

RF Sensors for Spectrum Monitoring Applications: Fundamentals and RF Performance Test Plan

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report series

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RF SENSORS FOR SPECTRUM MONITORING APPLICATIONS: FUNDAMENTALS AND RF PERFORMANCE TEST PLAN

Jeffery A. Wepman, Brent L. Bedford, Heather Ottke, Michael G. Cotton ¹

Great emphasis is seen on the networking and data management aspects of spectrum monitoring, but far less attention is given to the radio frequency (RF) sensor systems used to collect the spectrum data. This report focuses on these sensor systems and, in particular, the commercial-off-the-shelf (COTS) RF sensors used in the sensor systems. A test plan for evaluating the RF performance of COTS sensors is outlined. Evaluation of COTS sensors is an ongoing task of the Center for Advanced Communications (CAC) Spectrum Monitoring Program. The intent is to build a comprehensive cost/capability/performance matrix to help guide the selection of the appropriate COTS sensor for a given monitoring scenario. The test plan strives to standardize the tests and metrics, so that results can be compared from sensor to sensor.

Keywords: RF sensor, software defined radio, spectrum monitoring

1. INTRODUCTION

Seemingly insatiable demand for wireless broadband access [1] has prompted U.S. government initiatives [2] to make more frequencies available for commercial broadband applications. Desirable radio spectrum has been mostly allocated in the U.S., as can be seen on the National Telecommunications and Information Administration's (NTIA's) radio allocation chart [3]. There are two basic ways to make more spectrum available: (1) open frequency bands to shared use or (2) relocate incumbent users to other bands or to different sections of their allocated band.

Measured spectrum occupancy is useful information for planning, engineering, and enforcing new spectrum sharing and relocation scenarios. In an effort to provide high quality, easily accessible, and standardized measured spectrum occupancy data to the spectrum community, and pursuant to the 2013 Presidential Memorandum [4], NTIA and the National Institute of Standards and Technology (NIST) are developing a spectrum monitoring capability for the recently announced Center for Advanced Communications (CAC) [5]. The goals of this program are to (1) develop an infrastructure to acquire and amass spectrum monitoring data and make it available to the spectrum community in near real time via the Internet [6], and (2) establish and implement best practices for acquiring spectrum data. The acquisition of spectrum data is to be accomplished by a network of radio frequency (RF) sensor systems deployed in various locations throughout the U.S. A description of the overall network infrastructure and architecture is given in [7]; this report focuses on the sensor systems, with particular emphasis on their key component: commercial off-the-shelf (COTS) RF sensors.

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2. SENSOR SYSTEM ARCHITECTURE

Sensor system design, development, and deployments for CAC spectrum monitoring are being led by NTIA's Institute for Telecommunication Sciences (ITS). While sensor system designs tend to be frequency band and radio service specific, the sensor systems share a basic, general architecture. As seen in Figure 1, the general sensor system architecture includes an antenna, preselector, COTS RF sensor (hereafter referred to as the sensor), and measurement controller.

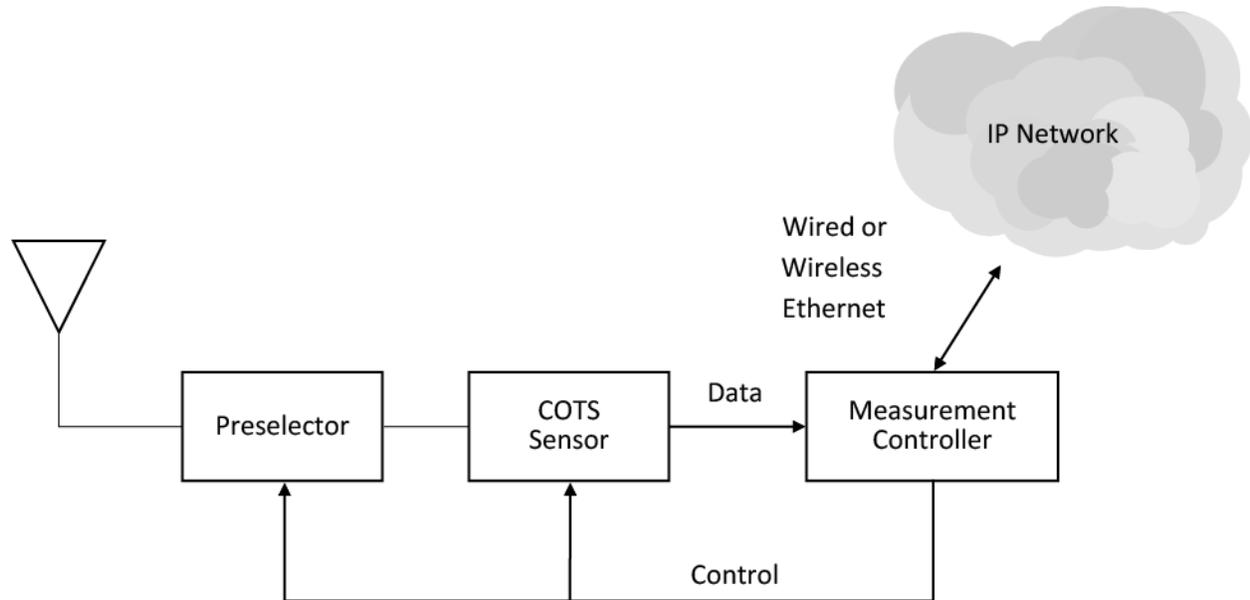


Figure 1. General architecture of a sensor system.

The type of antenna and its specifications (e.g., frequency range, gain, polarization, and directionality) are selected according to the specific band and service to be measured and topography of the installation site.

The preselector performs several crucial functions for the sensor system. It attenuates unwanted out-of-band signals, improves the sensitivity of the system, and enables sensor system calibrations. Sensor system calibrations are required to provide assurance that the sensor systems at remote locations are operating properly. They also provide measurements of the system noise figure from which the system noise level in a given bandwidth can be determined. The preselector typically provides the capability to switch between one or more low-loss, highly selective, RF bandpass filters. It also includes a low-noise amplifier and signal source for calibration.

The sensor is the core of the overall sensor system. It takes the RF signals received by the antenna and conditioned by the preselector, downconverts and digitizes these signals, and performs various digital signal processing (DSP) functions to provide complex sampled data vs. time or frequency output data. Control of the preselector and sensor and further signal processing is provided by the measurement controller if necessary. Some sensors include embedded processors and control ports that could be used for measurement control and signal processing, obviating the need for the measurement controller.

The sensor/measurement controller combination provides either complex sampled time data or amplitude vs. frequency data, formats the data according to a predefined data transfer specification, saves the data on a local hard drive, and pushes it to a centralized data staging server when the IP network is available.

3. SENSOR TYPES

Fundamentally, two types of sensors can be used for spectrum monitoring; swept-tuned or discrete Fourier transform (DFT)-based sensors.

3.1 Swept-Tuned Sensor

The swept-tuned sensor is the traditional superheterodyne swept-tuned spectrum analyzer. The swept-tuned spectrum analyzer downconverts an RF signal to a lower intermediate frequency (IF), typically using several frequency conversion stages. Traditional swept-tuned spectrum analyzers use analog signal processing (resolution bandwidth (BW) filtering and detection) to provide an output spectrum (display of amplitude vs. frequency). Some swept-tuned spectrum analyzers now digitize the IF signal and use DSP (digital downconversion, resolution BW filtering, and detection) to generate the output spectrum. More details about the operation of swept-tuned spectrum analyzers can be found in [8].

The key distinguishing feature of the swept-tuned spectrum analyzer is that the local oscillator (LO) for the first frequency conversion stage can be automatically tuned (swept) from a user specified start to stop frequency. This frequency sweeping action of the LO, in conjunction with the signal processing, generates the amplitude vs. frequency output data.

Laboratory quality swept-tuned spectrum analyzers have historically been used by ITS as the centerpiece of systems designed to measure short-term spectrum usage one location at a time, e.g., [9]. While their use in accurately measuring radio spectrum is well proven, they are quite costly. This high cost was not prohibitive in the traditional paradigm of measuring short-term spectrum usage one location at a time. However, for the development of the CAC spectrum monitoring capability that espouses the new concept of continuous, long-term spectrum monitoring at many locations simultaneously, it is necessary to reduce the cost of spectrum measurement (sensor) systems.

3.2 DFT-Based Sensor

DFT-based sensors first downconvert RF signals either to a lower-frequency IF (superheterodyne architecture) or directly to baseband (direct conversion architecture). The resulting IF or baseband signal is then digitized and processed, a window is applied, and then a DFT is performed to provide an amplitude vs. frequency data output. In DFT-based sensors the distinguishing feature is that all LOs are tuned to fixed frequencies before digitization occurs.

The IF or baseband filters determine the maximum bandwidth in the resulting DFT spectrum. To provide spectrum measurements over a wider range of frequencies than the IF or baseband filter bandwidth for DFT-based sensors, multiple DFT captures must be made with the center frequency retuned for each DFT capture. The individual DFTs are then stitched together to cover the entire range of frequencies from a starting frequency f_{start} to a stopping frequency f_{stop} as depicted in Figure 2.

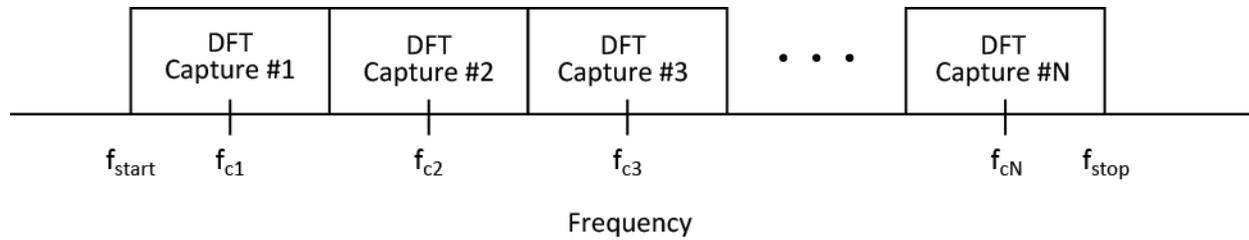


Figure 2. Multiple DFTs stitched together.

DFT-based sensors are a specific application of the more general software defined radio (SDR) receiver. While there are differing opinions as to what an SDR receiver actually is, a good general definition is a receiver that digitizes the received signal and then processes it using software-programmable DSP techniques (digitization may occur at the RF, IF, or baseband). The receiver's fundamental characteristics such as operating frequencies, bandwidths, demodulation, decoding, etc. can be easily changed via programmability [10].

SDRs represent the merging of many divergent fields including computer science, digital signal processing, digital circuit design, and RF design. While there are many different ways to design an SDR receiver, the primary differences are in the DSP platform used and whether digitization occurs at the RF, IF, or baseband. The DSP platform can be based on application specific integrated circuits (ASICs), digital signal processors, field programmable gate arrays (FPGAs), general purpose processors, or any combination of these.

4. SENSOR CLASSIFICATION

In considering sensors for use in spectrum monitoring, we categorize the sensors into five different tiers: high, mid, low, very-low, and ultra-low. The tiers are differentiated by capability, intended purpose, and also, somewhat loosely, by cost.

High-tier sensors include general purpose laboratory grade equipment such as spectrum analyzers, vector signal analyzers, and real-time analyzers and are typically quite costly (\$25,000 or more). These sensors tend to use relatively expensive superheterodyne RF front-end architectures.

Mid-tier sensors include products that are DFT-based sensors designed to be deployed outdoors in the field specifically for spectrum monitoring purposes. They are designed for unattended operation to collect RF data, have well-developed networking capability to enable remote control and data transfer, and are typically weatherproof, ruggedized, and lightweight with a small form factor. These sensors tend to be in the \$15,000–\$20,000 range and, as in high-tier sensors, also tend to use expensive superheterodyne RF front-end architectures.

Low-tier sensors are designed to be more general, experimental development SDRs but can be configured to have functionality similar to that of the mid-tier sensors. They are not designed for outdoor operation and are not weatherproof and ruggedized. The price range for these sensors tends to be very roughly in the \$1000–\$5000 range. Direct-conversion RF front-ends are often used for these sensors to achieve a substantial cost savings.

Very low-tier sensors are typically reduced cost versions of the low-tier sensors, truly geared toward the hobbyist. These sensors tend to use single integrated circuit, direct-conversion RF front-ends to help drive the cost down to a few hundred dollars. Sensors in the ultra-low tier category include Digital Video Broadcast – Terrestrial (DVB-T) television USB dongle receivers that can be used more generally as extremely low-cost (around \$20) SDR receivers.

With the tremendous number of sensors currently available and under development, we expect to see more of a continuum of capabilities and commensurate costs for sensors, rendering classification into our tier structure increasingly difficult. Nevertheless, the tier structure enables us to provide results of RF performance tests in the form of a cost/capabilities/performance matrix to the general spectrum community without divulging results for a specific manufacturer's products.

5. RF PERFORMANCE TESTING

We envision two types of testing to be performed on sensors. One, the focus of this report, is a set of fundamental RF performance tests. The second compares the detection capability of different sensors subjected to specific simulated real world signals and will be addressed at a later date.

Several factors motivate us to develop and conduct RF performance tests on sensors. First, we are observing rapidly growing interest and efforts in spectrum monitoring using a wide variety of sensors. While we have seen a tremendous amount of energy and effort expended on the processing, handling, and presentation of spectrum data and on the networking aspects of spectrum monitoring, we have seen significantly less emphasis on the RF performance of the sensors themselves. The integrity of the measured spectrum data is crucial to successful spectrum monitoring. A simple example of this is that spurious responses or intermodulation products must not be mistaken for actual signals.

It is very difficult to compare the specifications for sensors from different manufacturers for two reasons. First, manufacturers may use different sets of parameters to specify their sensors. Second, even if the same parameters are used, the conditions under which the parameters are specified are often different. We seek to conduct RF testing using a more unified set of parameters and test conditions to provide a more accurate comparison.

As mentioned earlier, since the prevailing concept of spectrum monitoring entails continuous, long-term spectrum monitoring at many locations simultaneously, reducing the cost of sensors is certainly attractive if not necessary. RF performance testing on sensors, along with detection capability testing, will help answer the question of whether a lower-tier/cost sensor will be suitable to use in a given spectrum monitoring scenario (frequency band and type of radio service). There very well may be scenarios where a lower-tier/cost sensor is clearly suitable and, conversely, scenarios where a higher-tier/cost sensor is necessary.

Testing a wide range of sensor types presents significant challenges. Software development required for many sensors to provide needed functionality for RF performance testing can be involved and time consuming. For many sensors, software development is unique to that specific sensor type, necessitating a new effort for each different type of sensor. Furthermore, developing a uniform set of tests over widely varying types of sensors is a significant effort. Despite these challenges—or perhaps because of them—we see great value in RF performance testing of sensors for the spectrum community.

6. TEST PLAN

The first decision in developing the test plan is to determine the frequency ranges over which to perform the tests. Mid-tier sensors typically can operate up to 6 GHz. High-tier sensors may have the capability of operation above 6 GHz and some low, very-low, and ultra-low tier sensors may not be able to operate up to 6 GHz. Many, if not all, of the sensors under consideration can operate at frequencies below 100 MHz. At this time, however, spectrum monitoring is expected to be conducted mostly at frequencies above 100 MHz and below 6 GHz. Therefore, testing will be limited to 100 MHz to 6 GHz (or the maximum sensor frequency up to 6 GHz) for all sensors. To achieve a consistent means of comparing sensors, the testing will be conducted over the octave frequency ranges: 100–200, 200–400, 400–800, 800–1600, 1600–3200, and 3200–6000 MHz. Note that any frequency band switching that may occur within sensors may very easily occur at other frequency ranges and will probably vary from one sensor type to another.

For all the RF performance tests, if a sensor has an internal preamp, it is turned off. Unless otherwise indicated, all tests are performed both with the sensor internal RF attenuation set to 0 and then to 10 dB (if it can be adjusted by the user).

6.1 Displayed Average Noise Level Test

The displayed average noise level (DANL) test is performed to provide a measure of the noise floor of the sensor, which generally provides an indication of the minimum signal level that can be observed in the sensor within a given measurement bandwidth. Similarly, the level of the noise floor, in conjunction with the maximum level of the spurious responses, is an important factor in determining the threshold level to be used to determine spectrum occupancy.

The DANL is measured by terminating the sensor RF input with a 50 Ω load and averaging the sensor spectrum output for each of the octave frequency bands. The test is performed in an equivalent noise bandwidth² (ENBW) of roughly 10 kHz. The DANL is normalized to 0 dB attenuation and a 1 Hz ENBW. Normalized DANL values are easily converted to noise figure (NF) simply by subtracting the thermal noise power in a 50 Ω load in a 1 Hz bandwidth (-174 dBm) from the DANL value. Figure 3 shows the results of an example DANL measurement for a high-tier sensor using an ENBW of 10.61 kHz and 10 dB attenuation. The maximum normalized DANL over this frequency range is found to be -154.0 dBm using the maximum power (P_{max}) from Figure 3 and

$$DANL = P_{max}(dBm) - L(dB) - 10\log_{10}(ENBW) \quad (1)$$

where L is the sensor internal RF attenuation.

² The minimum frequency separation between equal amplitude sinusoids when the two signals can be distinguished from each other is dependent on the resolution BW filter in a swept-tuned sensor and the sample rate, number of samples, and window applied in a DFT-based sensor. To achieve a consistent means of comparing RF performance test results between a wide variety of sensors, we use the equivalent noise bandwidth (ENBW) as a parameter for both swept-tuned and DFT-based sensors. The ENBW of a filter (or window) is the width of a fictitious rectangular filter such that the noise power that results from a white noise signal filtered by this rectangular filter equals the noise power that results from the same signal filtered by the original filter (or window).

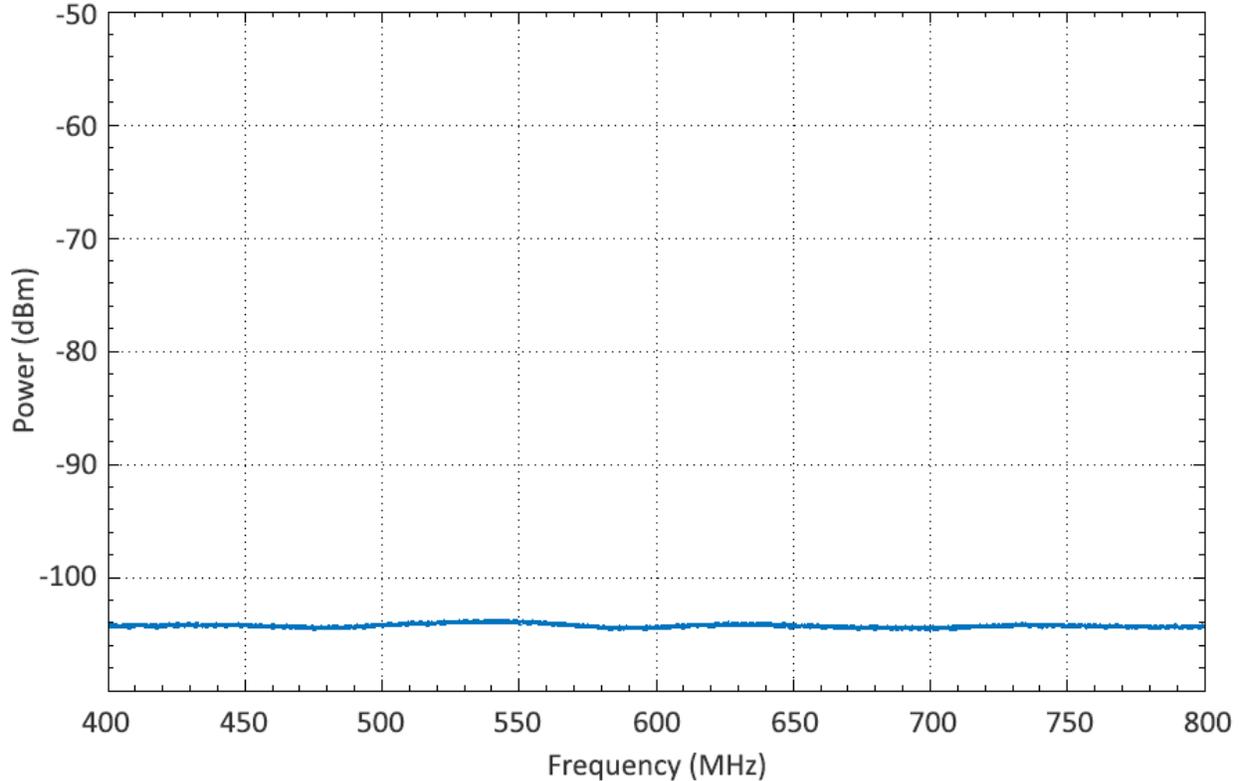


Figure 3. Measured data for the DANL test for a high-tier sensor over the 400–800 MHz octave frequency band.

6.2 Self-Generated Spurious Response Test

The DANL measurement as described above also serves as a self-generated spurious response test by exposing any unwanted spurious responses (spurs) that are generated internally in the sensor with no input signal. The amplitude and frequency of the highest spur are recorded in each octave frequency band. In addition, a spectrum plot for each octave frequency band is saved to illustrate the quantity, frequency, and amplitude of lower-amplitude spurs. Figure 4 is an example spectrum plot for a mid-tier sensor that illustrates the spurs that may occur.

Note that the maximum level spur is about -78 dBm with three other spurs above -90 dBm. Ideally, all of the spurious responses should be below the expected peak noise level in the bandwidth to be used for a given measurement. At a minimum, it must be ensured that any spurious responses higher than the expected peak noise level not be mistaken as valid signals to be measured during spectrum monitoring.

Since we have found that some spurs appear intermittently, the self-generated spurious response test is repeated, but this time peak detecting instead of averaging the spectrum output.

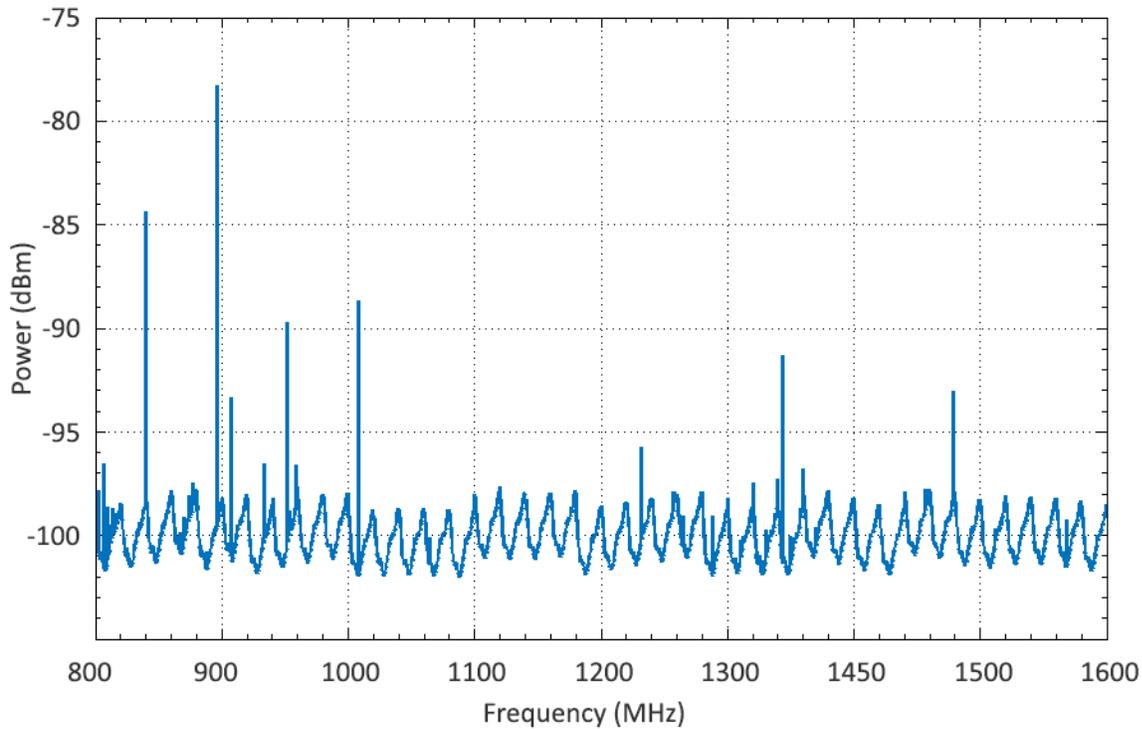


Figure 4. Example spectrum plot of a mid-tier sensor showing self-generated spurious responses.

6.3 In-Band Signal Overload Test

The results of this test provide an indication of the maximum RF signal level that can be reliably measured by the sensor. Signals greater than the overload level need to be avoided when collecting spectrum data since they can corrupt the data. The test is performed by injecting a low-level (say, 10 dB above the expected peak noise level) continuous wave (CW) signal into the sensor RF input within its measurement band and slowly increasing its amplitude until an overload condition occurs. Overload is defined as whichever occurs first: the input 1 dB compression point, or full count on the analog-to-digital converter (ADC). The input 1 dB compression point is one measure of the non-linearity of the sensor.

The test proceeds by starting with the low-level input signal and measuring the resulting output power level. From this the gain of the sensor is calculated as the output power (in dBm) minus the input power (in dBm). The input signal is increased by 1 dB and the gain is determined again. The gain should be essentially the same if the sensor is operating in its linear region. If not, lower the input signal and repeat this process to ensure operation in the linear region. Once the input signal level is found to be in the linear region of the sensor, increase the input signal level in 1 dB or finer increments until either the gain is 1 dB lower than that in the sensor's linear region or ADC overload occurs. The input signal level where the gain decreases by 1 dB from the gain in the linear region is the 1 dB compression point [11].

The test is performed for three different frequencies within each of the octave frequency bands. For each input frequency, the input signal power level at which overload occurs is recorded.

We believe that, in properly designed sensors that incorporate an ADC, ADC overload will occur before the 1 dB compression point is reached. This makes detection and reporting of the overload to the user easier. However, it is conceivable that not all sensors will be designed this way.

6.4 CW Signal Spurious Response Test

Spurious responses may be generated in a sensor by high-power input signals as well. As RF input signals approach overload, spurious responses can increase. This test seeks to characterize this potential phenomenon using a CW input signal set to 1 dB below the overload level. The test is performed for three different frequencies within each of the octave frequency bands with a roughly 10 kHz ENBW. The amplitude and frequency of the highest level spur is recorded for each input frequency and the spectrum plot is saved to illustrate the quantity, frequencies, and amplitudes of lower- amplitude spurs.

6.5 Third-Order Intercept Test

The third-order intercept (TOI) is a parameter that provides a way to predict the level of the third-order intermodulation (IM) products that can occur in a sensor given the power level of a two-tone input signal. Third-order IM products tend to be particularly difficult to deal with because they typically fall within the measurement bandwidth. Minimizing IM distortion (IMD) is important in spectrum monitoring because it can cause responses to appear in the output spectrum of the sensor that are not present at the input to the sensor. These responses (IM products) could be mistaken for signals present in the measurement environment. The higher the TOI, the lower the levels of third-order IM products will be for a given two-tone input signal power level [12].

The TOI measurement begins with injecting a two-tone signal into the sensor RF input: one tone, f_1 , at $f_c - \Delta f$ and the other tone, f_2 , at $f_c + \Delta f$ where f_c is the center frequency of the test signal and $2\Delta f$ is the frequency separation of the two tones. Each tone is set to a power level $P(\text{dBm})$ of 13 dB below the input overload level and Δf is set to 100 kHz. The test is conducted for three center frequencies in each octave frequency band using an ENBW of roughly 1 kHz. The sensor spectrum output is averaged if necessary to allow easier identification of third-order products that appear close to the peak noise level. The higher power level of the two third-order IM products ($2f_2 - f_1 = f_c + 3\Delta f$ and $2f_1 - f_2 = f_c - 3\Delta f$) that appear in the spectrum output is measured. The difference, Δ , between $P(\text{dBm})$ and the higher-power third-order IM product is computed and from that the TOI is calculated as $\text{TOI} = P(\text{dBm}) + \Delta/2$ [13].

For successful TOI testing, the frequency source for the two-tone signal must have low IMD itself. IMD levels in the signal source should at least be lower (ideally, 10 dB or more lower) than the IMD levels in the sensors to be measured. Use of a vector signal generator provides a convenient way to generate a two-tone signal using a single signal generator and offers the capability to apply predistortion or other advanced techniques to reduce the inherent IMD in the signal source itself [14], [15]. Figure 5 portrays an example measurement of third-order IM products on a sensor with $f_c = 1$ GHz and $\Delta f = 100$ kHz. Here the power level of each tone, P , is set to -13.1 dBm. The highest level third-order IM product is seen at 1000.3 MHz with a power of -95.2 dBm. The resulting TOI is $+28.0$ dBm.

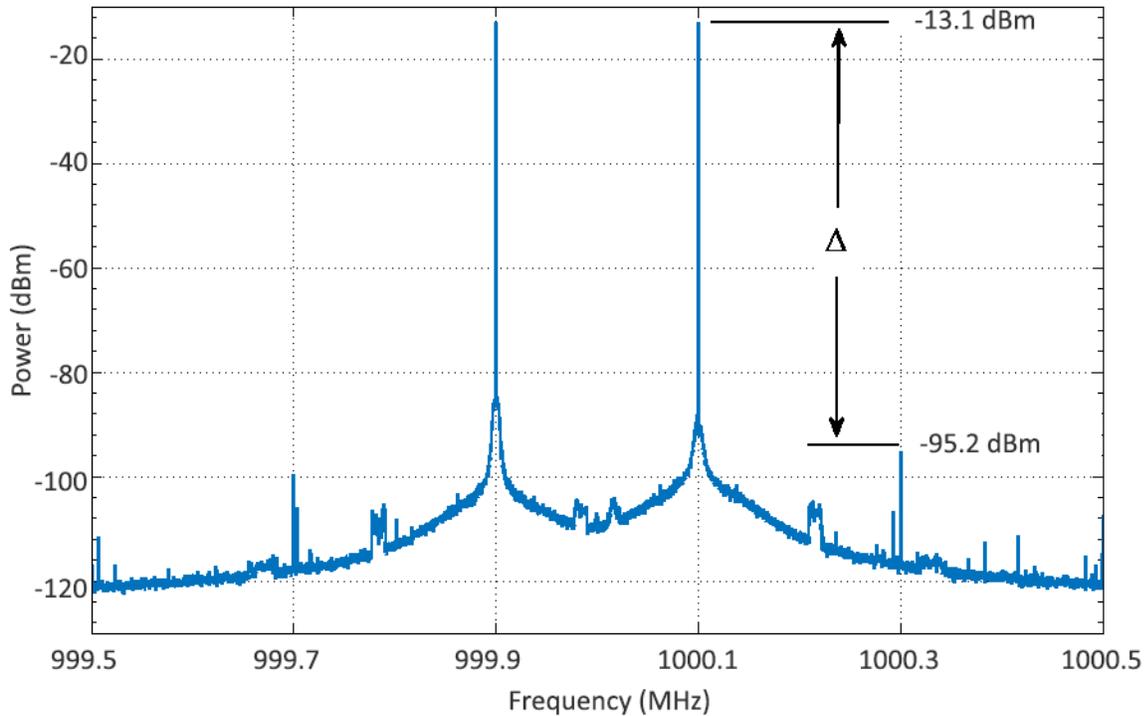


Figure 5. Example of third-order IM products generated from a TOI test.

6.6 Noise Power Ratio Test

Noise power ratio (NPR) is another measure of IMD of a sensor that simulates a much harsher signal environment than just a two-tone signal. The NPR test simulates a worst-case, very densely packed, large signal environment with either many narrowband signals, some wideband signals, or a combination of both occupying a large portion of the sensor bandwidth. To perform this test, a complex Gaussian noise signal is generated. The signal has a flat spectrum with a null-to-null bandwidth less than one-half the sample rate of the sensor to be tested. Additionally, a narrow band of frequencies is removed from the center of the noise signal forming a notch in the noise signal. The bandwidth of the notch should be less than 10% of the noise bandwidth [16]. Vector signal generators are ideal for generating the notched noise signal.

The notched noise signal is injected into the sensor RF input using an ENBW of roughly 10 kHz and the sensor output spectrum is averaged. The test is performed for noise power levels of 3 dB and then 10 dB below where the noise signal causes overload for three frequencies in each of the octave frequency bands. The NPR is computed by dividing the power spectral density of the noise outside of the notch by the power spectral density of the noise within the notch.

6.7 Frequency and Amplitude Stability/Accuracy Measurement

Sensors that have poor accuracy and/or a large variation in the frequency and amplitude of the signals that they measure can yield false results in spectrum monitoring applications. This test quantifies the degree of frequency and amplitude accuracy and stability in a sensor. For this test,

a high-quality, laboratory-grade signal generator is used with the external reference input connected to a highly stable frequency reference. The test is performed with the sensor ENBW set to roughly 100 Hz and repeated for all sensor frequency reference options available (e.g., internal local reference, external reference, internal GPS reference). A CW signal, at one selected frequency, is injected into the sensor RF input 10 dB below the overload level and spectrum data from the sensor is collected once a minute over a seven day period. Using a calibrated power meter, the power level of the CW signal at the RF input of the sensor is monitored and recorded along with each sensor spectrum data capture. The resulting amplitude and frequency of the CW signal from the spectrum data is compared to the actual signal generator frequency and power level measured by the power meter.

6.8 Phase Noise Measurement

Frequency or phase instability in the local oscillators (LOs) of a sensor causes phase noise, otherwise known as noise sidebands [8]. Phase noise appears on the spectrum output of a sensor as a noise-like frequency spreading near the base of a signal. This spreading due to phase noise is in addition to the spreading caused by the resolution BW filter in a swept-tuned sensor or the window used in a DFT-based sensor. The latter spreading results from a frequency-domain convolution of the signal with the resolution BW filter or window. Figure 6 shows these frequency spreading effects for a CW input signal.

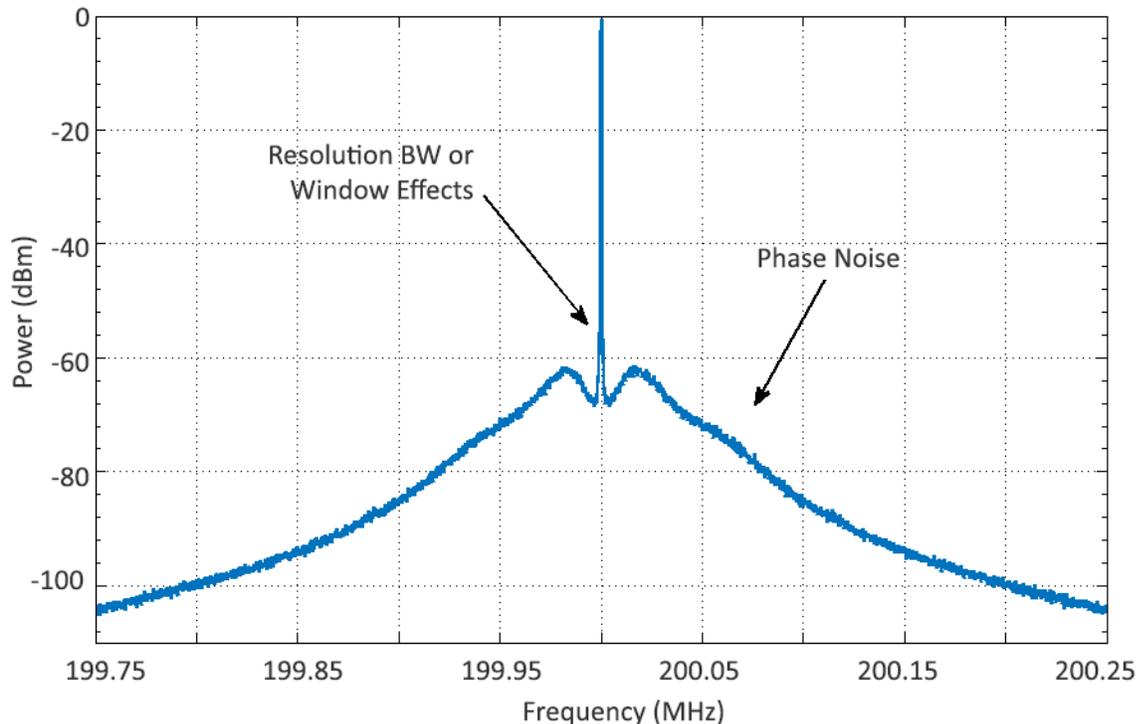


Figure 6. Spectrum plot of a sensor with a CW input signal showing the phase noise and resolution BW or window effects in a sensor.

High levels of phase noise in a sensor can be problematic for spectrum monitoring since the phase noise can be higher in amplitude than low-level signals near (in frequency) a given high-

level signal that may be present at the sensor RF input. Note that some sensors allow the choice of different LO modes that change the amount and shape of the phase noise.

To measure phase noise, a CW signal 3 dB below the input overload level is injected into the sensor RF input. The spectrum output is averaged and the level of the CW signal and the level of the spectrum at frequency offsets of 1 kHz, 10 kHz, 100 kHz, and 1 MHz from the CW signal are determined. The difference in average power level between the CW signal and the levels at the frequency offsets is computed. The results are normalized to a 1 Hz ENBW. The measurements are performed with the CW frequency set to three frequencies in each octave frequency band using an ENBW of roughly 100 Hz. It is important to use a high-quality signal generator with low phase noise for phase noise measurements of sensors. At a minimum, the phase noise in the signal generator must be lower than the phase noise of the sensor, otherwise the measurement results will show the phase noise of the signal generator and not the sensor.

6.9 Image Frequency Rejection Test

Image frequencies occur for each mixing stage in a sensor using a superheterodyne front-end since two different input frequencies can produce the same output frequency for a given LO frequency. One of these input frequencies is the desired input, the other is the image frequency. As an example, for a downconversion mixing stage with low-side injection (LO frequency is lower than the desired input RF) the frequency of the output of the mixer is given as $f_{IF} = |f_{RF} - f_{LO}|$ where f_{RF} is the frequency of the RF input to the mixing stage and f_{LO} is the frequency of the local oscillator. If $f_{IF} = 70$ MHz and $f_{LO} = 100$ MHz, the frequency of the desired RF input f_{RF} is 170 MHz. The image frequency for low-side injection downconversion is given as $f_{IMAGE} = f_{RF} - 2f_{IF}$ so for this example, $f_{IMAGE} = 30$ MHz. Determination of image frequencies for high-side injection downconversion and upconversion mixing stages is somewhat similar; details can be found in [17].

To test for image frequency rejection, the possible image frequencies for a sensor must be determined. This requires identification of the IF and LO frequencies for each mixing stage and analysis of how image frequencies of mixing stages after the first mixer stage affect the possible image frequencies at the sensor RF input [18]. Once the possible image frequencies are determined, a CW signal is injected into the sensor RF input at one of the possible image frequencies. The sensor is set up with a 100 Hz ENBW to measure the desired RF input signal that corresponds to the image frequency. The spectrum output is averaged. The amplitude of the CW signal is increased until either a response is detected in the averaged sensor spectrum output or the maximum safe RF input signal level is reached and no response is seen.

The level of the CW signal that either elicits a detectable response or reaches the maximum safe RF input level is recorded. A CW signal at the desired RF input frequency is then injected into the sensor RF input and its amplitude is adjusted until the response is the same amplitude as the

response for the image frequency input.³ The difference between the amplitudes of the two CW input signals is the image rejection. The test is repeated for all possible image frequencies.

6.10 IF Signal Rejection Test

In sensors using a superheterodyne front-end it is possible that signals at the RF input of the sensor occurring at the IF frequencies can be coupled into the IF stages indirectly. The IF Signal Rejection Test is a measure of how well the sensor attenuates these IF signals [12]. To accomplish this test, all IF frequencies in the sensor must be identified. The sensor is tuned to a frequency range that does not include the IF frequencies. The measurement then follows exactly the same procedure as in the Image Frequency Rejection Test, except using the IF frequencies instead of the image frequencies.

6.11 Resolution BW Filter or DFT Window Characterization

This test determines either the resolution BW filter shape for a swept-tuned sensor or the DFT window shape (in the frequency domain) for DFT-based sensors. The ability to distinguish two equal amplitude signals closely spaced in frequency is affected by the resolution BW filter or the DFT window shape along with the DFT frequency bin size (determined by f_s/N where f_s is the sampling frequency and N is the number of samples). Knowing the resolution BW filter or the DFT window shape in the frequency domain along with f_s/N allows determination of the ENBW for the sensor.

The DFT window frequency domain shape furthermore provides for characterization of scallop loss and sidelobes. Scallop loss shows the maximum loss of amplitude accuracy for signals that fall midway between DFT sample points. The sidelobes give an indication of the spectral leakage (spreading of the spectral content of a signal into adjacent DFT frequency bins) that occurs with the window.

6.11.1 Resolution BW Filter Characterization

This test is performed by injecting a CW signal at one chosen frequency into the sensor 3 dB below the overload level and sweeping the sensor over a band of frequencies wide enough to show the magnitude response of the filter down to the system noise level. A sensor input attenuation of 10 dB is used. Several resolution BW filters ranging from narrowband to wideband should be measured. The spectrum output shows the magnitude response of the resolution BW filter.

6.11.2 DFT Window Characterization

A CW signal at one chosen frequency 3 dB below the overload level is injected into the sensor RF input. A sensor input attenuation of 10 dB is used. The complex DFT output is recorded and

³ For cases where no response was seen for the image frequency input, the CW signal at the desired RF input frequency is increased until the response just begins to appear above the system noise level.

the inverse DFT is computed. The resulting complex time domain data is then zero-padded and the DFT is taken to provide the spectrum output revealing the detailed window shape in the frequency domain. Zero-padding the complex time domain data provides a much better (higher resolution) approximation to the discrete time Fourier transform (DTFT) and thereby gives a much finer resolution of the DFT window shape in the frequency domain [19].

6.12 Additional RF Performance Tests

Several other RF performance tests have been identified that are currently under consideration. These include an adjacent band signal desensitization test, an aliasing response test, an amplitude flatness test, a second-order IMD test, and a spectrum data throughput test. Details of these tests are planned to be formalized in the near future.

7. SUMMARY

In the U.S., a scarcity of unallocated, desirable radio spectrum coupled with unrelenting demand for wireless broadband access has fueled U.S. Government interest in making more frequencies available for commercial broadband applications via spectrum sharing or spectrum relocation. Measured spectrum occupancy is important to successful planning, engineering, and enforcement of new spectrum sharing and relocation scenarios. To help address these issues, the CAC is developing a spectrum monitoring capability that includes developing an infrastructure to acquire and amass measured spectrum data, provide web access to this data for the spectrum community, and establish and implement best practices for acquiring spectrum data.

As a part of the CAC effort, ITS is designing and developing RF sensor systems to be deployed in various locations throughout the U.S. to acquire spectrum data. The general architecture of these RF sensor systems includes an antenna, preselector, sensor, and measurement controller, with the sensor being the primary subject of this report.

Fundamentally, two types of sensors can be used for spectrum monitoring: swept-tuned or DFT-based sensors (a specific application of the more general SDR receiver). We categorize the sensors into five different tiers (high, mid, low, very-low, and ultra-low) differentiated by capability, intended purpose, and also, somewhat loosely, by cost.

Two types of testing are considered important for sensors: a set of fundamental RF performance tests (presented in this report) and testing that compares the detection capability of different sensors subjected to simulated real world signals.

Several factors motivate us to develop and conduct RF performance tests on sensors. First, we are observing rapidly growing interest and efforts in spectrum monitoring using a wide variety of sensors. The networking and data management aspects of spectrum monitoring are crucial elements of a successful spectrum monitoring endeavor. However, since the integrity of measured spectrum data is vitally important, the sensor systems used to collect the spectrum data represent another critical, but sometimes neglected, element. Furthermore, it is very difficult to compare the specifications of sensors from different manufacturers.

Since the prevailing concept of spectrum monitoring entails continuous, long-term spectrum monitoring at many locations simultaneously, reducing the cost of sensors is certainly attractive if not necessary. RF performance testing on sensors, along with detection capability testing, will help answer the question of whether a lower-tier/cost sensor will be suitable to use in a given spectrum monitoring scenario (frequency band and type of radio service). Even though testing a wide variety of sensor types requires significant effort in sensor software development and in developing a uniform set of tests, we see great value in RF performance testing.

The RF performance test plan presented here is our initial plan for these measurements. We are just beginning to implement these tests in the laboratory. We do expect that the test plan will evolve through both refinement of existing tests and the addition of new tests as other performance factors of interest are identified.

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