AN1200.26
LoRa™ and FCC Part 15.247: Measurement Guidance

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1   Introduction

The purpose of this application note is to assist the engineer in understanding the requirements, including test methodology, of the Federal Communications Commission (FCC) towards compliance of devices employing Semtech's proprietary LoRa spread spectrum modulation to FCC Part 15.247 and the US 902 - 928 MHz ISM license-exempt frequency band.

This application note makes reference to the latest FCC OET guidance for the testing methodology of systems employing digital modulation techniques [2] and while the focus of this document is on the compliance of Semtech's LoRa modulation to all relevant FCC regulations [2], the information contained within is equally applicable to all modulation modes (Part 15.247 is agnostic with regards to the physical layer) and as such supersedes Semtech Application Note AN1200.06 [3] and Section 4.2 of Semtech Application Note AN1200.04 [4]

This application note will describe three permitted modes of operation:

- Systems employing digital modulation techniques (DTS)
- Systems employing frequency hopping spread-spectrum
- Systems employing hybrid mode operation

The measurements and analysis included in this application note is based upon Semtech's interpretation of the measurement methodology described by the FCC OET. Semtech recommend that a FCC approved Telecommunications Certification Body (TCB) be consulted prior to certification testing.

2   Summary

A summary of the measured results are tabulated below.

2.1   Systems Employing Digital Modulation

Specification	Parameter	Limit	Measured	Margin
15.247(a)(2)	6 dB BW	≥ 500 kHz	SF = 7: 808.5 kHz	308.5 kHz
			SF = 12: 838.5 kHz	338.5 kHz
15.247(b)(3)	Emission Output Power	+30 dBm	SF = 7: 18.5 dBm	11.5 dB
			SF = 12: 18.74 dBm	11.26 dB
15.247(e)	Power Spectral Density	+8 dBm / 3 kHz	SF = 7: -1.42 dB /3 kHz	9.42 dB
			SF = 12: -1.47 dB /3 kHz	9.47 dB
15.247(d)	Non-Restricted Bands	-30 dBc	-58.7 dBc	28.7 dB
	Restricted Bands	-41.2 dBm	-56 dBm	14.8 dB

Table 1: Summary of Measured Results for Systems Employing Digital Modulation

2.2   Systems Employing Frequency Hopping Spread Spectrum

Specification	Parameter	Limit	Measured	Margin
15.247(a)(1)	20 dB BW	< 500 kHz	BW = 125 kHz, SF = 7: 148 kHz	352 kHz
			BW = 250 kHz, SF = 12: 308 kHz	192 kHz
15.247(d)	Non-Restricted Bands	-30 dBc	-58.7 dBc	28.7 dB
	Restricted Bands	-41.2 dBm	-56 dBm	14.8 dB

Table 2: Summary of Measured Results for Systems Employing Digital Modulation

2.3   Hybrid Mode Systems

Specification	Parameter	Limit	Measured	Margin
15.247(e)	Power Spectral Density	+8 dBm / 3 kHz	BW = 125 kHz: 4.78 kHz / 3 dBm	3.22 dB
			BW = 250 kHz: 2.22 kHz / 3 dBm	5.78 dB

Table 3: Summary of Measured Results for Hybrid Mode

3   An Overview of FCC Part 15.247 in the 902 – 928 MHz band

3.1   Systems Employing Digital Modulation Techniques

The FCC regulations for systems using digital modulation techniques (often referred to as "DTS") can be summarized as follows:

- The 6 dB bandwidth of the transmitted signal shall be at least 500 kHz *(ref: 15.247(a)(2))*
- The maximum peak conducted output power is 1 W (+30 dBm). Part 15.247 allows for compliance with the 1 W limit to be based on the maximum conducted output power, defined as the total transmit power delivered to all antennas and antenna elements averaged across all symbols in the signaling alphabet when the transmitter is operating at maximum output power *(ref: 15.247(b)(3))*
- The conducted output power limit is based on the use of antennas with directional gains that do not exceed 6 dBi. If antennas with a directional gain greater than 6 dBi are used, the conducted output power shall be reduced below the stated values by the amount in dB that the directional gain of the antenna exceeds 6 dBi *(ref: 15.247(b)(4))*
- The conducted power spectral density shall not exceed 8 dBm in any 3 kHz band during continuous transmission, measured in accordance with the same method as used to determine the conducted output power *(ref: 15.247(e))*
- While the FCC does not place any restriction on any spurious emissions that occur within the 902 – 928 MHz band (such as adjacent or alternate channel power limits), any spurious emissions measured in any 100 kHz bandwidth outside of this band must be at least 20 dB below the level measured in a 100 kHz bandwidth within this band. If the conducted output power was measured using averaging techniques, this limit is tightened to 30 dB *(ref: 15.247(d))*
- There are restrictions placed on radiated field strength emission limits that fall within what are referred to as Restricted Bands in Part 15.205 and tabulated below in Table 4 shall not exceed the radiated emission limits of Part 15.209, as listed in Table 5. Only spurious emissions are permitted within the restricted frequency bands.
- The radiated emission limits is a field strength measurement (in μV/m). This field strength can be converted to dBm by applying the formula below. If the gain of the DUT antenna is known then an approximation to the Effective Radiated Power (ERP) limits can be estimated by tightening the limit by the gain of the antenna in dBi.

$$P_{TX} = 20 * log\big(Field\ Strength\ (\mu V) * d(m)\big) - 104.77$$

MHz	MHz	MHz	GHz
0.090–0.110	16.42–16.423	399.9–410	4.5–5.15 * (5)
0.495–0.505	16.69475–16.69525	608–614	5.35–5.46 * (6)
2.1735–2.1905	16.80425–16.80475	960–1240	7.25–7.75 * (8)
4.125–4.128	25.5–25.67	1300–1427	8.025–8.5 * (9)
4.17725–4.17775	37.5–38.25	1435–1626.5	9.0–9.2 * (10)
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 * (3)	22.01–23.12
8.41425–8.41475	162.0125–167.17	3260–3267	23.6–24.0
2.29–12.293	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 * (4)	Above 38.6
13.36-13.41			
* Harmonic (n) of emission between 902 – 928 MHz falls within the Restricted Band			

Table 4: Restricted Frequency Bands

Frequency (MHz)	Field Strength (µV/m)	Measurement Distance (m)	Conducted Power (dBm)
30-88	100	3	-55.2
88-216	150	3	-51.7
216-960	200	3	-49.2
Above 960	500	3	-41.2

Table 5: Part 15.209 Radiated Emission Limits for Frequencies above 30 MHz

3.2　Systems Employing Frequency Hopping Spread Spectrum

The FCC regulations for systems using frequency hopping spread spectrum (FHSS) techniques, where they differ from the rules that apply to systems using digital modulation techniques, can be summarized as follows:

- Frequency hopping systems shall have hopping channel carrier frequencies separated by a minimum of 25 kHz or the 20 dB bandwidth of the hopping channel, whichever is greater. The system shall hop to channel frequencies that are selected at the system hopping rate from a pseudo randomly ordered list of hopping frequencies. Each frequency must be used equally on the average by each transmitter *(Ref: 15.247(a)(1))*

- If the 20 dB bandwidth of the hopping channel is less than 250 kHz, the system shall use at least 50 hopping frequencies and the average time of occupancy on any frequency shall not be greater than 400 ms within a 20 second period (= 0.4 * 50 channels). If the 20 dB bandwidth of

the hopping channel is 250 kHz or greater, the system shall use at least 25 hopping frequencies and the average time of occupancy on any frequency shall not be greater than 400 ms within a 10 second period (= 0.4 * 25 channels). In addition the maximum allowable 20 dB bandwidth of any hopping channel is 500 kHz *(Ref: 15.247(a)(1)(i))*

- The maximum peak conducted output power shall not exceed 1 W (+30 dBm) for systems employing at least 50 hopping channels and 250 mW (+24 dBm) for systems employing less than 50 hopping channels, but at least 25 hopping channels. As opposed to systems employing digital modulation, averaging measurement methods are not permitted *(Ref: 15.247(b)(2))*

3.3 Hybrid Mode Operation

Hybrid mode permits a system to employ a combination of both frequency hopping and digital modulation techniques as summarized below *(ref: 15.247(f))*

- The frequency hopping operation, with the direct sequence or digital modulation operation turned off, shall have an average time of occupancy on any frequency not to exceed 400 ms within a time period 0.4 * number of channels
- The digital modulation operation, with the frequency hopping operation turned off, shall comply with the power density requirements of 15.247(d)

There is an FCC OET publication [5] that details a possible hybrid mode scenario:

It is possible for a device to be designed to operate as a DTS, as a FHSS system, or using a combination of these two modulation types.

A hybrid system uses both digital modulation and frequency hopping techniques at the same time on the same carrier. As shown in Section 15.247(f), a hybrid system must comply with the power density standard of 8 dBm in any 3 kHz band when the frequency hopping function is turned off. The transmission also must comply with a 0.4 second / channel maximum dwell time when the hopping function is turned on. There is no requirement for this type of hybrid system to comply with the 500 kHz minimum bandwidth normally associated with a DTS transmission; and, there is no minimum number of hopping channels associated with this type of hybrid system.

As a possible application scenario, consider a system operating with eight 200 kHz channels.

To comply with the requirements for hybrid operation the channel dwell time in frequency hopping mode must not exceed 400 ms in any (400 ms * 8 channels) 3.2 seconds. In addition, the power spectral density shall not exceed +8 dBm in any 3 kHz bandwidth.

4 Measurement Methods for Systems Employing Digital Modulation

All measurements were performed with the DUT configured for +20 dBm output power and 500 kHz LoRa bandwidth unless otherwise specified. In addition the DUT is set to TX continuous mode, enabling a 100% transmit duty-cycle to be achieved.

4.1 500 kHz Bandwidth

4.1.1 Methodology

The following test method is used to determine that the 500 kHz bandwidth LoRa modulated signal complies with 6 dB bandwidth requirement of 15.247(a)(2).

1. Set the Resolution Bandwidth (RBW) of the spectrum analyzer to 100 kHz and the video bandwidth (VBW) to ≥ 3 * RBW
2. Using the spectrum analyzer's peak detector and with the trace mode set to max. hold, allow the trace to stabilize
3. Measure the maximum width of the emission between upper and lower frequency points that are attenuated by 6 dB, relative to the maximum level measured in the fundamental emission

Alternatively, the automatic bandwidth measurement capability of a spectrum analyzer may be employed using the X dB bandwidth mode with X set to 6 dB, if the instrument's configuration can be configured as defined above.

4.1.2 Results

Independent of spreading factor (SF), LoRa modulation complies with the 6 dB bandwidth requirement as illustrated below.
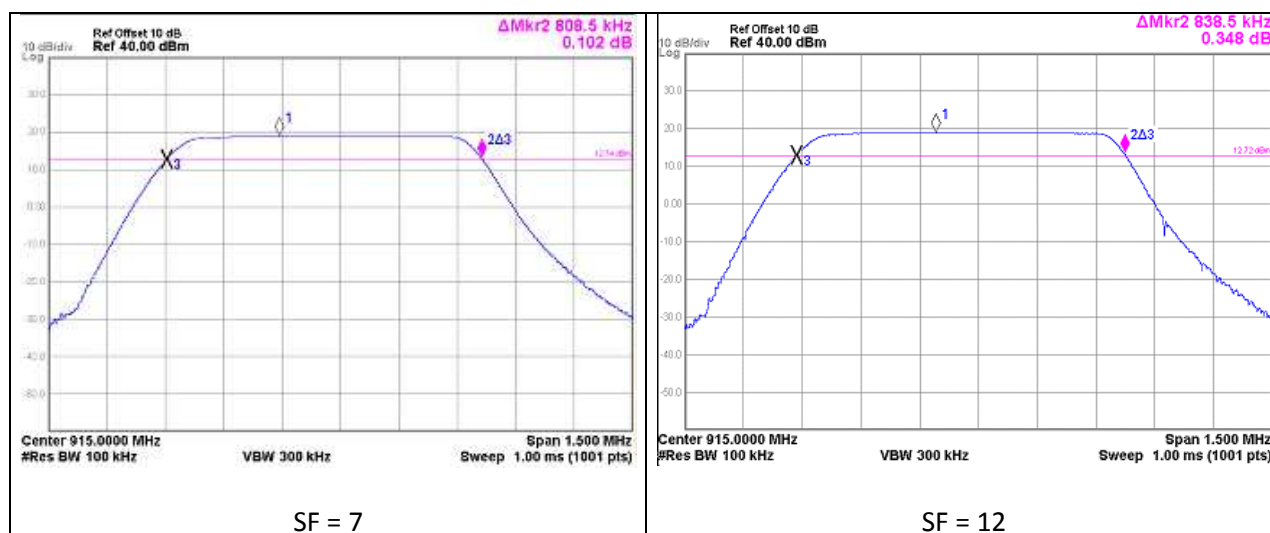

SF = 7   SF = 12

Figure 1: 6 dB Bandwidth

4.2   Fundamental Emission Output Power

To demonstrate compliance with Part 15.247(b)(3) we implement the maximum conducted (average) output power method, AVGSA-1, of [1], since we will use averaging methods to show compliance with the power spectral density requirements of 15.247(e).

4.2.1   Occupied Bandwidth

When using averaging methods to determine the conducted output power, the total power is averaged over the Occupied Bandwidth (OBW) of the fundamental emission. A procedure for measuring the OBW is presented in Section 6.9.3 of ANSI C63-10 [6] and is based upon the 99% power bandwidth (i.e. the occupied bandwidth is the frequency bandwidth that below its lower and above its upper frequency limits, the mean powers are each equal to 0.5% of the total mean power of the given emission).
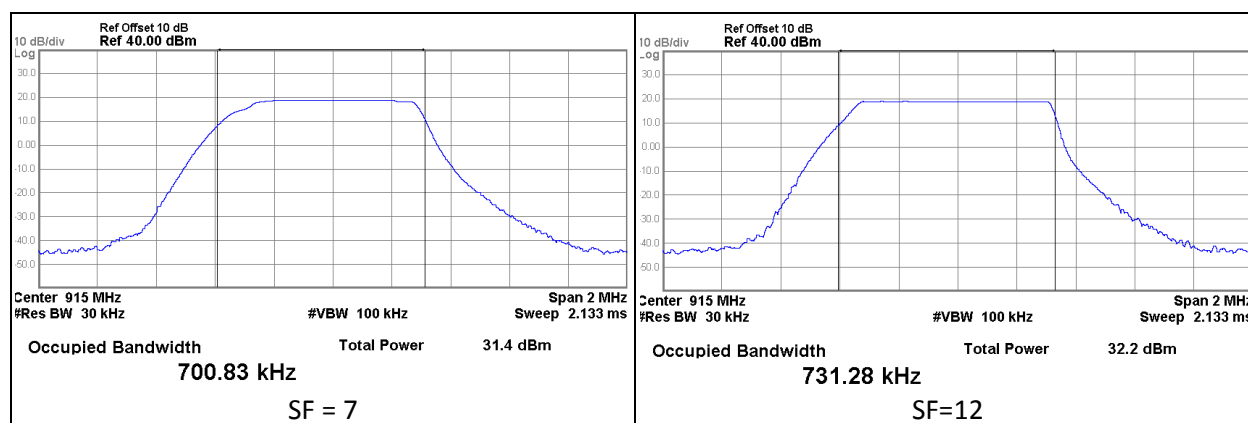

Figure 2: Occupied Bandwidth

4.2.2   Methodology

The following test method was used to determine the average conducted output power at the antenna port.

1.   Set the frequency span of the spectrum analyzer to at least 1.5 times the OBW (determined in 4.2.1, above)
2.   Set the RBW to between 1 to 5 % of the OBW and the VBW to ≥ 3 * RBW
3.   This method assumes that the number of points that the spectrum analyzer can sweep over is at least (2 * Span / RBW). Assuming a RBW setting of 30 kHz (approx. 4% of OBW) and a span of 2 MHz, then the minimum number of points swept is 133 points.
4.   With the sweep time set to auto and free-run, use the RMS detector (i.e. power averaging) and average over at least 100 sweeps in power-averaging mode. If an RMS detector is not available, the sample detector may be substituted
5.   Calculate the power by integrating the spectrum across the OBW of the signal, using the spectrum analyzer's band power measurement function, with the band limits set equal to the OBW band edges

4.2.3 Results

Independent of spreading factor (SF), LoRa modulation complies with the conducted output power limit as illustrated below.
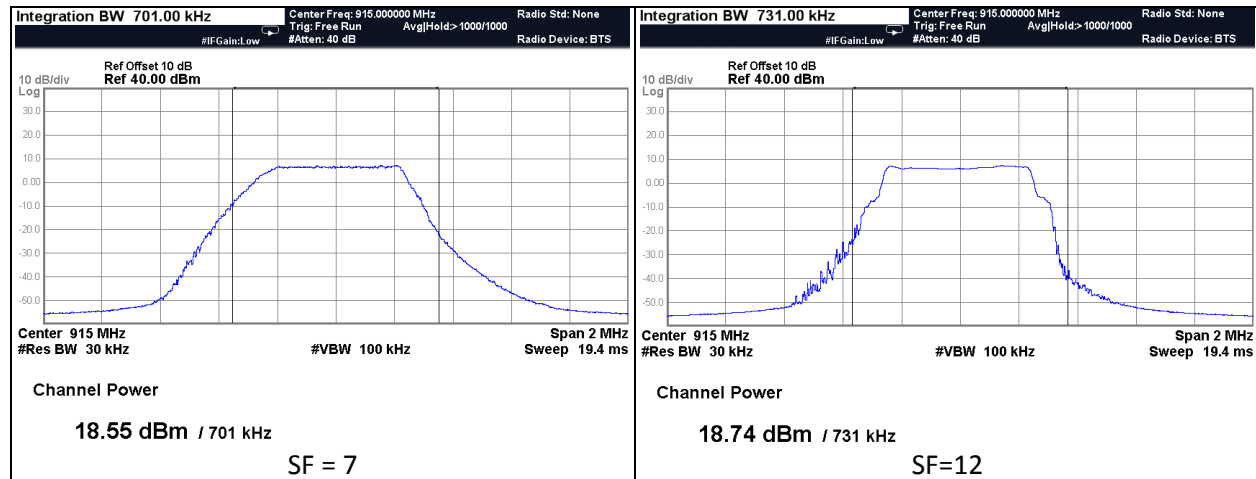

Figure 3: Conducted Output Power

4.3 Power Spectral Density of the Fundamental Emission

To demonstrate compliance with the PSD limit defined in 15.247(e), we use the AVGPSD-1 method described in [1]. The use of power averaging techniques is identical to those used to determine the emission power.

4.3.1 Methodology

1. Set the spectrum analyzer center frequency to DTS channel center frequency and frequency span to at least 1.5 times the OBW.
2. Set the RBW such that 3 kHz ≤ RBW ≤ 100 kHz and the VBW ≥3 x RBW. Semtech recommends setting the RBW to 3 kHz.
3. Set the detector to power averaging (RMS) or sample (when RMS not available)
4. Ensure that the number of measurement points in the sweep ≥ 2 x span/RBW and the sweep-time to auto
5. Employ trace averaging (RMS) mode over a minimum of 100 traces and use the peak marker function to determine the maximum amplitude level

4.3.2 Results

Independent of spreading factor (SF), LoRa modulation complies with the power spectral density limits even when configured for +20 dBm output power mode of operation, as illustrated below in Figure 4.
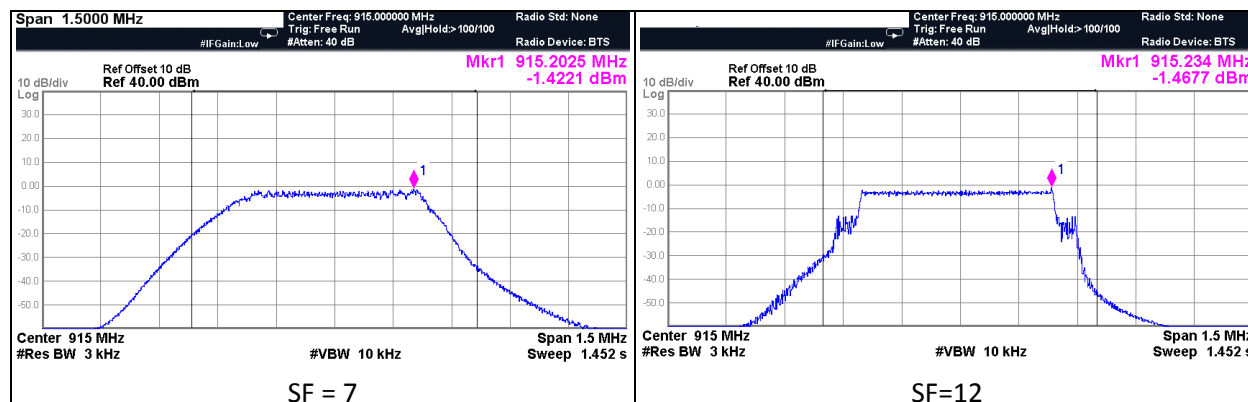
Figure 4: Power Spectral Density

Note that the PSD measurement is a conducted measurement and is not subject to the reduction in conducted output power that is applied should the antenna gain exceed 6 dBi.

4.4   Emissions in Non-Restricted Frequency Bands

To demonstrate compliance with the emissions limit for the non-restricted frequency bands, the following procedure was implemented. As noted by 15.247(d), since power averaging was used to determine the conducted emission output power, the limit for emissions falling outside of the 902-928 MHz band is 30 dB below the maximum emission within the band.

4.4.1   Methodology

Firstly determine the reference level of the wanted emission in the band as outlined below:

1. Set the spectrum analyzer center frequency to DTS channel center frequency and frequency span to at least 1.5 times the DTS bandwidth.
2. Set the RBW to 100 kHz and the VBW ≥3 x RBW
3. Set the detector to peak
4. Set the sweep time to auto and the trace mode to max. hold
5. Using the peak marker function determine the maximum power level

 The wanted emission reference level is illustrated below in Figure 5.

To determine the emissions in the non-restricted bands set the span of the spectrum analyzer to cover the frequency band of interest. In the example below we look at the upper and lower band-edges of the 902-928 MHz band, since a more detailed analysis of spurious emissions in both non-restricted and restricted frequency bands will be performed during radiated emissions measurements as detailed in Section 4.5.

4.4.2   Results

As illustrated in Figure 6, emissions in the non-restricted band are greater than 30 dB below the reference emission level and hence LoRa modulation can be seen to comply with the 15.247(d).
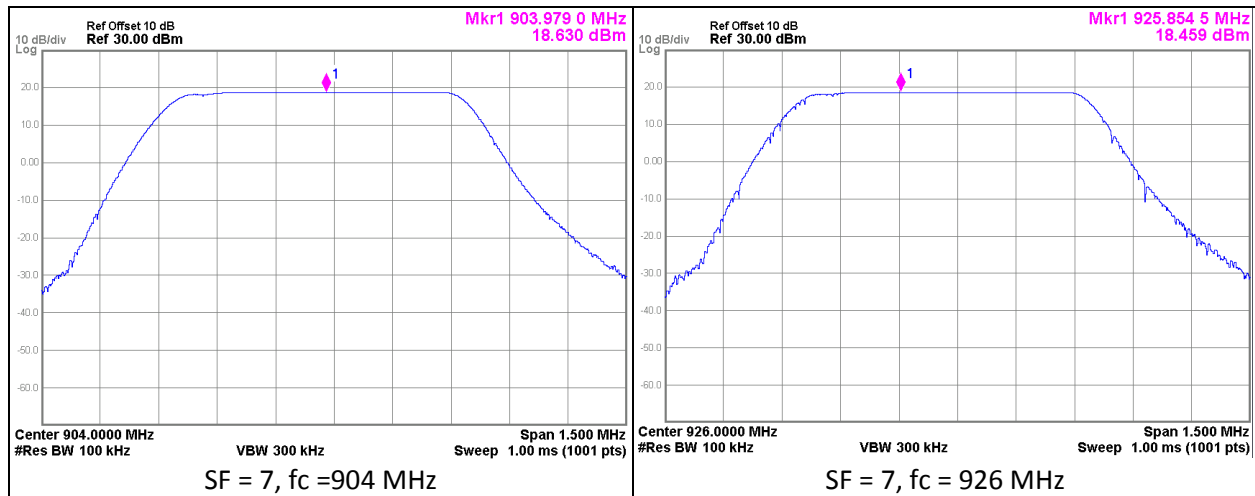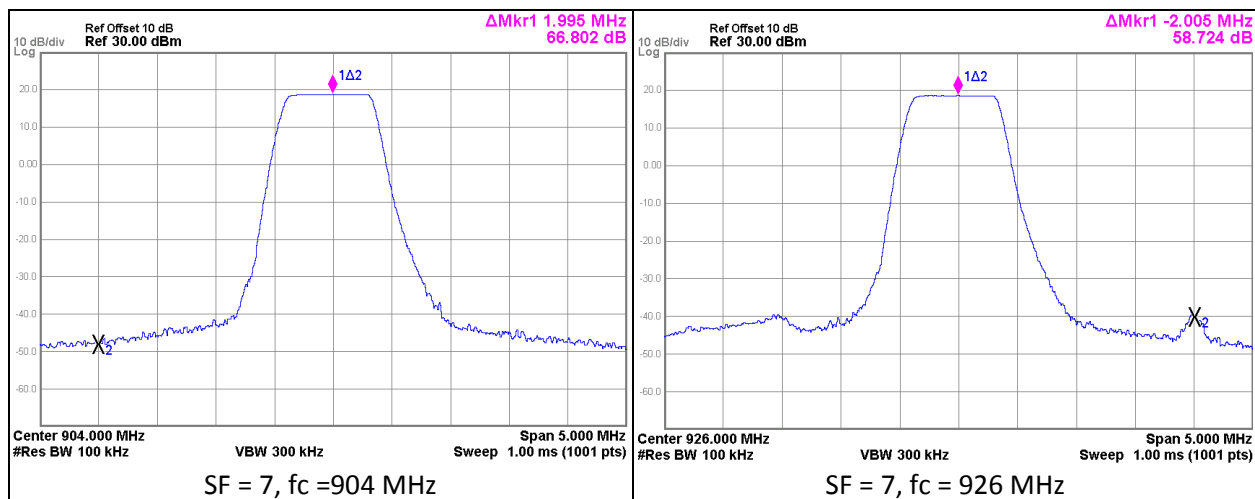
Figure 5: Wanted Emissions Reference Level

Figure 6: Non-Restricted Band Emissions

4.5 Emissions in Restricted Frequency Bands

The FCC requires measurements to be made up to the 10th harmonic frequency of the wanted emission and since the emission limits are specified in terms of radiated field strength levels, measurements performed to demonstrate compliance have traditionally relied on a radiated test configuration.

However, conducted measurements may be performed in the laboratory and the recommended procedure is listed below:

1. Set the analyzer RBW to 1 MHz (unless otherwise specified in Part 15.35 [2]) and ensure that the VBW ≥ 3 x RBW.

2. Use the spectrum analyzer's RMS detector assuming the number of points swept over he analyzer's frequency span is at least (2 * span / RBW). Note that satisfying this condition may require either increasing the number of points in the sweep or reducing the span. If this condition cannot be satisfied, then the detector mode shall be set to peak.

3. The trace averaging type shall be set to power (i.e. RMS)

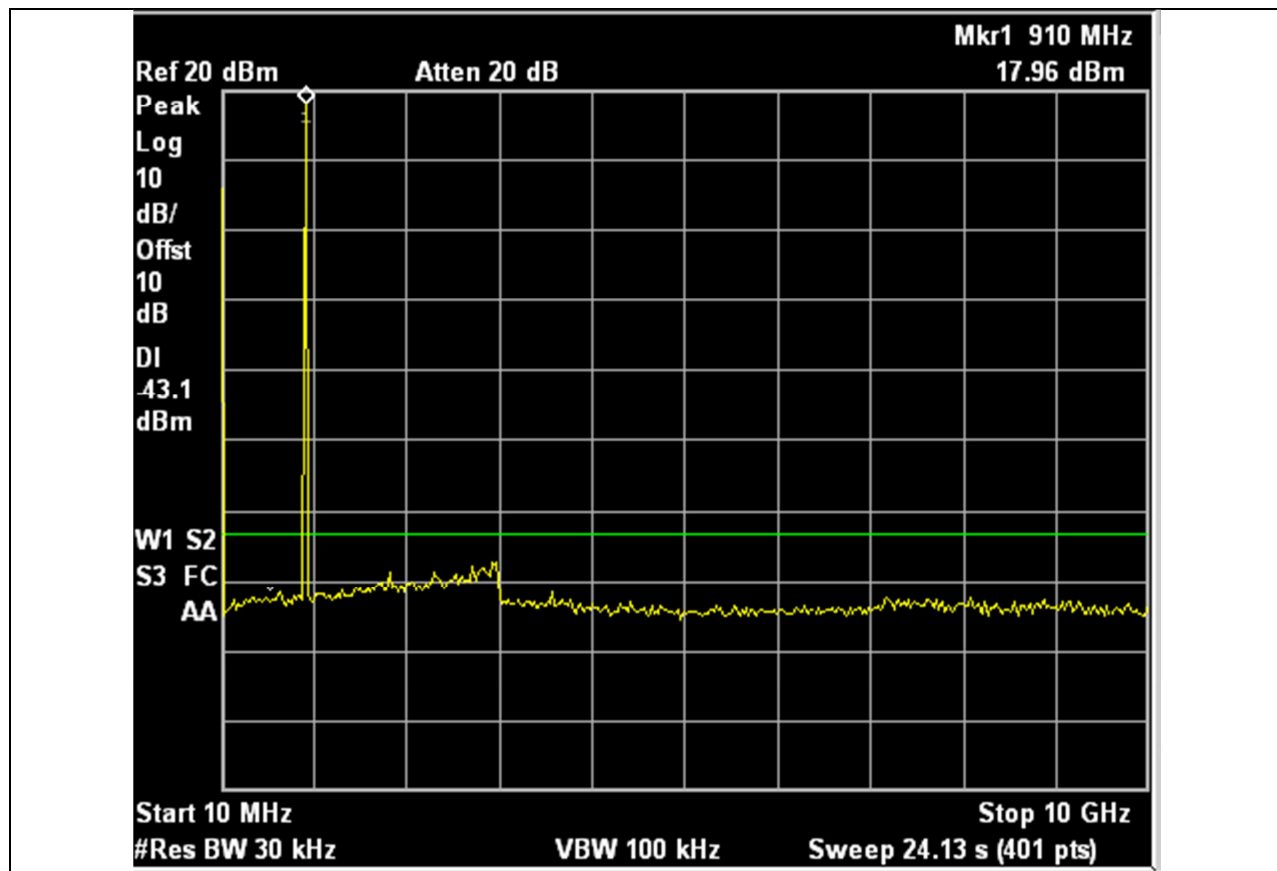4. Set the sweep time to auto and perform a trace average over at least 100 traces

Figure 7: Laboratory Pre-scan

Figure 7, indicates the results of a laboratory pre-scan analysis extending up to the 10th harmonic of the fundamental emission. Note that the reference line is set to -43 dBm, tightening the limit in the restricted bands above 960 MHz by the gain of the antenna provided with the Semtech DVK.

By dividing the frequency band as outlined in (2) above, we observe that the highest amplitude spurious emission identified is the 3rd harmonic of the fundamental emission. The indicated amplitude of this emission is -56 dBm, better than 10 dB margin to our tightened limit.

5   Measurement Methods for Systems Employing FHSS

All measurements were performed with the DUT configured for +20 dBm output power and both 125 kHz and 250 kHz LoRa bandwidths unless otherwise specified. In addition the DUT is set to TX continuous mode, enabling a 100% transmit duty-cycle to be achieved.

The recommended test procedure for systems employing frequency hopping is described in FCC Public Notice DA 00-705 [5].

5.1   20 dB Bandwidth

The maximum 20 dB bandwidth of a hopping channel is 500 kHz as defined in 15.247(a)(1).

5.1.1   Methodology

1. Set the frequency span of the spectrum analyzer to approximately 2 to 3 times the 20 dB BW, centered on the hopping channel
2. Set the RBW to approximately 1% of the 20 dB BW and the VBW ≥ RBW. For the purposes of the analysis VBW is set to 3 * RBW
3. Set the sweep to auto, the analyzer's detector function to peak and use the max hold when displaying the trace

5.1.2   Results

As is illustrated in Figure 8, the 20 dB BW of a LoRa modulated signal over both 125 kHz and 250 kHz does not exceed the 20 dB bandwidth limit.
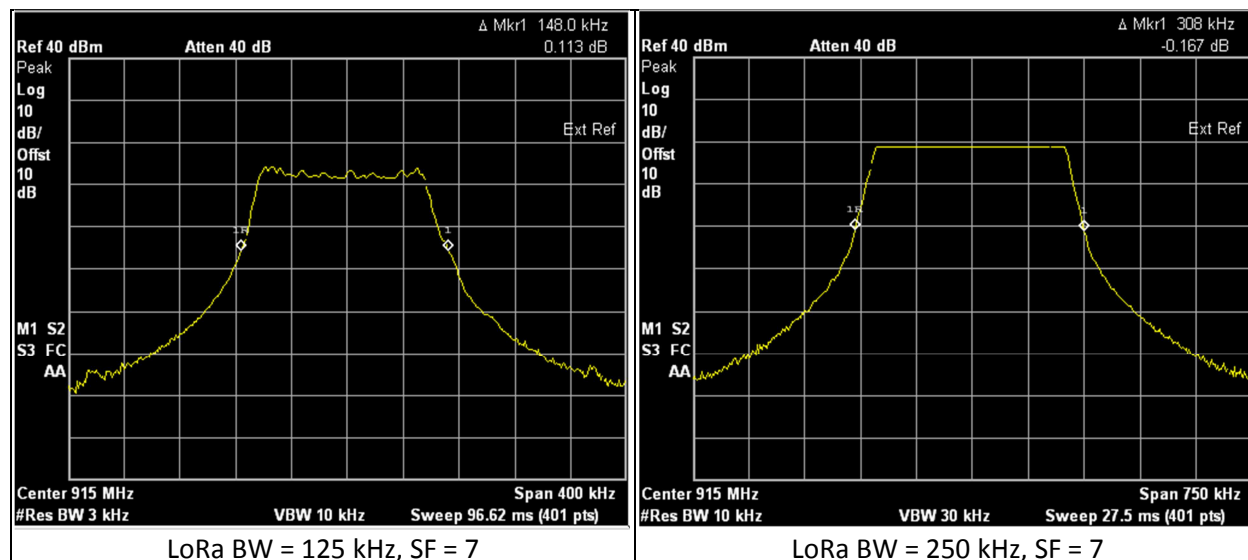

Figure 8: 20 dB Bandwidth

5.2   Carrier Frequency Separation

5.2.1   Methodology

15.247(a)(1) stipulates that frequency hopping systems must have a hopping channel separation that is the greater of 25 kHz or the 20 dB BW of the modulated hopping channel signal.

It can be observed from Section 5.1 that when operating with a 125 kHz LoRa bandwidth, the minimum hopping channel separation shall be at least 150 kHz, while for a 250 kHz LoRa bandwidth, a separation of at least 310 kHz would be required.

5.3   Maximum Peak Conducted Output Power

Frequency hopping systems employing 125 kHz BW LoRa modulation must use at least 50 hopping channels, while a system using 250 kHz BW LoRa modulation must use a minimum of 25 hopping channels. 15.247(b)(2) stipulates that the maximum peak conducted output power is dependent upon the number of hopping channels deployed. For a minimum of 50 channels, the limit is 1 W (+30 dBm) and for a minimum of 25 channels up to 50 channels, 250 mW (+24 dBm).

The maximum peak conducted output power available at the PA_Boost port is +20 dBm and thus Semtech's sub-GHz LoRa transceivers [6], [7] comply with this ruling.

5.4   Band-Edge Compliance

We will use the results obtained in Section 4.4 to show compliance with the requirements of 15.247(d). Note however that since a peak detector is specified, the limit is relaxed by 10 dB to -20 dBc. The end user should always ensure that a sufficient guard band is employed to ensure compliance.

5.5   Emissions in Restricted Frequency Bands

The results obtained in Section 4.5 are used to indicate compliance with the requirements of the regulations.

5.6   System Level Considerations

Part 15.247 states that a frequency hopping system is not required to employ all available hopping channels during each transmission, or use the entire available frequency band. However, the system, consisting of both the transmitter and the receiver, must be designed to comply with all of the applicable regulations should the transmitter be presented with a continuous data stream. Semtech's LoRa design tool [10] and application note [11] can assist the user in ensuring that the channel dwell time does not exceed 400 ms.

In addition, a system employing short transmission bursts must comply with the definition of a frequency hopping system and must distribute its transmissions over the minimum number of hopping channels specified *(Ref: 15.247(g))*.

The user must also demonstrate that the hopping sequence is pseudo-random and that the system receiver bandwidths match the bandwidth of the hopping transmitter and that frequency hopping occurs in synchronization with the transmitted signal *(Ref: 15.247(a)(1))*.

Finally, a system may incorporate intelligence that permits the system to recognize other users within the spectrum band so that it individually and independently chooses and adapts its hopping sequence to avoid hopping on occupied channels is permitted. However, the coordination of frequency hopping systems in any other manner for the express purpose of avoiding the simultaneous occupancy of individual hopping frequencies by multiple transmitters is not permitted *(Ref: 15.247(h))*.

The requirements summarized above are implemented at a higher level than the physical layer and are thus considered out of the scope of the document.

6   Hybrid Mode Operation

As has been documented in Section 3.3, hybrid mode operation permits a system to employ a combination of both frequency hopping and digital modulation techniques.

All measurements were performed with the DUT configured for +20 dBm output power and both 125 kHz and 250 kHz LoRa bandwidths unless otherwise specified. In addition the DUT is set to TX continuous mode, enabling a 100% transmit duty-cycle to be achieved.

This section illustrates that when operating as a hybrid device, LoRa modulation complies with the PSD emission limits of 15.247(e) even when configured for +20 dBm output power and with LoRa modulation bandwidths that would result in a 6 dB BW (as measured in 4.1) of less than 500 kHz.

6.1   Power Spectral Density

6.1.1   Methodology

To demonstrate compliance with the PSD limit defined in 15.247(e), we again employ the AVGPSD-1 method described previously in Section 4.34.3.1. Note that the maximum conducted output power is again averaged over the Occupied Bandwidth (OBW) of the fundamental emission (as described in Section 4.2).

6.1.2   Results

Figure 9 and Figure 10 illustrate the resultant PSD for modulation over both 125 kHz and 250 kHz LoRa bandwidths. It can be observed that Independent of spreading factor (SF), LoRa modulation complies with the power spectral density limits even when configured for +20 dBm output power mode of operation.
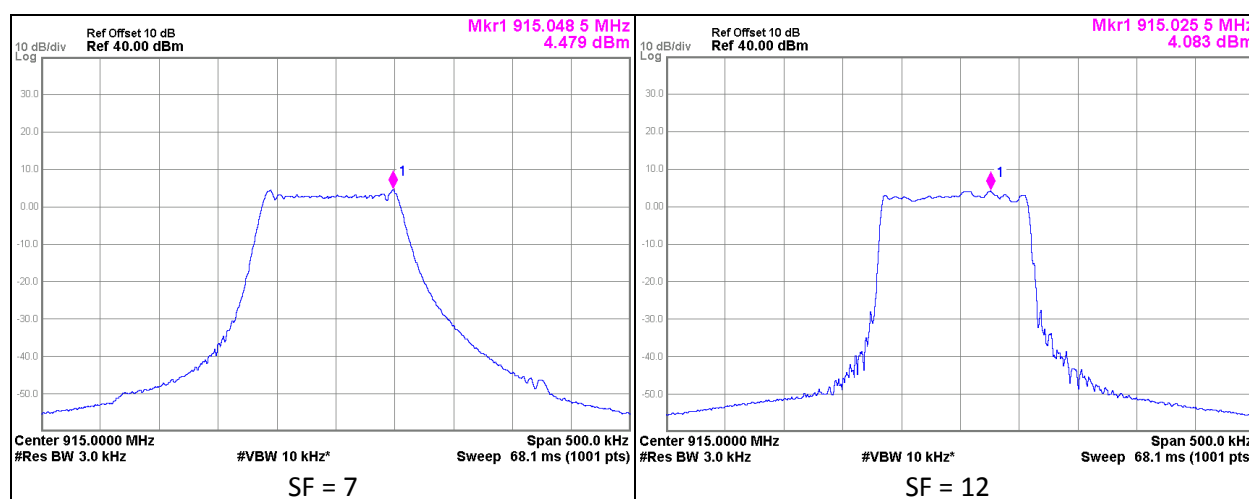

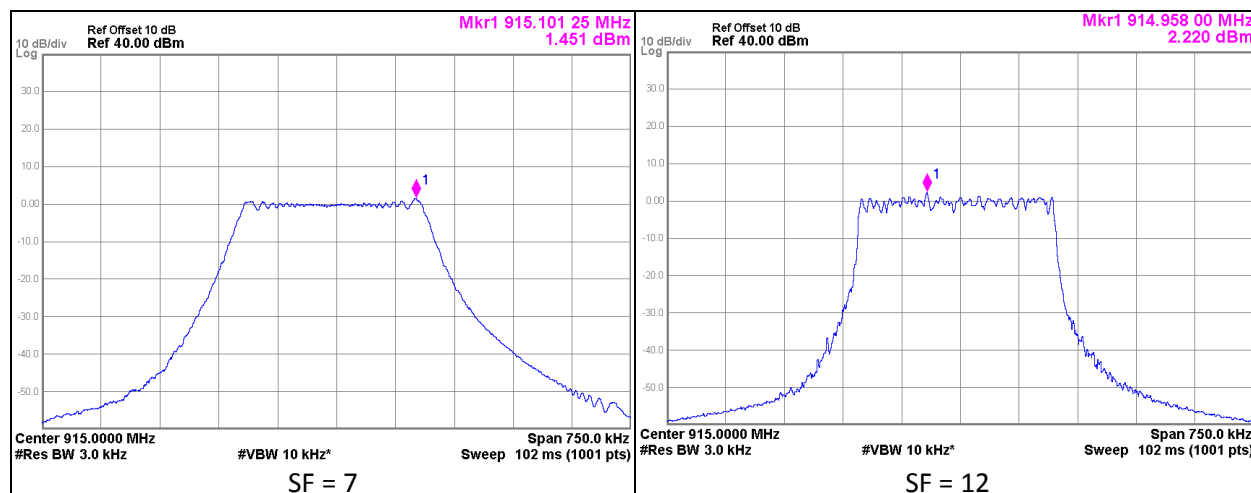Figure 9: 125 kHz Bandwidth LoRa Modulation PSD

Figure 10: 250 kHz Bandwidth LoRa Modulation PSD

7   Conclusions

This application note demonstrates the compliance of Semtech's sub-GHz LoRa transceiver operating in LoRa modulation mode with the requirements of Part 15.247 for systems employing digital modulation. It further indicates that LoRa modulation may also be employed in frequency hopping systems.

Finally the application note discusses hybrid mode operation and demonstrates compliance with the PSD limits for bandwidths less than 500 kHz and when configured to transmit at a transmitter output power of +20 dBm.

8   References:

[1]. FCC OET KDB Publication 558074 "Guidance on Measurements for Digital Transmission Systems (47 CFR 15.247)"; v03r02, June, 2014

[2]. Part 15 of Title 47 of the Code of Federal Regulations

[3]. Semtech Application Note AN1200.06: "FCC Rules for Systems Using Digital Modulation" (http://www.semtech.com/apps/filedown/down.php?file=fcc_digital_modulation_systems_semtech.pdf)

[4]. Semtech Application Note AN1200.04: "FCC Regulations for ISM Band Devices" (http://www.semtech.com/apps/filedown/down.php?file=fcc_part15_regulations_semtech.pdf)

[5]. FCC OET Publication Number 453039; March 23, 2007

[6]. ANSI C63.10-2013: "American National Standard of Procedures for Compliance Testing of Unlicensed Wireless Devices"; June 2013

[7]. FCC Public Notice DA 00-705 "Filing and Measurement Guidelines for Frequency Hopping Spread Spectrum Systems"; March 30, 2000

[8]. SX1272 Datasheet: (http://www.semtech.com/apps/filedown/down.php?file=sx1272.pdf)

[9]. SX1276 Datasheet: (http://www.semtech.com/apps/filedown/down.php?file=sx1276.pdf)

[10]. LoRa Calculator: (http://www.semtech.com/apps/filedown/down.php?file=SX1272LoRaCalculatorSetup1%271.zip)

[11]. Semtech Application Note AN1200.13: "LoRa Modem Designer's Guide" (http://www.semtech.com/apps/filedown/down.php?file=LoraDesignGuide_STD.pdf)

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