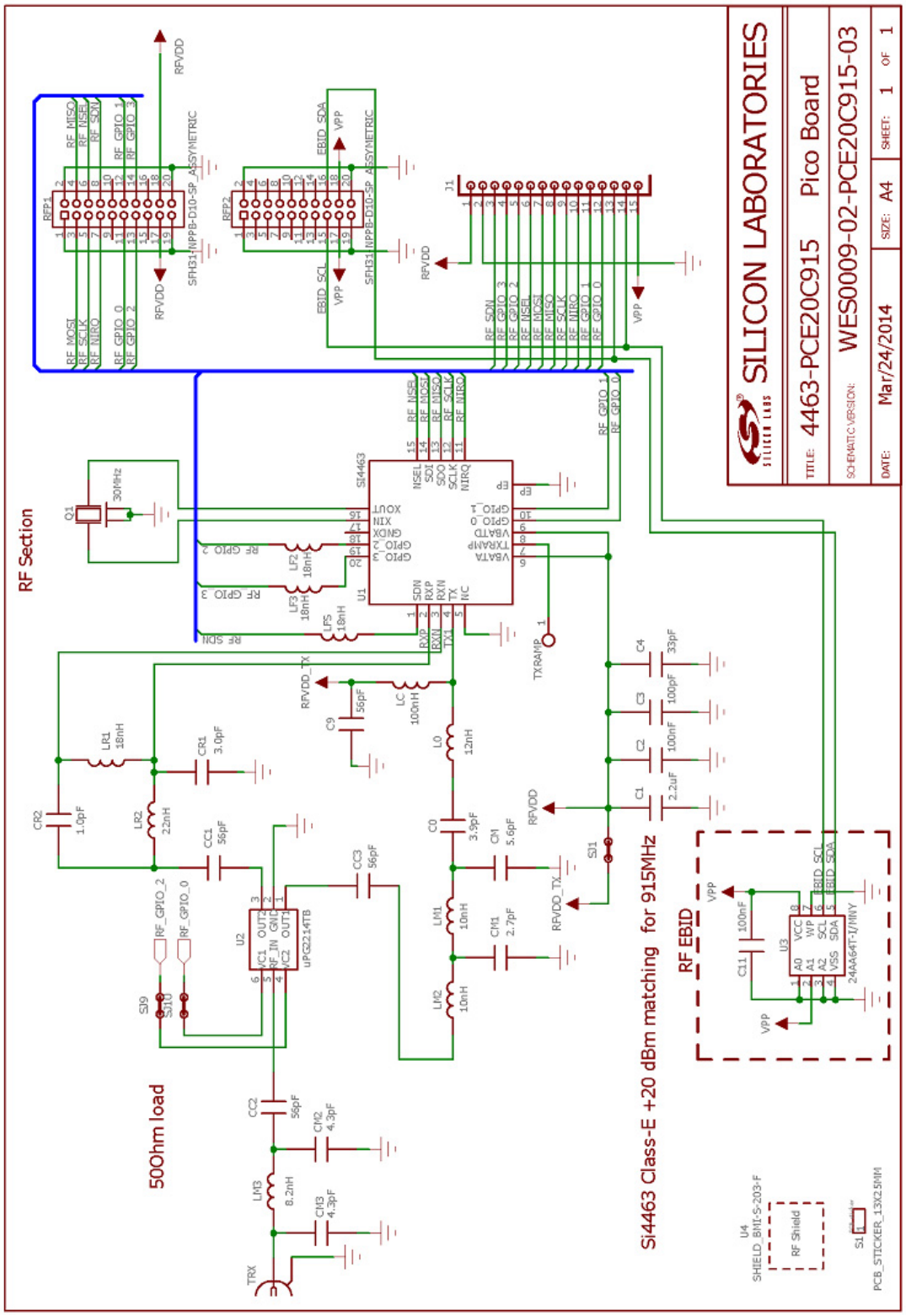
4.2. WDS Script for RX 913.0 MHz Ber 2GFSK DR=150 K Dev=200 K Configuration

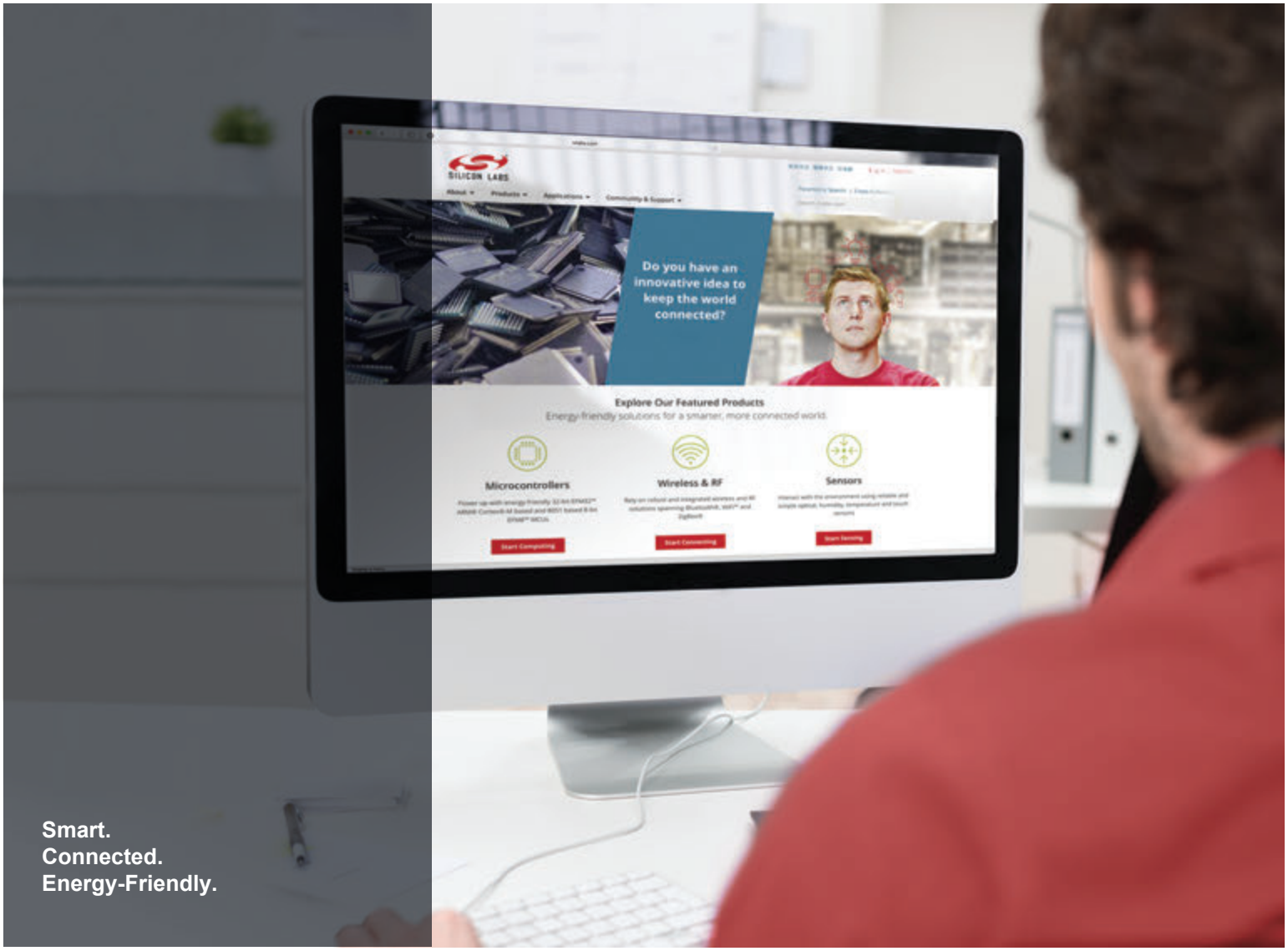
RX BER measurements at F=913.0 MHz with modulation of 2GFSK DR=150 kbps Dev=200 kHz used the following WDS script.

```
#BatchName RX 913.0 MHz BER 2GFSK DR150K Dev200K
# StdPream XO30M 0ppm NoPLLAFC NoModemComp AsyncDemod BW=593.6K
# Revision Date: 10/31/2014, ModemCalc 1.1.0.2
# Start
RESET
'POWER_UP' 01 00 01 C9 C3 80
'PART_INFO'
'FUNC_INFO'
# Adjust Crystal Osc cap bank to center oscillator frequency
'SET_PROPERTY' 'GLOBAL_XO_TUNE' 4A
# General parameters, Mod Type = 2GFSK
'SET_PROPERTY' 'MODEM_MOD_TYPE' 03
'SET_PROPERTY' 'MODEM_CLKGEN_BAND' 08
# Freq control group = 913.0 MHz
'SET_PROPERTY' 'FREQ_CONTROL_INTE' 3B
'SET_PROPERTY' 'FREQ_CONTROL_FRAC_2' 0E
'SET_PROPERTY' 'FREQ_CONTROL_FRAC_1' EE
'SET_PROPERTY' 'FREQ_CONTROL_FRAC_0' EE
'SET_PROPERTY' 'FREQ_CONTROL_W_SIZE' 20
# Rx parameters
'SET_PROPERTY' 'FREQ_CONTROL_VCOCNT_RX_ADJ' FF
'SET_PROPERTY' 'MODEM_MDM_CTRL' 80
'SET_PROPERTY' 'MODEM_IF_CONTROL' 08
'SET_PROPERTY' 'MODEM_IF_FREQ_2' 03
'SET_PROPERTY' 'MODEM_IF_FREQ_1' C0
'SET_PROPERTY' 'MODEM_IF_FREQ_0' 00
'SET_PROPERTY' 'MODEM_DECIMATION_CFG1' 00
'SET_PROPERTY' 'MODEM_DECIMATION_CFG0' 30
'SET_PROPERTY' 'MODEM_BCR_OSR_1' 00
'SET_PROPERTY' 'MODEM_BCR_OSR_0' C8
'SET_PROPERTY' 'MODEM_BCR_NCO_OFFSET_2' 02
'SET_PROPERTY' 'MODEM_BCR_NCO_OFFSET_1' 8F
'SET_PROPERTY' 'MODEM_BCR_NCO_OFFSET_0' 5C
'SET_PROPERTY' 'MODEM_BCR_GAIN_1' 01
'SET_PROPERTY' 'MODEM_BCR_GAIN_0' 48
'SET_PROPERTY' 'MODEM_BCR_GEAR' 02
'SET_PROPERTY' 'MODEM_BCR_MISC1' C2
'SET_PROPERTY' 'MODEM_BCR_MISC0' 00
'SET_PROPERTY' 'MODEM_AFC_GEAR' 04
'SET_PROPERTY' 'MODEM_AFC_WAIT' 47
'SET_PROPERTY' 'MODEM_AFC_GAIN_1' 01
'SET_PROPERTY' 'MODEM_AFC_GAIN_0' B5
'SET_PROPERTY' 'MODEM_AFC_LIMITER_1' 03
'SET_PROPERTY' 'MODEM_AFC_LIMITER_0' 64
'SET_PROPERTY' 'MODEM_AFC_MISC' 80
```

```
'SET_PROPERTY' 'MODEM_AGC_CONTROL' E2
'SET_PROPERTY' 'MODEM_AGC_WINDOW_SIZE' 22
'SET_PROPERTY' 'MODEM_AGC_RFPD_DECAY' 16
'SET_PROPERTY' 'MODEM_AGC_IFPD_DECAY' 16
'SET_PROPERTY' 'MODEM_OOK_CNT1' A4
'SET_PROPERTY' 'MODEM_OOK_MISC' 02
'SET_PROPERTY' 'MODEM_RAW_SEARCH' D6
'SET_PROPERTY' 'MODEM_RAW_CONTROL' 83
'SET_PROPERTY' 'MODEM_RAW_EYE_1' 00
'SET_PROPERTY' 'MODEM_RAW_EYE_0' D8
## RX channel filter coeff
# WB filter k1=5 (BW=593.6 kHz), NB filter k2=5 (BW=593.6 kHz)
'SET_PROPERTY' 21 0C 00 7E 64 1B BA 58 0B DD CE D6 E6 F6 00
'SET_PROPERTY' 21 06 0C 03 03 15 F0 3F 00
'SET_PROPERTY' 21 0C 12 7E 64 1B BA 58 0B DD CE D6 E6 F6 00
'SET_PROPERTY' 21 06 1E 03 03 15 F0 3F 00
# Skip sync detection, Std Preamble, PreDetTh=8 bits
#  (9-bit preamble may be found in PN9 or higher sequences)
'SET_PROPERTY' 'PREAMBLE_CONFIG_STD_1' 88
'SET_PROPERTY' 'PREAMBLE_CONFIG' 01
# GPIO configuration
# RxState/RxClk/TxState/RxData
'GPIO_PIN_CFG' 21 11 20 14 00 00 60
# Start receiving
'START_RX' 00 00 00 00 00 01
```

5. Reference Design Schematic





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