Test Strategies for IoT (Internet of Things)

White Paper

Abstract:

The Internet of Things is providing exciting opportunities to enhance products for consumer, industrial, medical and others. This paper discusses these unlicensed wireless connections and the special testing required to meet government regulations for IoT devices. The primary focus will be on the United States Federal Communications Commission (FCC), but the tests that need to be carried out are similar in most of the world. Testing for compliance can be complicated and time consuming but the testing is easier with knowledge and the correct test equipment.

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1 Introduction

Connecting a wide variety of consumer, industrial, medical and other devices to the internet has become very popular for many different reasons. These include remote monitoring, remote control, and providing early warning of problems with the connected device. While some devices can be hard wired to the internet, for many devices, hard wiring is impractical or impossible. This has led to tremendous growth of the application of wireless, mostly radio, technology. For almost all radio connections, there is the requirement to conform to country by country rules governing the performance of the radio system. In addition a substantial number of commercial radio communications standards have evolved to, at least theoretically, allow interoperability among various devices.

Most IoT devices exploit sections of the rules for unlicensed operation. This avoids the need to go through a typically lengthy and expensive process to acquire a license to exclusively use part of the radio spectrum. The widely used data communications systems such as WiFi, Bluetooth, and ZigBee use unlicensed spectrum so no license is needed before operating the system. These unlicensed portions of the spectrum also are wide enough to allow relatively high data rates compared to many of the licensed spectrum allocations. The tradeoff is that there is little or no protection from the interference of other users of this spectrum.

This paper discusses these unlicensed wireless connections and the special testing required to meet government regulations for these devices. The primary focus will be on the United States Federal Communications Commission (FCC), but the tests that need to be carried out are similar in most of the world. The major differences are the measurement limits, the documentation required, and the amount of the fees. We will not address the testing for conforming to the protocol of various radio standards such as Bluetooth and WiFi among many others because that is often straight forward once approved modules and integrated circuits are used in the design. Note that even under standards such as WiFi, Bluetooth, and ZigBee, there are multiple variations. These variations can be useful for different applications and have their own issues for standard compliance. However, there is little or no difference in the regulatory tests that need to be conducted. Except in limited circumstances where a certified module with integrated or specified antennas is used, the full set of tests must be performed, documentation submitted, and fees paid.

There are many approaches used to connect devices to the internet. One option is to equip the device with WiFi and connect to the local WiFi router which has a wired connection to the internet. However, in other cases, considerations of power consumption, size, cost and others mean that another standard or non-standard radio is used to connect to a hub which in turn has a wired connection to the internet or uses WiFi to connect to an existing or specially provided router. Figure 1 shows some typical IoT configurations.

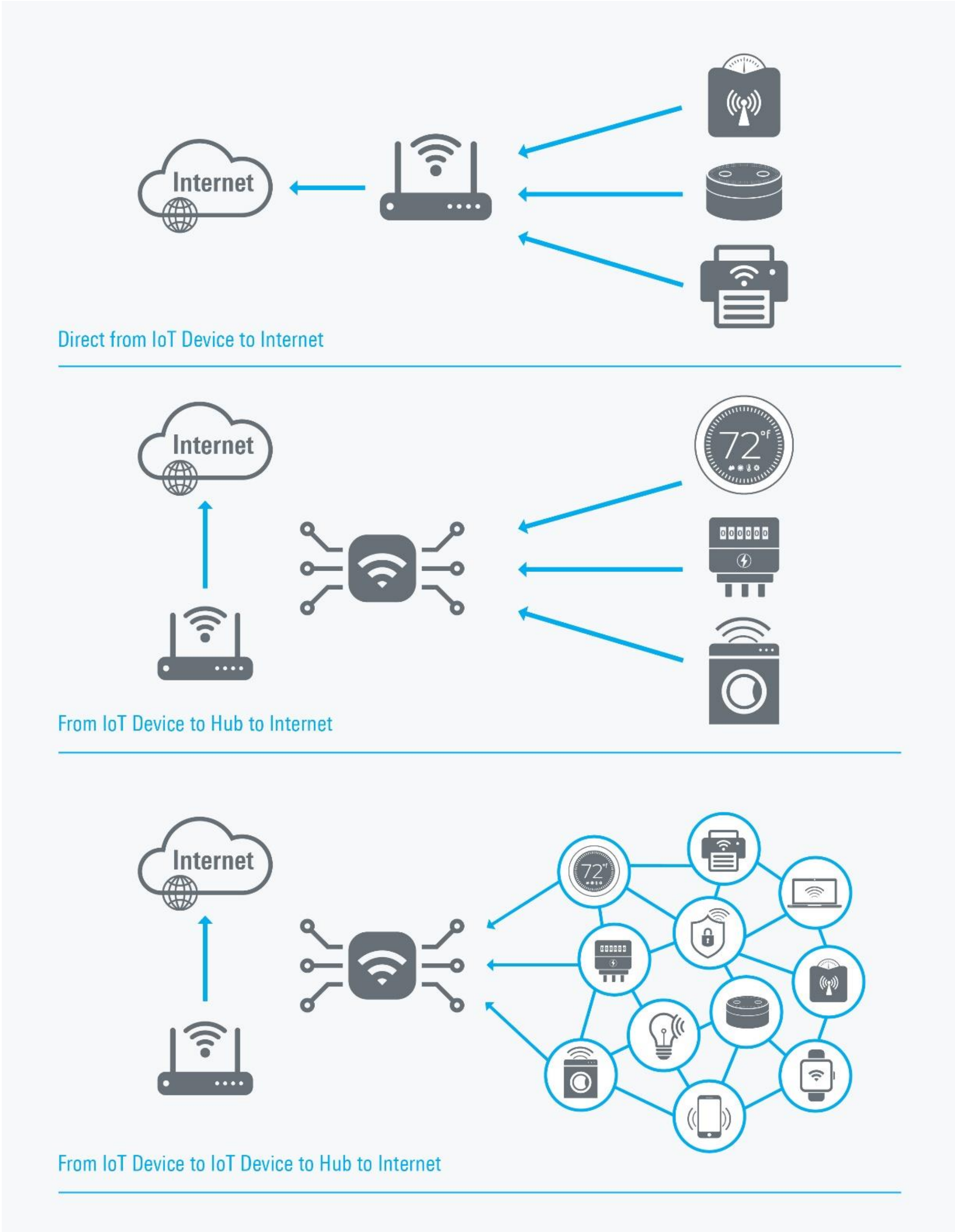


Figure 1: The three general configurations of IoT.

The approach to be used depends on many factors including the distances between devices and routers, amount and rate of data to be transferred, power and energy availability, cost considerations, size restrictions, and interference sources. Physical considerations in the environment such as concrete walls, large metal objects etc. may limit radio propagation. This may require a more complex radio system even if the distances are relatively short.

There are two primary approaches to addition IoT communications to an existing or new product. The approach with the lowest unit cost, but the highest engineering cost is to incorporate a commercial integrated circuit radio with the other necessary components to provide a radio link. A second popular approach, especially if the volume is low and/ or if there is not enough time to develop a chip level solution is to incorporate a commercially available radio module into the product. If the module is used with an included and tested antenna, some, but generally not all of the testing can be avoided. The trade-off is that the product cost will be higher.

Following is a discussion of the key tests that must be carried out under appropriate sections of the FCC rules.

2 Emissions Testing

The FCC rules have two broad categories of transmitted radio signals that have to be tested; "intentional radiators" which are the radio signals to be used to communicate the information over the radio, and "unintentional radiators" which are not part of the desired signal and can come from the radio, other digital and analog circuits, and power supplies.

2.1 Intentional radiation

Intentional radiator regulations depend on the frequency of the transmission as well as the selection of the rules under which the transmitter is operated. Some of the rules allow higher transmitted power than others, but typically have greater constraints on the characteristics of the transmitted signal. There are some frequencies and modulation types that are permitted in most parts of the world. Others are only available in limited geographic areas.

Note that for most countries, the intentional radiation testing must be carried out by a certified test lab.

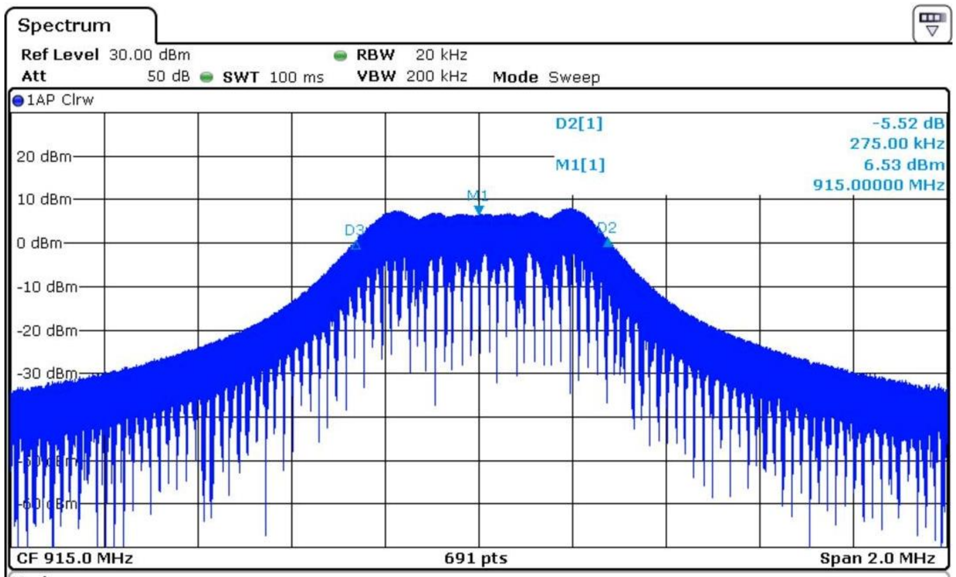
There are three radio communications schemes that are most popular for unlicensed operation and are widely used for IoT devices. The key tests for each of these are described below:

1. Digital Modulation (FCC section 15.247). This type of modulation is widely used for such popular data communications standards as WiFi and ZigBee, the recently introduced LoRa. This type of modulation is allowed in the 902 – 928 MHz, 2400 – 2483.4 MHz and 5725-5850 MHz bands.

   The key test to meet the requirements of this section of the rules involves measurement of occupied bandwidth where the requirement is a minimum 6 dB bandwidth of 500 kHz. The maximum output power of the transmitter is 1 watt. For most applications, if the antenna gain is more than 6 dB, the output power must be reduced proportionately. There are some special cases laid out in the rules for transmitters with multiple beams.

   In addition, the rules require that for any 100 kHz bandwidth outside the frequency band of operation, the power must be at least 20 dB below the power of highest in-band 100 kHz.

   These measurements must be made with peak detector. Figure 2 shows a signal that conforms to the regulations which require that the 6 dB down points include at least a 500 kHz bandwidth. Figure 3 shows a signal that does not because of the dip of more than 6 dB in the frequency region where the signal must be within 6 dB of the peak as well as a signal outside the band that exceeds the requirement that signals outside the band be attenuated more than 20 dB.



Type	Ref	Trc	X-value	Y-value	Function	Function Result
M1		1	915.0 MHz	6.53 dBm		
D2	M1	1	275.0 kHz	-5.52 dB		
D3	M1	1	-263.4 kHz	-5.96 dB		

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Figure 2: Digital modulation signal that conforms to the FCC rules. The measurement is made with a peak detector. There must not be a variation of more than 6 dB peak to minimum in the passband and the passband must be at least 500 kHz.

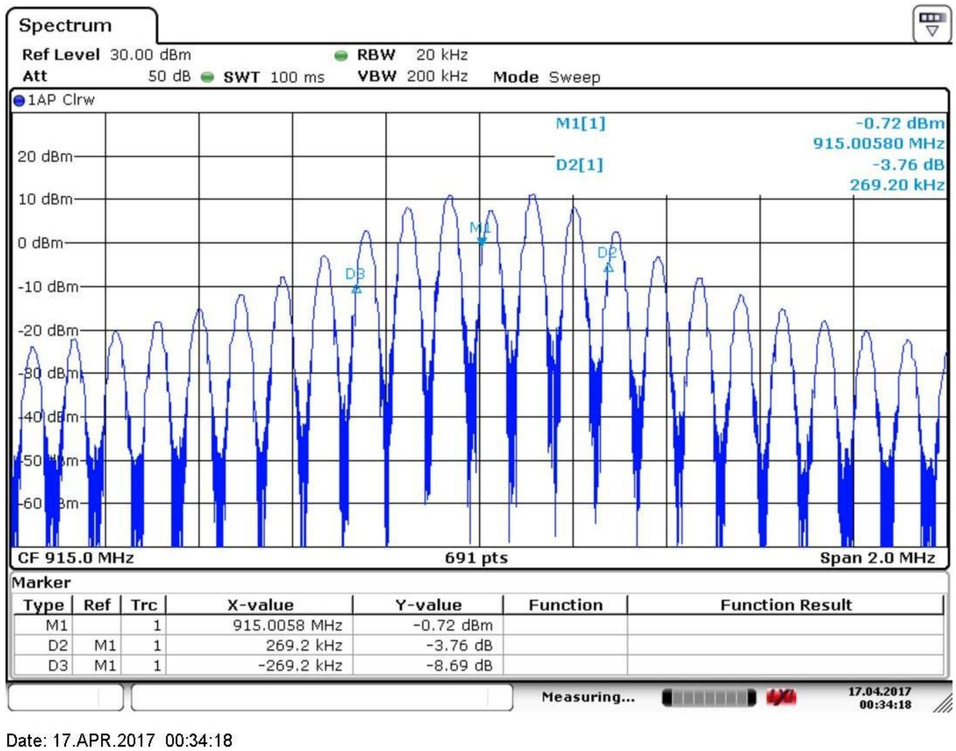

Figure 3: Digital modulation signal with impairments. Note that there are peaks and valleys within the information band.

The FCC rules allow measurement of the signal with a direct wired connection to the measuring instrument or measurement of the radiated signal with a reference antenna. Where allowed, direct connection is simpler because there will not be effects from the area around the device under test and the measurement antenna. However, the output power limit of 1 watt must be reduced in proportion to the gain of the device antenna over 6 dB for conducted measurements, and spurious signals must be reduced by 30 dB instead of 20 dB.

2. Frequency Hopping Modulation (FCC section 15.247). Bluetooth in several versions is the most common use of this type of modulation, though proprietary systems are also widely used. This type of modulation is available for use in the same bands as Digital Modulation. It is based on the requirement to occupy multiple different frequencies in the band in a random or pseudorandom sequence. The number of frequencies and the occupied bandwidth vary with the band selected. The frequencies used must be separated by at least 25 kHz or the 20 dB occupied bandwidth whichever is greater. There is a special case for low power 2.4 GHz implementations.

In the 902 to 928 MHz band, if the 20 dB occupied bandwidth of the hopping channel is less than 250 kHz, 50 different frequencies must be used and no channel can be used for more than 0.4 seconds out of 20 seconds. Up to 1 watt of output power is allowed. If the occupied bandwidth is greater than 250 kHz, 20 channels shall be used and no channel can be used for more than 0.4 seconds out of 10 seconds. Up to 0.125 watts of output power is allowed for this implementation. The maximum occupied bandwidth under this rule is 500 kHz. However, if more bandwidth is needed, the Digital modulation rules should be used, though hybrid frequency hopping and digital modulation systems are permitted.

In the 2400 – 2483.5 MHz band at least 15 channels are required and the average time on any frequency is to be no more than 0.4 seconds in a period of 0.4 seconds multiplied by the number of frequencies used. If 75 channels are used, the maximum output power is 1 watt. For fewer channels, the maximum output power is 0.125 watts.

In the 5725-5850 MHz band at least 75 channels are to be used with a maximum 20 dB bandwidth of 1 MHz. The maximum occupancy is 0.4 seconds in a 30 second period. The maximum output power is 1 watt.

Figure 4 shows a frequency hopping signal that conforms to the rules. Figure 5 shows a frequency hopping signal that has frequencies that are not spread uniformly enough to conform to the rules.

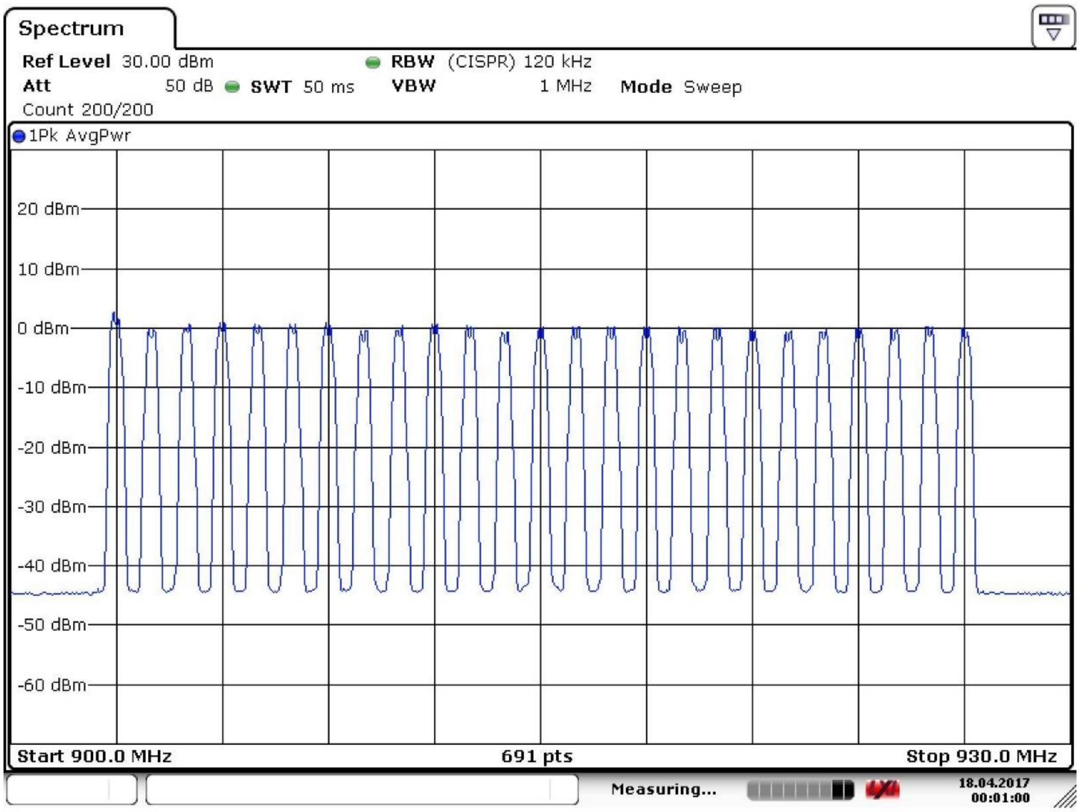

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Figure 4: Good frequency hopping signal. There are the required 25 different hopping frequencies and they are evenly used.

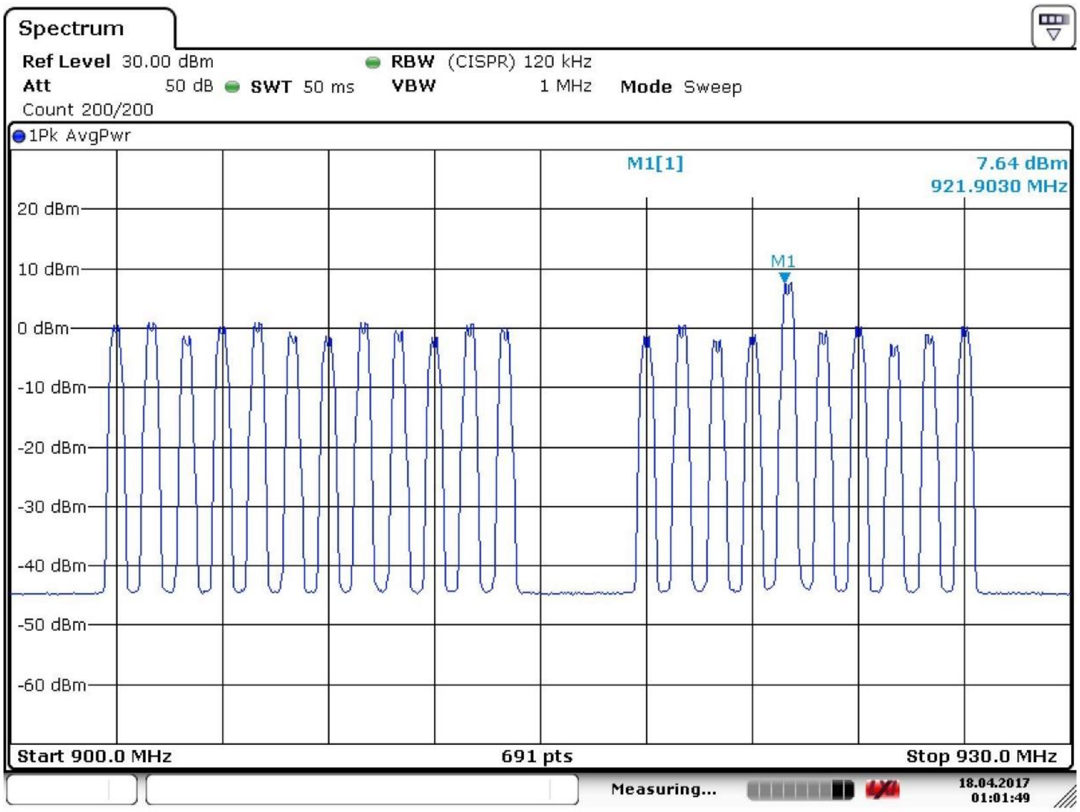

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Figure 5: Not a good frequency hopping signal. There are several hops skipped and one (designated by the marker M1) is used multiple times in a scan.

3. Another set of options for lower data rates and relatively short distances is to use the narrow band transmission under FCC rules section 15.231 which is permitted in a wide range of frequencies, but at very low power and typically low duty cycle. There are higher power options in section 15.249 in the same bands as allowed for Digital and Frequency hopping modulation discussed above. Section 15.231 transmitters are commonly used for garage door openers and remote keyless entry for automobiles. Because of the short range, these options are not often used for IoT and will not be discussed further.

   In addition, some IoT devices incorporate cellular modems which operate in cellular licensed bands. Generally this is done with preapproved modules or subassemblies approved by carrier can be used so only unintentional radiation levels need to be confirmed for the product.

2.2 Unintentional radiation

The rules for unintentional radiated emissions are similar around most of the world, though some regulations are specific to the incidental emissions from specific signal types. For many jurisdictions, only self-certification is needed.

Unintentional emissions are the undesired signals from the radio or other parts of the device including the IoT radio receiver, clock generator, power supplies and digital circuits. For most rule sections, the unintentional emissions must be measured to the 10th harmonic of the transmitting signal which requires a relatively high frequency spectrum analyzer or similar device.

Unintentional emissions rules are generally specified for radiated rather than conducted measurements. There is one exception in section 15.247, but this has issues that limit the practicality of using other than radiated testing. The limits on spurious radiation in any 100 kHz band for Digital modulation and Frequency hopping radio transmissions under FCC rules section 15.247 are 20 dB below the maximum emissions, tested in any 100 kHz band outside the transmitted signal. Below 1,000 MHZ, the spurious signals are measured with a CISPR quasi-peak detector. Above 1,000 MHz, an averaging detector can be used to provide up to a maximum of 20 dB additional margin for very low duty cycle operation. (See the discussion of detector types below). However, there is a large number of what are called “Restricted bands” for which the radiated limit is 500 microvolts per meter at 3 meters as listed in FCC rules section 15.205. These bands include the 2nd, 3rd, 5th and 6th harmonics of the 2.4 GHz band. The limits in the restricted bands are very low and can represent a substantial engineering challenge to meet the limits. Accurate testing is critical to avoid retest due to failing to meet these rules.

For devices operated from line AC power, most countries require that unintentional emissions conducted back down the power line be measured to the standards in the regulations. These emissions are measured with a line impedance stabilization network (LISN) and must be measured from 150 kHz to 30 MHz. The limits are provided in FCC rules section 15.207. The emissions can be measured with either a quasi-peak or average detector with alternate limits provided in the rules. Generally it is not the radio that causes unwanted emissions in these frequencies, but the power supplies and/ or digital circuits.

3 Other Considerations

3.1 Pretest

There are a number of reasons to pretest during product development. One of the most important is to avoid the cost and time for major design changes late in the product development process. To meet the regulations on emissions, major circuit and/ or enclosure design changes may be needed. It is much easier and less expensive to make these changes based on early prototypes before final designs, tooling and documentation are developed.

A second set of reasons to pretest emissions include the time and cost for making changes and retesting during final test. Often there is a time delay for getting in the test house's schedule for retest. In addition, even a partial retest can cost many thousands of dollars. Even more important can be the lost market opportunity because the product cannot be sold without the certification of emissions compliance.

3.2 Preparation for testing

Before testing, either pretest or regulatory test there is recommended preparation for the test process. Usually the test time and cost can be reduced if special software can be provided to have the device make a typical transmission as often as possible – at least a few times per second. Note, though it should not transmit so often to negate the test advantage of signal averaging if applicable for the transmissions type. Emissions testing is typically done on a turn table to test all around the product and moving the antenna or device to get the emissions in vertical positions.

Also, it is important to use an antenna on the device with gain and directivity that is representative of the final product antenna in gain and directivity. Also, the device should be tested in an enclosure that is representative for the final product since the enclosure can attenuate some signals but may cause peaks in the emissions in some orientations due to reflections.

3.3 Detector

The type of detector and measurement bandwidths used for testing can make a large difference in the measurement. It is important to use the detector specified in the rules, or the pretesting results may be misleading and likely useless. FCC section 15.35 defines both the detector type and the measurement bandwidth to be used. The three types of detectors are the CISPR quasi-peak detector, the peak and average detector. These detectors can give substantially different results for signals that vary in time. Figure 6 shows the difference in the measurement results for a common pulsed type of transmission. A caution is that the quasi-peak detector is not standard on some spectrum analyzers. While a peak detector is allowed, for some signals, it may indicate a problem that is not really there. This could lead to putting excessive engineering or material cost into the device.

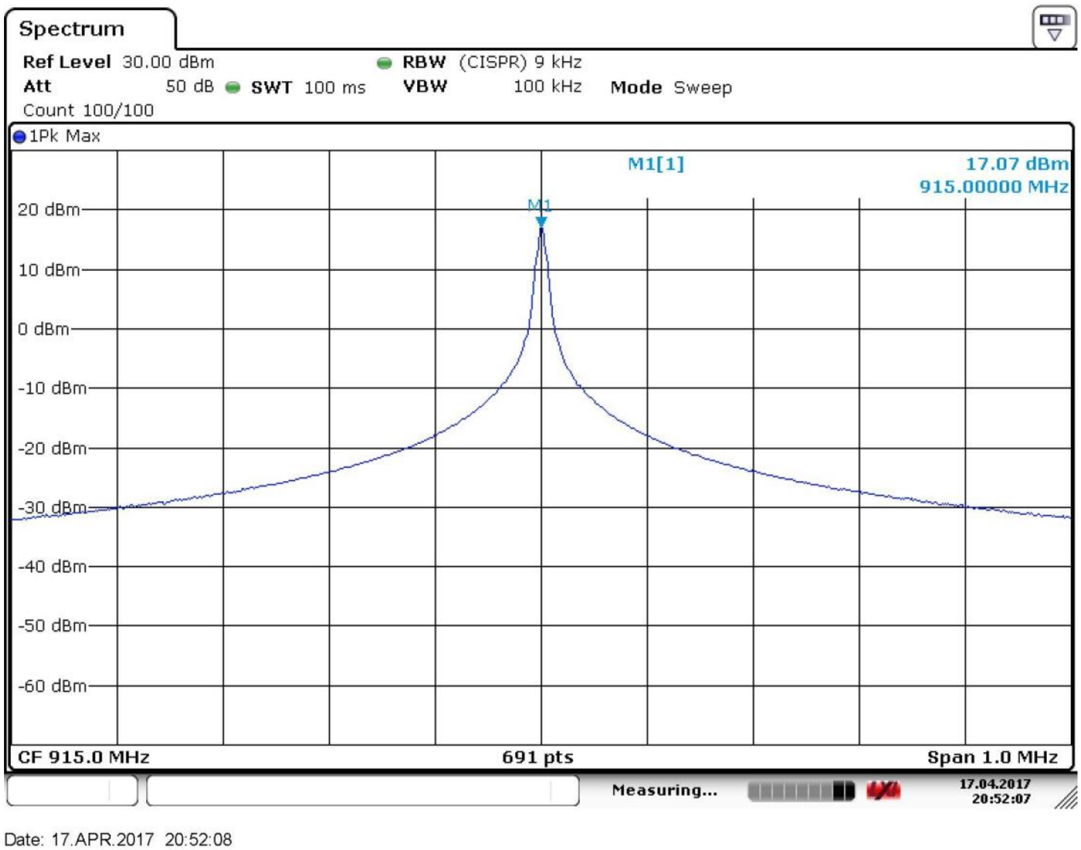

Figure 6a: Measurement results with a Peak detector. This example shows a pulsed signal that is on for 1/10th of the time.

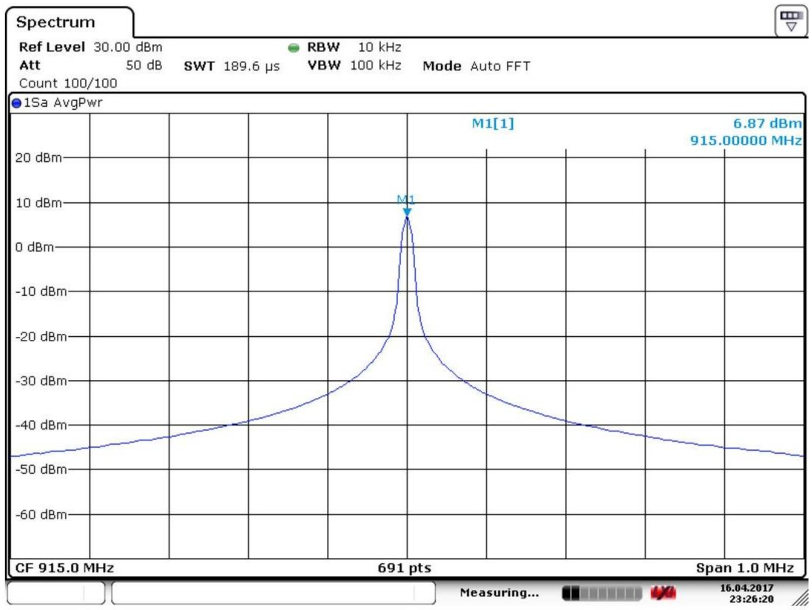

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Figure 6b: Measurement results with an Average detector. The average value is about 10 dB lower than the peak reflecting the 1/10th duty cycle. This is a major difference, especially when trying to meet the stringent limits in the restricted bands.

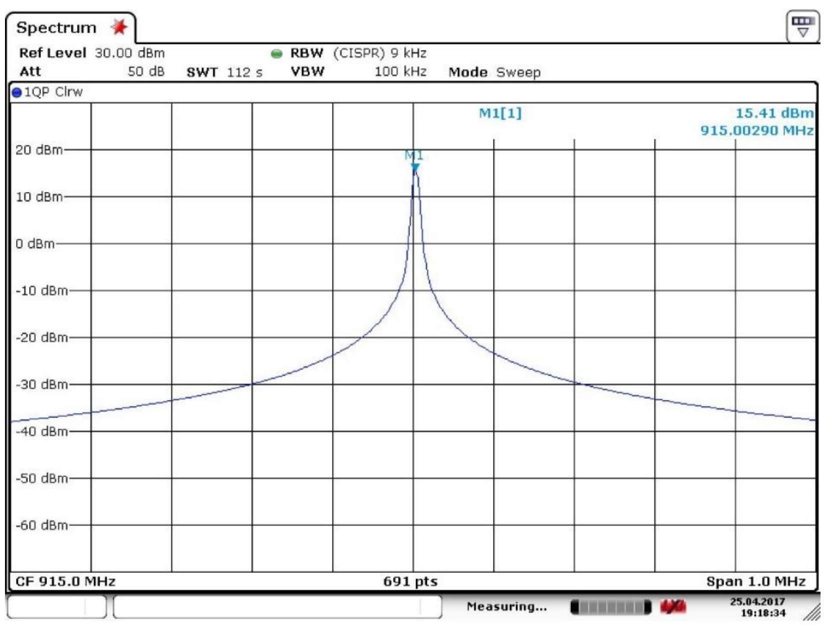

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Figure 6c: Measurement results with a Quasi-Peak detector. For a low duty cycle and with short on times, the quasi-peak level will be significantly lower than the peak value.

4 8 Issues and Cautions for Regulatory Testing

Experience has shown that there are a number of common problems that arise for testing both in pretest and final regulatory testing at an approved test facility.

1. Accuracy of test equipment and procedures – The absolute accuracy of the equipment used for pretest and the equipment at the final test facility can cause a number of problems. The FCC rules in section 15.31 lay out the measurement standards for various tests. Section 15.31 refers to several ANSI standards that provide more detail of the test setups and accuracy. These standards only require that the equipment to be calibrated to +/- 2 dB. This means that even with conforming equipment there could be a 4 dB difference in pretest versus final test. This is larger than the margin that would be desirable to have the best possible performance and lowest cost of the IoT device.

   There are several sources of inaccuracy that should be considered. For in house testing, it may be tempting to purchase low cost equipment, especially from some of the newer vendors, or used equipment that has not been refurbished and calibrated to original specifications. Some of this equipment has been found to have level errors of as much as 7 dB which is a huge amount of error. This much error could mean spending unnecessary effort to meet rules, or having a product with less performance that it should. Alternatively, if the test equipment is reading low, a device that passes pre-test could fail in final test causing delays and extra expenditure.

   An excellent option for all of the tests discussed above is the Rohde & Schwarz model FSV30 spectrum analyzer. It provides measurement frequencies to 30 GHz which includes the 10th harmonic of the 2.4 to 2.4835 GHz band. The amplitude uncertainty is only 0.28 dB in the 915 MHz and 2.4 GHz bands and only 1.32 dB at 30 GHz. The FSV series provides all three primary detector types of Peak, Quasi-Peak, and average. It also provides the CISPR resolution bandwidths to allow testing as required for many countries.

Figure 7: Rohde & Schwarz FSV

In addition, preamplifiers, if used, can add error or uncertainty. The actual gain of any amplifiers needs to be checked with high accuracy equipment and the errors corrected in the evaluation of the final test results.

It is also critical to use the correct type of detector, resolution bandwidth, and measurement span so that spurious signals are not missed. The rules generally specify these parameters, but some spectrum analyzers and receivers may not have the correct detector type or resolution bandwidth. For some spectrum analyzers, the test standards require special options, for example for the quasi-peak detector or specified resolution bandwidth, at extra cost, but these should be purchased if not already on the equipment to avoid costly measurement errors. Figure 8 shows the difference is readings for different resolution bandwidth and sweep times.

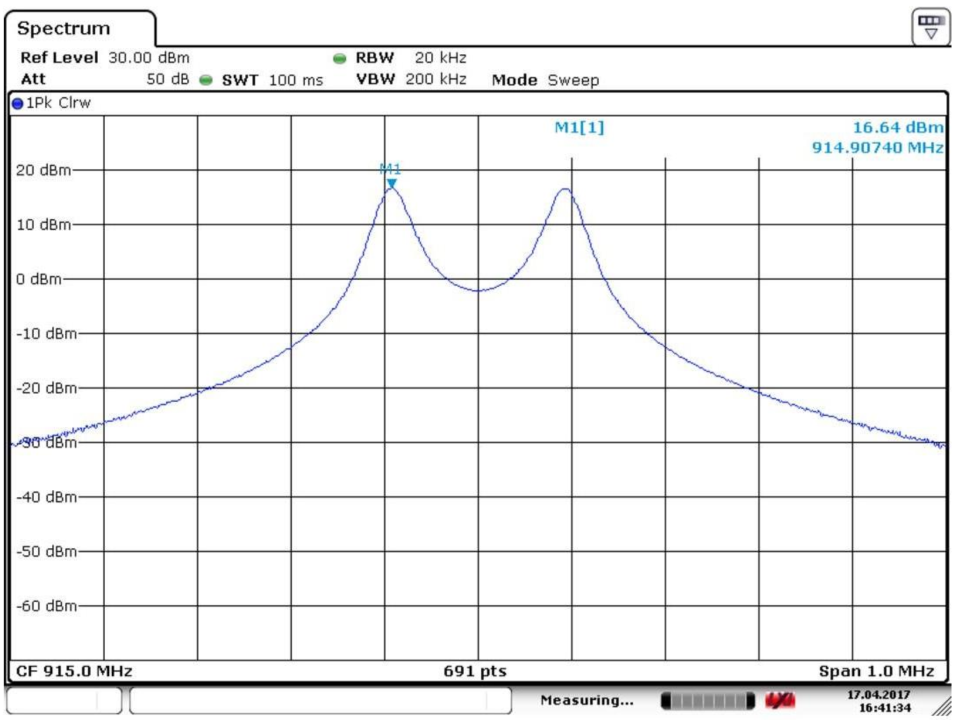

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Figure 8a: Measurement effects of RBW - 10 kHz.

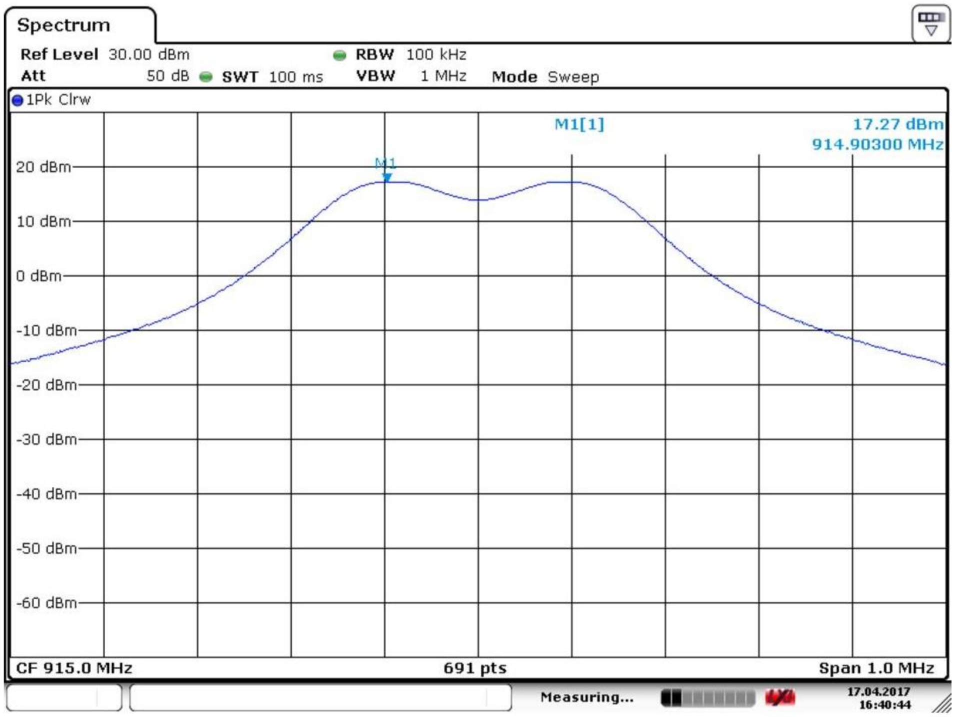

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Figure 8b: Measurement effects of RBW - 100 kHz. The wider bandwidth shows a slightly higher peak value as well as a much wider occupied bandwidth. Using the wrong bandwidth in pretest can give results that may mean incorrect final test results.

The test antennas are a critical part of the test equipment. They must have the correct frequency range and be properly calibrated. Antennas can be easily damaged in a busy lab and must be recalibrated or replaced if dropped or otherwise damaged.

Likewise cables and connectors must be checked for losses and the corrections included in the measurements. They are also subject to damage and should be rechecked frequently.

In pretest it is also critical to set up a test area that is free from interfering radio sources including cellular, WiFi, and Bluetooth radios. There can be interference from some infrastructure such as airports, police and fire stations, and local radio and TV stations. It is important to separate these signals from the signals that need to be measured. They can lead to chasing problems that are not there, or even worse, mask spurious signals from the device and lead to failing final test.

The pretest area needs to be reasonably free of reflective materials which can increase the values of measurements beyond what is really there causing more engineering effort than is really needed.

2. Misunderstandings of the FCC rules – The FCC rules (and others) are a combination of technical and legal words and ideas. It is often difficult for engineers or lawyers to correctly interpret some of the rules. This applies to pretest personnel as well as to test house staff.

   One common mistake is for engineering staff to not understand that the testing and certification are needed at all. Failure to test and certify products can lead to substantial fines and sales can be stopped.

   The rules for Digital modulation and Frequency hopping are quite complex. It is not uncommon for the wrong bandwidth or number of hops to be designed into the device. The rules governing the limits on output power and antenna gain are also frequently misinterpreted.

   The rules covering the periodic transmissions on FCC section 15.231 are also frequently misinterpreted. Even for very low duty cycles, there is a 20 dB limit on radiated emissions over the base limit.

   The limit on radiation that falls into the restricted bands is easy to miss. The levels in these bands are very low, but it is critical to meet these lower limits.

   In pretest and final test it is important to select the correct detector. For most intentional signals, the detector used must be the quasi-peak detector. This type of detector is an extra cost option for many spectrum analyzers. The peak detector is allowed by the rules instead of the quasi-peak detector, but this may indicate higher emissions than are actually present.

   Some pretest and final test house engineers do not understand that for most unintentional emissions above 1,000 MHz the averaging detector can be used. For low duty cycle transmissions, this can make a big difference in the level of emissions observed. If the final test personnel do not use the averaging detector when allowed, the device may be declared to have failed the test even though it is fully compliant.

3. Limitations of test equipment – There are several issues affecting even high quality test equipment that must be watched for. Amplifiers and spectrum analyzers will generate harmonics and other noise if presented with strong signals. For the rules that allow relatively high output power such as section 15.247, it is very easy to cause problems, especially in the restricted bands where the maximum allowable signal is very low regardless of the fundamental transmitted power. The solution is to use a high pass filter or pre-selector to attenuate the fundamental frequency while allowing the higher frequency spurious signals to pass. Note that it is also important to include the losses in the filter or pre-selector in the measurement. Figure 8 shows the harmonics generated and the effect of adding a high pass filter.

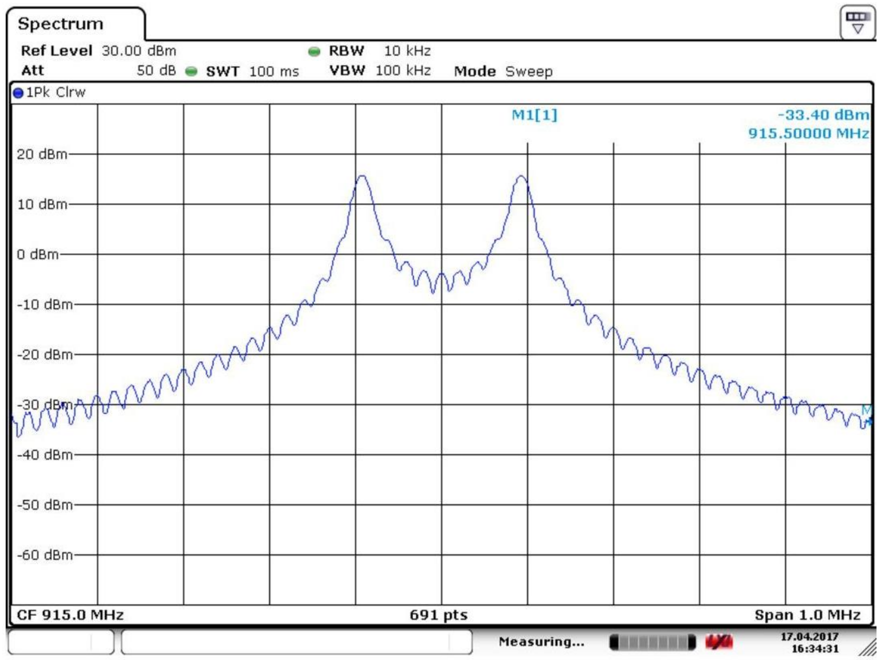

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Figure 9a: Signal at fundamental frequency using an off the shelf amplifier.

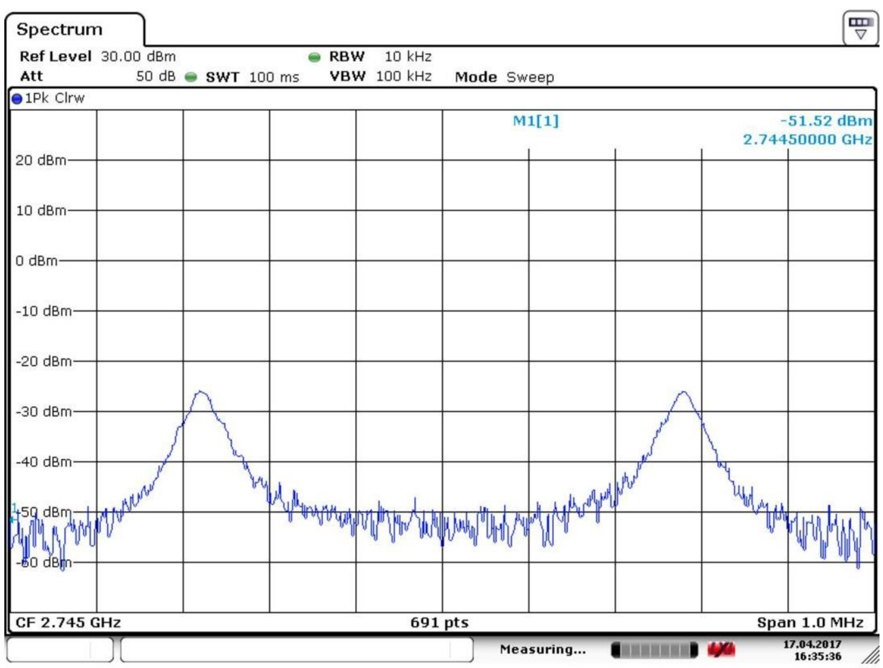

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Figure 9b: Measured signal at the 3rd harmonic. This signal is due to the amplifier.

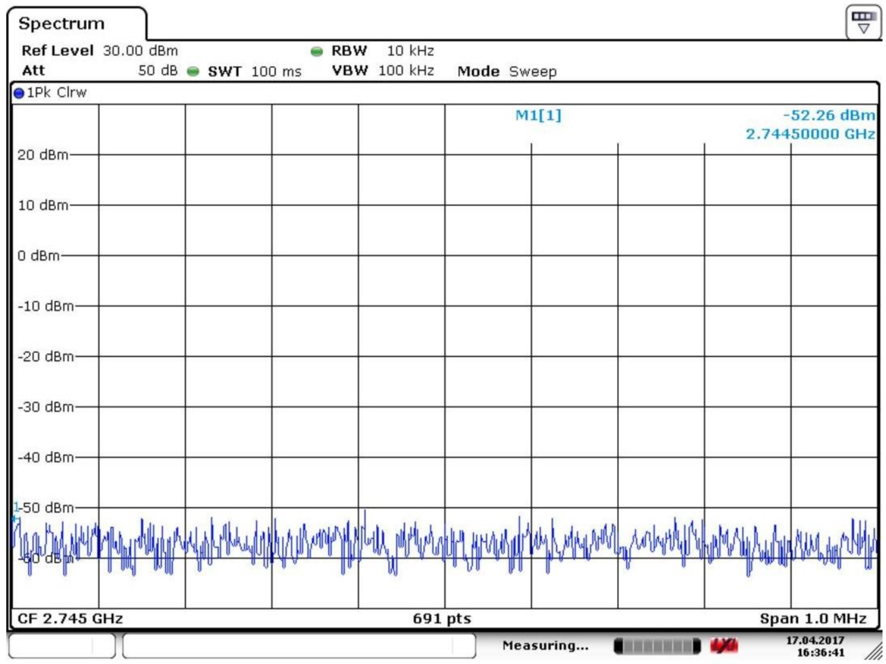

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Figure 9c: High pass filter before amplifier. Note that the amplifier is no longer generating significant harmonics.

When the signals are near the noise floor of the spectrum analyzer, the noise floor adds to the signal and can show emissions larger that they are. In pretest this can lead to thinking that more engineering is needed to reduce the signals, or to incorrect test failure in final testing. Use of a preamplifier can address this problem, though the caution mentioned above about spurious signals generated in the amplifier is important to watch.

Amplifiers, cables, filters and connectors can have losses that vary with frequency. It is critical to measure these losses and include them in the measurement process or incorrect pass or fail indications may arise.

As previously mentioned, the operating frequency range of the spectrum analyzer must be high enough to measure the 10th harmonic of the transmitted signal. This rules out most of the low cost spectrum analyzers and receivers on the market. A possible shortcut is to only test the 7th harmonic because experience shows that this is usually the highest harmonic that causes compliance problems. However this is still a high frequency for most applications.

4. Peaks in radiation pattern - Spatially small radiation peaks can be caused by the configuration of the antenna(s) and rest of product. It is easy to miss emissions violations in pretest if it is not done carefully. Since test house will use a rotating

table, and vertical up & down, they are more likely to catch spatial peaks. Also, if the device under test is moved manually, the hand may change the pattern of emissions.

5. Small valleys in receiver sensitivity - The same issue as in item 4, can apply to the receiver. There can be positions of the device that have much lower receiver sensitivity than most of the directions. This is not a regulatory issue, but can adversely affect the performance of the device.

6. Effects of hand or other environmental issues - Hand effects or proximity issues in installation can affect the radiation from the device and/ or the receiver performance. If the device will be used held in a hand or in proximity to reflective materials, it is important to test it as it will be used. This will generally not affect regulatory testing, but may result in customer problems like the one a cell phone had with the antenna design on one of its models. If pretest is done using manual movement of the device, it is important to use a low loss plastic rod to hold the device to minimize absorption or reflection from the hand.

7. Variation in unit to unit performance – The actual sample device or devices to be submitted for final test should be pretested to avoid a surprise in the final test because the device submitted does not conform to the rules. If device components or assembly process have tolerances that are too wide, some units may not work satisfactorily or may fail to meet FCC or similar rules in production.

8. Variation in performance over temperature and humidity – It is also important to assure that the components selected will not change value enough to fall out of regulatory compliance in normal use due to changing values with temperature, PCB moisture absorption, moisture trapped by conformal coating.

5 Conclusion

The Internet of Things is providing exciting opportunities to enhance products for consumer, industrial, medical and others. Most often these products use radio for at least part of the link to the internet. These radio systems require testing to show conformance with standards that vary somewhat throughout the world. Testing for compliance can be tricky and time consuming, but the testing can be made easier with the knowledge and the correct test equipment.

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

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