Spectrum Analysis and the Frequency Domain
FieldFox Fundamentals — Lesson 2

Introduction

Signals are analyzed in either the time or frequency domain. Mathematically, either Fourier and Laplace transforms connects the two representations. Signals are measured in the laboratory in either domain, but using different instruments. While the oscilloscope is the most common instrument for time domain measurements, the spectrum analyzer is the most common instrument for frequency domain measurements.

Linear systems are characterized by either their time domain impulse response or by their frequency domain transfer function. The transfer function is straightforward; this is because you multiply input signals by the transfer function to produce the output frequency domain representation. With time domain input signals, you must convolve them with the impulse response to produce the output time domain waveform. Spectrum analyzers allow viewing of the frequency domain representation of a signal, and network analyzers provide a direct measurement of the transfer function in the frequency domain. In Lesson 2, you will learn about the basic functionality of a spectrum analyzer and measurements you can make with it.

The FieldFox Fundamentals series is written for Keysight's FieldFox N9914A 6.5 GHz handheld analyzer. However, you can substitute the N9914A with any of the following models: N9913/15/16/17A, N9918A with adaptors, N9950/51/52A with adaptors, or N991xB.

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Overview

There are two fundamentally different ways to obtain the frequency domain representation of a signal. The first method is computational. You acquire the signal in the time domain and transform it into its corresponding frequency domain representation using a fast Fourier transform (FFT) algorithm. The second method involves directly measuring the output amplitude as the signal feeds through a narrow bandpass filter swept across the frequency span of interest.

The first method is digital signal analysis (DSA) — referencing the computation performed after fully acquiring the signal in the time domain. The input acquisition must sample at twice (minimum) of the highest frequency component of the signal to capture the full frequency spectrum of a signal for computation. This sample rate is known as the Nyquist rate. For low frequency signals in the audio range with a signal bandwidth of 20 Hz to 20 kHz, the Nyquist rate is only 40 kS/s. Modern analog-digital converters (ADCs) quickly achieve this rate.

Digital signal analyzers or dynamic signal analyzers, both known as DSAs, operate in this manner. They acquire the input signal with a fast input sampler and ADC, store the acquired signal into local memory, compute the FFT, and display the result as the frequency spectrum of the signal. DSAs run continuously — the displayed frequency spectrum lags only a fraction of a second behind the input signal. This process provides a nearly real-time analysis.

High-speed digital oscilloscopes can also capture higher frequency signals and store them into memory. Fast oscilloscopes acquire repetitive signals of up to 500 MHz or more. Plus, many models provide soft key functions to compute and display the FFT of the acquired signal. These FFT computations do not run continuously; instead, they take the form of post-acquisition analysis of a given waveform. This post-acquisition analysis is similar in many ways to the measurement function suite of most modern digitizing oscilloscopes. Examining the frequency spectrum of signals higher than a few hundred MHz is challenging because of the limitations on input sampling rate and computational throughput. These limitations inhibit the production of a fast-responding displayed output.

DSAs or oscilloscope FFTs do not have the frequency capability to perform signal analysis in the RF and microwave ranges. At frequencies of several hundred MHz and higher, there is not enough time to perform an acquisition or computation on the signal. Instead, you use a swept frequency analyzer or swept filter analyzer (SFA) for this.

In this second method, a narrow bandpass filter sweeps across the frequency range of interest. The analyzer uses the output from that filter to directly measure the frequency spectrum of the input signal. Although the center frequency of the filter is quite high, the speed of the frequency sweep is much slower. This allows sampling of the output from the swept filter, digitization, storage, and display. This function is similar to what an oscilloscope does for a low frequency time domain signal.

While it is possible to create exceptionally sharp bandpass filters for signal analysis, it is challenging to sweep them across a range of frequencies without significantly changing their bandpass characteristics. The filtering part of an SFA is straightforward. The challenge, however, lies within the sweep. It is practical to construct an oscillator with an output frequency that sweeps linearly over a range of frequencies to address

this challenge. A voltage-controlled oscillator, or VCO, is a sine wave oscillator that allows for frequency tuning with an applied DC voltage. Driving the VCO from a ramp or sweep generator produces an output that starts at one frequency, increases linearly with time up to an end point frequency, and repeats. The combination of a VCO and a sweep generator is known as a "sweeper." Sweeping an oscillator is significantly easier than sweeping a filter.

How does that help solve the problem of spectrum analysis at RF frequencies? An important principle, expressed as a law of trigonometry, details the result of multiplying two sinusoids:

$$\cos(\omega_1 t)\cos(\omega_2 t) = \frac{1}{2}\cos\big((\omega_1 - \omega_2)t\big) + \frac{1}{2}\cos\big((\omega_1 + \omega_2)t\big)$$

$$\sin(\omega_1 t)\sin(\omega_2 t) = \frac{1}{2}\cos\big((\omega_1 - \omega_2)t\big) - \frac{1}{2}\cos\big((\omega_1 + \omega_2)t\big)$$

The multiplication of two sinusoids of different frequencies ω_1 and ω_2 produces an output that contains the difference and the sum of those frequencies, $\omega_1 - \omega_2$ and $\omega_1 + \omega_2$. A mixer is a nonlinear electronic device that produces this desired multiplication of two signals. A mixer combined with a fixed oscillator input often referred to as the local oscillator (LO) signal, moves an input signal up or down in frequency by an amount equal to the frequency of the LO.

Extracting only the sum or difference frequency with a filter is known as heterodyning. It is a fundamental system concept to many types of radio receivers. If the local oscillator instead becomes a swept oscillator, the output from the mixer is the input signal spectrum moving up and down in frequency by an offset equal to the LO frequency.

For example, you can apply a narrow bandpass filter to the output of the mixer. Then, as the input signal spectrum moves up and down through the frequency sweep, the bandpass filter does not block only those components which align to its passband. Basically, the filter performs as if the filter itself was sweeping.

Figure 1 illustrates the essential blocks of an SFA. The common names for the signals are:

RF – the radio frequency input.
IF – the intermediate frequency output from the mixer.
LO – the local (voltage controlled) oscillator.
f_{IF} – the filtered IF, its strength represents the frequency content of the input signal at the frequency selected by the LO.
SWP – the voltage sweep signal, most commonly a ramp or sawtooth waveform from the sweep generator.
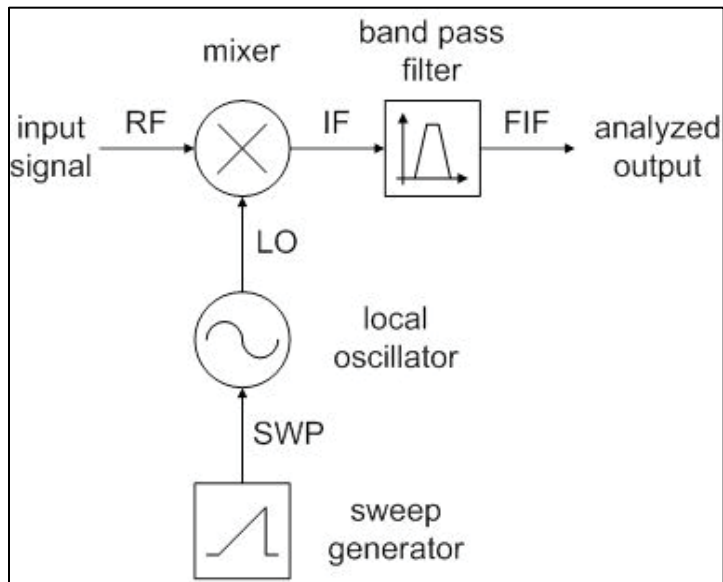
Figure 1. Block diagram of principal elements of a swept frequency analyzer (SFA)

Example: Suppose the input signal is a sinusoidal carrier at 2.0 GHz with amplitude modulation (AM) of 100 MHz. This gives the frequency spectrum of the input a main carrier peak at 2.0 GHz with two smaller sidebands at 1.9 GHz and 2.1 GHz because of the modulation. The sweep generator produces a ramped voltage that controls the LO and sweeps it over a range of 1.0 GHz to 2.0 GHz.

The bandpass filter is a fixed-tuned filter centered at 500 MHz with a bandwidth of 10 MHz and a Q factor of 50. When the sweep starts with the LO at 1.0 GHz, the mixer produces sum and difference frequencies with the RF input. These frequencies shift the 2.0 GHz RF carrier down to 1.0 GHz and up to 3.0 GHz. The modulation sidebands track along with the carrier.

At this point, no signals line up with the bandpass filter selected range of 500 MHz, so there is no output. At the other extreme, when the LO sweeps up to 2.0 GHz, the 2.0 GHz RF carrier shifts down to DC and up to 4.0 GHz. Again, nothing appears at the 500 MHz window of the bandpass filter.

However, when the sweep is midway with the LO at 1.5 GHz, the 2.0 GHz RF carrier shifts down to 500 MHz and up to 3.5 GHz. The downshifted RF carrier aligns with the 500 MHz selection of the bandpass filter, which outputs an IF frequency proportionate to the amplitude of the input RF carrier (Figure 2).
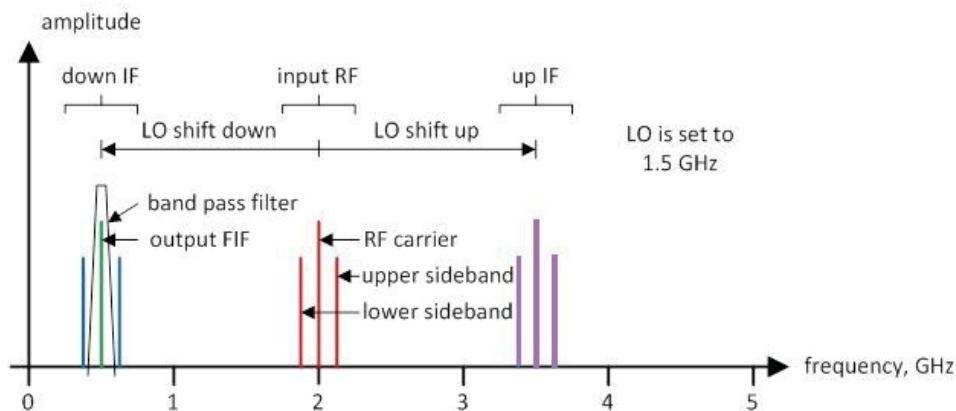
Figure 2. Mixing the RF with the LO to produce an IF which aligns to the bandpass filter (BPF)

When the LO is at 1.4 GHz, the lower modulation sideband of the RF input aligns with the bandpass filter producing an output. Similarly, when the LO is at 1.6 GHz, the upper sideband of the RF input aligns with the bandpass filter, producing another output. Notice that as the LO sweeps up, the bandpass filter scans upward through the input RF signal spectrum.

The filtered IF that passes through the bandpass filter is a sinusoid at 500 MHz. The amplitude of this sinusoid, when matched to the known LO frequency established by the sweep generator, gives the amount of signal present in the RF input at a frequency of $f_{BPF} + f_{LO}$. Each sweep of the sweep generator thereby creates an f_{IF} output with an amplitude that traces out the frequency spectrum of the RF input.

Your analyzer must convert the amplitude of the 500 MHz f_{IF} output to a lower frequency voltage level. It accomplishes this by using an envelope detector, a semiconductor diode in its simplest form, followed by a low-pass filter. This low-pass filter is sometimes known as the video filter. It sets the speed at which the spectrum is swept and enables the display output to follow the sweep accurately.

Two important concepts for spectrum analyzers are the resolution bandwidth (RBW) and the video bandwidth (VBW). The resolution bandwidth is effectively the frequency width of the IF bandpass filter. It determines how closely two input signal peaks are spaced and has the spectrum analyzer resolve the difference between them. The VBW is the bandwidth of the low-pass filter that follows the envelope detector. It determines how fast the sweep occurs so that the data acquisition and display still accurately follow it.

A complete spectrum analyzer system usually incorporates a few more blocks. The input RF signal passes through an adjustable input attenuator and buffer amplifier, which fine-tune the signal level. This process optimizes the performance of the mixer. Because we expect a spectrum analyzer to operate over a rather wide dynamic range of input signal amplitudes, the f_{IF} output typically passes through a logarithmically responding amplifier. This amplifier makes the output proportional to the input signal strength in units of decibels (dB). Frequency accuracy is important for spectrum analysis, so the LO is usually derived from an oven-stabilized quartz crystal frequency reference. In some cases, it synthesizes digitally. With many modern analyzers, you can increase the reference frequency accuracy by locking to the GPS signals.

The video output from the envelope detector feeds into an analog-digital converter to digitize the data. The data moves to both digital memory, used for buffering the displayed output, and to storage for calibration, normalization, and archiving. Figure 3 depicts a complete block diagram of a spectrum analyzer system. In this figure, the conditioned RF input signal is CRF, the frequency reference if FR, and the video output from the envelope detector and low-pass filter is VID.
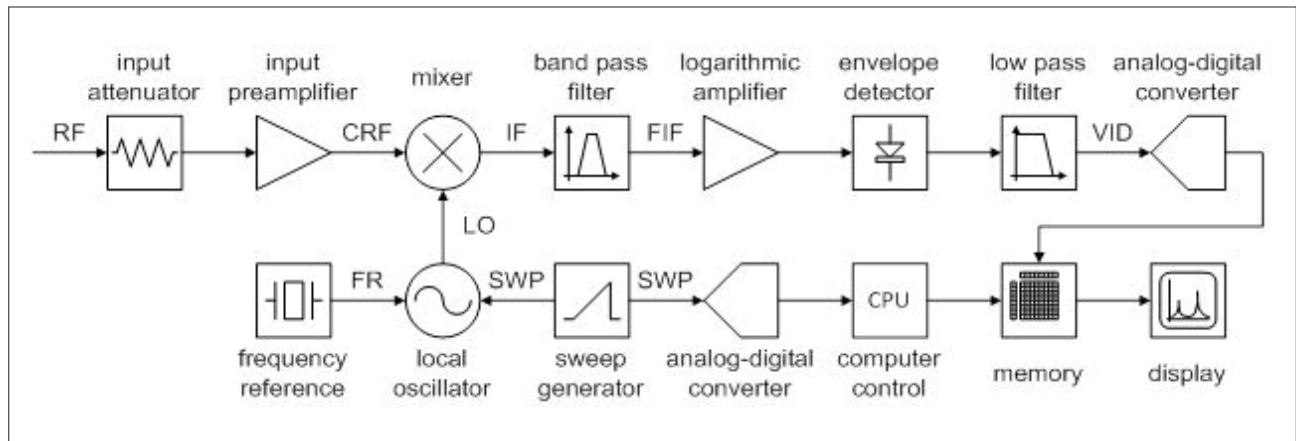

Figure 3. Block diagram of a spectrum analyzer system

Another way to perform spectrum analysis is to use a stepped FFT analyzer, like the technique used in FieldFox analyzers. FieldFox spectrum analyzers are FFT analyzers that operate in stepped sweep or stepped FFT mode. Conceptually these analyzers operate similarly to swept analyzers, but they implement the functionality in a different way. For example, the analyzer accomplishes VBW filtering by averaging measurement bins, instead of a using a low-pass filter. The application note "*Spectrum Analyzer Basics*," publication number 5952-0292, examines the diverse types of spectrum analyzer architectures.

How to perform spectrum measurements

Keysight's N9914A FieldFox analyzer contains a spectrum analyzer (SA) application which implements the RF system described above. In this lesson, the Keysight N5181A 100 kHz -3 GHz MXG analog signal generator provides an input signal for the FieldFox to analyze. This signal generator is a very high frequency version of the standard laboratory function generator. Although, instead of creating sine, square, triangle, and pulse wave shapes, the MXG creates sinusoidal carriers with several types of applied modulation.

Before applying any external signal to an analyzer, regardless of the type, you need to consider the RF power levels. This is critical so that the delicate and expensive front-end amplifier of the analyzer is not impacted from excessive power dissipation or over-voltage.

The N9914A FieldFox inputs handle a maximum of +27 dBm or 0.5 Watts. The maximum output from the N5181A signal generator is +17 dBm or 50 mW. In this lesson, there is no chance for the signal generator

to destroy the FieldFox. It is critical to check the power levels before running the risk of damaging an expensive instrument.

Step 1. Set up the N9914A FieldFox so that it runs off the AC power supply. Power up the FieldFox and wait for the CAT application to load and launch. Attach a Type-N to the SMA adapter to Port 2. After the CAT application launches, press the mode button to bring up the application selection. Press the SA soft key to load and launch the SA application. Note that the SA input needs to go into Port 2 and that the SA starts with the full-span sweep of 0 Hz to 6.5 GHz.

Step 2. Configure the signal generator to output a 500 MHz sine wave at a power level of -20 dBm or 10 µW. Ensure the signal generator has AC line power. The amber LED above the power button glows indicating that the instrument is in standby mode.

Step 3. Press the power switch to turn the instrument on, and the amber LED changes to a green LED. The front panel display lights up into its default state. Attach a Type-N to SMA adapter to the output Type-N connector on the front panel.

Step 4. Use an 18-inch-long SMA coaxial cable to connect the output of the signal generator to the input on Port 2 of the FieldFox.

Step 5. Press the FREQ button to configure the sine wave carrier from the signal generator to reach the frequency menu. The instrument normally wakes up with this menu as the default.

Step 6. Press 500 on the keyboard to set the frequency followed by the MHz soft key to the right of the display.

Step 7. Press the AMPTD button to obtain the amplitude menu.

Step 8. Press -20 on the keyboard followed by the dBm soft key.

Step 9. Press the RF On/Off button above the output connector. The green LED below this button glows, and the display panel indicates an output amplitude level of -20.00 dBm.

The FieldFox should now show a prominent single peak on its display with a peak power level of -20 dBm. A single sharp peak in the frequency domain indicates a perfect sine wave in the time domain.

FieldFox can reveal more details about the signal generator. Increase the output power from the signal generator to 0.0 dBm, or 1.0 mW. A straightforward way to do this is to first navigate into the amplitude options by pressing the AMPTD button.

1. Position the cursor under the units position of the -20.00 dB indicator by using the arrow keys on either side of the Select button. Once the cursor highlights the unit's position, simply rotate the control dial to increase or decrease the amplitude in 1.00 dB increments.

2. Slowly increase the signal generator amplitude from -20.00 dBm upwards to 0.00 dBm, and observe that the main peak displayed on the FieldFox also increases in amplitude. As the power level increases, a secondary peak starts to appear to the right of the main peak. You can toggle the signal generator output to verify that this secondary peak is indeed coming from the signal generator.

3. Increase the RF attenuation on the FieldFox by pressing the Scale/Amptd key and then the RF Atten soft key. Set the RF attenuation to 20 dB. On some signal generators, you may have to increase the power level beyond 0 dBm to see the secondary peak. If the increase in signal generator power results in an "ADC Over Range" message on the FieldFox,

4. Press the Marker button on the FieldFox to bring up the marker menu and turn on the first marker point. The marker function will provide some quantitative numbers for these two peaks. The coordinates of the first marker appear in green letters in the upper right of the display, and the display also shows a solid green diamond at the current marker position.

5. Press the soft key labeled Peak to move the marker to the main peak. The marker jumps to the largest peak in the display. In this example, it has coordinates close to 500.000 MHz and 0.00 dBm.

6. Record the specific values of this main peak. Now use the dial on the FieldFox to move the marker to the top of the secondary peak (Figure 4). The coordinates for this are 1.000 GHz and -45 dBm. Similarly, record the values of this secondary peak. The high frequency accuracy of the SA shows that the frequency of the secondary peak is exactly twice that of the primary peak; it is the second harmonic of the first peak. Instead of creating a perfect sine wave, the signal generator is producing one with a minimum amount of second harmonic distortion.
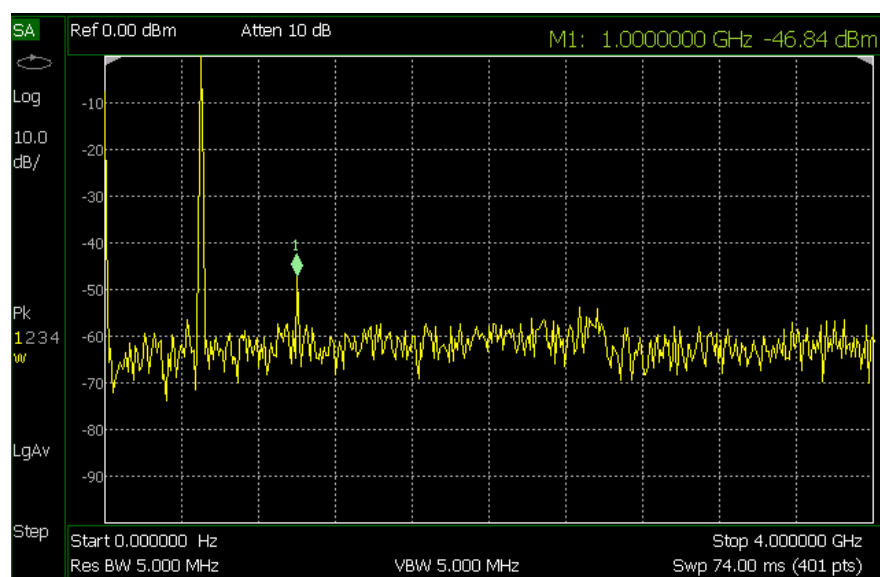

Figure 4. Screenshot of the first and secondary peak with marker

As the power level of the signal generator varies, the amplitude of the secondary peak moves with the first peak. Rather than giving the secondary peak an absolute power level, it is important to specify its power level relative to the main carrier peak. From the previous measurements, the secondary peak remains at a level of about 45 dB below that of the carrier. The second harmonic peak has an amplitude of -45 dBc, which simply means 45 dB below the carrier.

Compute the signal level of the second harmonic from the previously recorded readings, and express this in dBc. The measurement of 45 dB converts to 31,600 in power, or 177 in voltage, so the second harmonic is small in comparison to the carrier. Having a -45 dBc second harmonic distortion is very good for a signal generator. The wide dynamic range of the FieldFox SA is what allows this measurement to be made. This same measurement is difficult to make in the time domain using an oscilloscope. Notice that the output of the signal generator required an increase to 0.00 dBm in order to get the second harmonic peak to emerge from the noise level.

Effects of frequency span and RBW on noise level

In this section, you will learn the effects of frequency span and RBW on the displayed noise level. Adjust the FieldFox frequency sweep to a center frequency of 500 MHz with a frequency span of 500 MHz. At the bottom of the FieldFox display, it indicates an RBW (or Res BW) and VBW of 3.00 MHz. The sweep time shows about 100 ms for the 401 display points indicating about a 10 Hz refresh rate on the spectrum analyzer display. The RBW is set by the IF bandpass filter, and the VBW is set by the low-pass filter that follows the envelope detector.

When the frequency span of the FieldFox changes, the control software (firmware) automatically determines the best RBW and VBW filter cutoffs to use. You must adjust these manually on older style signal analyzers. At the current span of 500 MHz, the displayed average noise level (DANL) is around -70 dBm. At the prior full frequency span of 30 kHz – 6.5 GHz, roughly a factor of 10 wider, the DANL was around -60 dBm. Now, change the span to 50 MHz. The carrier peak looks about the same, but the DANL falls to about -80 dBm. The RBW and VBW also reduce to 300.0 kHz. At this span of 50 MHz, 401 points in the display means125 kHz between points. When comparing that to the 300 kHz RBW, the display is not quite three times oversampled.

You can experiment a little further by reducing the span to 5.0 MHz, which produces an RBW of 30.0 kHz and a DANL of -90 dBm. Keep going until something on the display changes, and make a note of what that is. The key point to observe is how frequency span, RBW, and DANL interact. This is a basic trade-off in all SFA instruments.

How to measure amplitude modulation

Return the FieldFox to a center frequency of 500 MHz and a span of 500 MHz. Return the signal generator to a carrier of 500 MHz with an amplitude of -20 dBm[1]. Press the AM menu button on the signal generator to bring up the AM options. Using the soft keys to the right of the display panel, set the AM Type to EXP, set the AM modulation rate to 1.00 MHz, and set the modulation depth to its maximum value of 40.00 dB. Press the uppermost soft key to set AM to On. Ensure that you enable the modulation output by pressing the Mod On/Off

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[1]The amplitude modulation exercise uses the Keysight A model signal generators; signal generators where the model number ends in the letter A. This section is not applicable to B model signal generators.

button above the output connector. Its green LED glows along with the one beside it to indicate the carrier output or RF is on.

You may expect to see some change in the FieldFox display with modulation turned on; however, the display remains unchanged. The reason for this is that the AM modulation of 1.00 MHz only introduces sidebands of 1.00 MHz away from the carrier, and the current span setting of 500 MHz produces an RBW of 3.00 MHz — too wide to pick up the AM sidebands.

This span and sweep setting cannot resolve the AM of the carrier peak. Reduce the span further to 5.0 MHz, and the two AM sidebands now become quite distinct. Each are located exactly two divisions to either side of the carrier peak. Notice that the AM sideband peaks are rather small in amplitude in comparison to the carrier. To detect these AM sidebands, it was necessary to reduce the frequency span which reduced the RBW and the DANL to where the sideband peaks emerged. Capture a screen image of the AM sidebands and carrier — it serves as a reference point for later.

One reason the AM sidebands are so small is because the AM modulation rate is rather high at 1.00 MHz. Reduce the AM modulation rate to 10 kHz. Set the AM Type to LIN and the modulation level to 100% using the soft keys of the signal generator.

Reduce the span on the FieldFox to 500 kHz and notice now that the carrier appears to have many sidebands on either side of it. Each matching pair of sidebands corresponds to different harmonics of the modulation frequency of 10 kHz.

Change the span to 50 kHz; the display now shows five clear peaks:

- Center carrier at 500.000 MHz and -20.00 dBm
- First harmonic pair at 500.000 MHz ± 10 kHz and -26.00 dBm
- Second harmonic pair at 500.00 MHz ± 20 kHz and -45 dBm

Note the second harmonic distortion arises from the modulator section of the signal generator. It is distinct from the second harmonic distortion from the signal generator's carrier oscillator. Use the knob on the signal generator to vary the AM modulation rate in 1.00 kHz increments. Observe that the separation between each of the adjacent peaks is equal to the AM modulation rate.

How to measure frequency modulation

Turn AM modulation off by pressing the soft key of the signal generator to set AM to Off. Press the Mod On/Off button above the output connector to disable the modulation for the time being. It is always good practice to disable the output of a generator before making new adjustments. Once you make the adjustments, turn the output back on. Press the FM/ΦM menu button to bring up the FM options of the signal generator. Use the soft keys to set FM mode, FM to On, FM deviation to 10 kHz, and FM rate to 1.0 kHz. Press the Mod On/Off button above the output connector to enable the modulation output. On the FieldFox, set the center frequency to 500 MHz and the span to 50 kHz. Many peaks appear in the display. Capture a screen image of the FM modulated carrier to reference later.

Use the knob on the signal generator to increase the FM modulation rate from 1.0 kHz to 10.0 kHz in 1.0 kHz increments. Notice that the separation between the adjacent peaks is again equal to this modulation rate, just as in the case of AM. Return the FM modulation rate to 1.0 kHz.

Use the knob on the signal generator to increase the FM deviation from 1.0 kHz up to 100 kHz in 1.0 kHz increments. Change the FieldFox span to 500 kHz to observe the full spectrum of the output. The overall width of the FM spectrum is approximately twice the FM deviation. The signal generator's carrier remains at an amplitude of -20 dBm. When the FM deviation is small, the carrier is present close to its prescribed amplitude of -20 dBm. However, when the FM deviation is significant, the carrier splits into many smaller peaks, each with a significantly smaller amplitude in the range of -30 dBm to -40 dBm.

FM is often categorized as a narrow or wide deviation, or sometimes narrow or wideband, depending on how the FM modulation rate compares to the FM deviation. Narrow deviation FM is where $f_{mod} > f_{dev}$, and the FM spectrum appears similar to AM with a distinct and strong carrier. Wide deviation FM is where $f_{mod} < f_{dev}$, and the FM spectrum is spread out into many peaks without any prominent carrier.

Additional analysis

A deviation FM is recognizable by its extensive frequency spread and its lack of a prominent carrier. It is often challenging to distinguish between AM and narrow deviation FM. Commercial FM radio broadcast stations are usually wide deviation FM with a deviation of around 75 kHz. This wide deviation FM gives them a higher signal-to-noise ratio (SNR) than an AM system of the same average power.

Short-range personal radios operating in the FRS (family radio service) band are usually narrow deviation FM with a deviation of only a few kHz. Knowing the FM deviation helps identify various signals. Both AM and FM are expressed in fairly simple mathematical terms for sinusoidal carriers with single tone modulation.

sinusoidal:

$$c(t) = C cos(\omega_c t)$$

Modulation tone:

$$m(t) = M cos(\omega_m t)$$

Output of an AM system:

$$y_{AM}(t) = [1 + m(t)]c(t)$$

Using the same trigonometric relations presented earlier, the output of an AM system is:

$$y_{AM}(t) = C cos(\omega_c t) + \frac{1}{2} CM cos\big((\omega_c - \omega_m)t\big) + \frac{1}{2} CM cos\big((\omega_c + \omega_m)t\big)$$

This expression represents the observed AM frequency spectrum. The first term describes the carrier, the second term describes the lower modulation sideband, and the third term describes the upper modulation sideband. Suppressed carrier AM systems only transmit the sidebands and eliminate the unity term, which reproduces the carrier.

Such suppressed carrier AM systems are considerably more power efficient — although it makes it more challenging to build a receiver. Reduced carrier AM systems compromise by reducing or lowering the amplitude of the carrier. Since the information content in the sidebands is redundant, single sideband (SSB) AM systems filter off one or the other of the sidebands to create a slightly more power and frequency spectrum-efficient transmission.

AM systems do have one limitation — the depth of the modulation. The amplitude M cannot exceed unity; Otherwise the term in square brackets becomes negative, producing phase inversion of the carrier. This leads to a variety of distortion problems and also a loss of carrier phase lock. The depth of AM modulation is usually expressed in terms of the modulation index, varying between 0 and 1.

The factor M is equivalent to this modulation index. FM systems avoid this limitation because there is no such hard limit on the depth of FM. You can use considerable FM modulation depths to increase the effective SNR.

In an FM system, the mathematics are complex. Here, we modulate the frequency ω_c of the carrier instead of the amplitude C. The argument of the cosine is the integral of the frequency, also known as the phase. We express FM as:

$$\omega = \omega_c + \omega_\Delta m(t)$$

where ω_Δ is the FM deviation, so that the phase argument of the cosine carrier is:

$$\omega t = \omega_c t + \int^t \omega_\Delta m(t) dt$$

For a sinusoidal carrier and a single tone modulation, the FM signal is then:

$$y_{FM}(t) = C cos\left[\omega_c t + M\frac{\omega_\Delta}{\omega_m}\sin(\omega_m t)\right]$$

Instead of multiplying two trigonometric functions as in AM, FM uses a trigonometric function that is the argument of another, a considerably more complex relationship. You may still be able to decompose the FM signal into its frequency spectrum representation, although that involves Bessel functions of the first kind, $J_k(x)$:

$$y_{FM}(t) = CJ_0\left(M\frac{\omega_\Delta}{\omega_m}\right)\cos(\omega_c t) + C\sum_{k=1}^{\infty} J_k\left(M\frac{\omega_\Delta}{\omega_m}\right)\left[\cos((\omega_c + k\omega_m)t) = (-1)^k\cos((\omega_c - k\omega_m)t)\right]$$

Note that this is an infinite series with an infinite number of sidebands for FM. However, the Bessel functions do fall off with increasing argument in an oscillatory manner. In practice, only a few of the terms in the infinite series remain with a significant contribution. The key parameter in how many terms remain significant is the ratio $M\omega_\Delta/\omega_m$, a measure of the FM deviation, relative to the modulation rate. A guideline for the effective bandwidth of an FM system is:

$$BW_{FM} \approx 2(f_\Delta + f_m)$$

This argument is what we observed in the previous FM spectrum measurements.

Measurement assignment

Because of their wide dynamic range and superb frequency accuracy, spectrum analyzers are the premier instrument for electronic monitoring of radio signals and other wireless transmissions. Because of its portability, FieldFox is a robust instrument for signal monitoring.

This example examines the commercial United States FM broadcast band of 87.5 MHz to108.0 MHz to gain insight to additional features of the FieldFox spectrum analyzer.

Steps for this exercise:

1. Connect a suitable antenna to Port 2 of the FieldFox.

2. Disconnect the FieldFox from the signal generator; you may shut down the signal generator as you do not need it further for this lesson.

3. Remove the Type-N to SMA adapter and replace it with a Type-N to BNC adapter.

4. Connect a telescopic whip antenna to the BNC connector and extend the antenna to its full length of about 19 inches. By adjusting the length, most telescopic whip antennas have reception over a range of 25 MHz to 1300 MHz.

5. Set up the FieldFox for its spectrum analyzer application and set the frequency sweep to run from 87.5 MHz to 108.0 MHz. Alternatively, 90 MHz to 110 MHz also works well and aligns the display divisions to even MHz multiples. At this point, several peaks are visible in the display, typically at power levels of -50 dBm to -30 dBm. These are the local commercial FM radio stations.
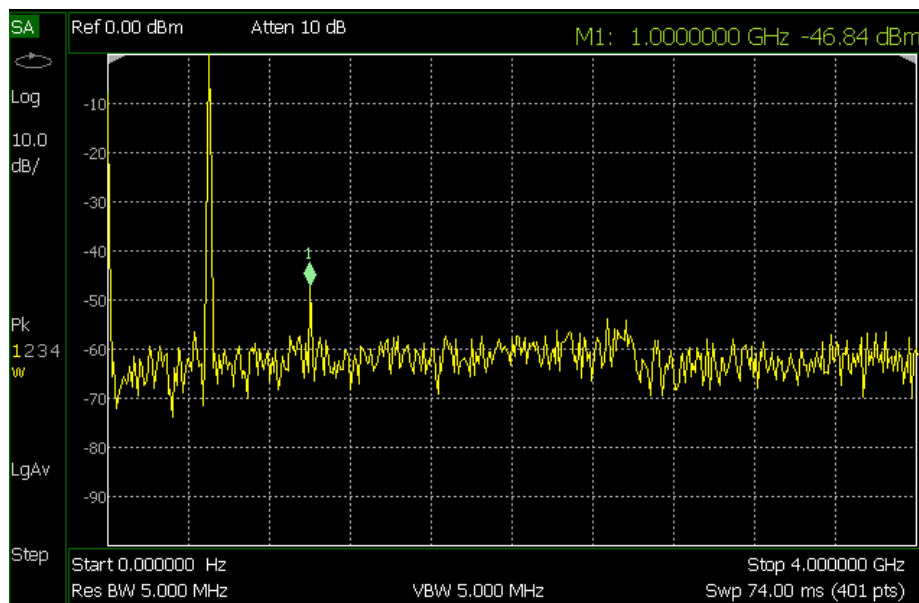

Figure 5. Local commercial FM radio station frequencies captured on the FieldFox

6. Press Measure (key 1), from the frequency sweep menu, which brings up some useful options for the spectrum analyzer.

7. Press Radio Standard, left soft key.

8. Press Radio Standard (None) to show a vertical list of predefined radio standard frequency bands. Use the dial to select the desired frequency band, followed by the Enter key. Since the frequency band is set; select None at the top of the list and Enter.

9. Press the Back button to return to the measurement options. You can also load different radio standards into FieldFox to make specific measurement set ups easier and to avoid memorizing different frequency bands.

10. Press the Tune & Listen soft key, then the FM Wide soft key. This turns on the wide deviation FM demodulator and routes the output to the built-in audio subsystem and speaker on the FieldFox. A white vertical marker bar appears on the display.

11. Press the Tune Freq soft key and use the dial to move the white marker bar onto one of the signal peaks. You can hear the FM radio station through the FieldFox speaker. The default listen time is 2.5 seconds, so press the Listen Time soft key and rotate the dial to increase play time and keep the sound from segmenting.

Control the volume using the Volume soft key. Experiment with this feature of the FieldFox spectrum analyzer and record the frequencies and power levels of some of the FM stations received. The marker function is very handy for doing this.

Use the FieldFox to scan through the commercial AM radio band from 540 kHz to 1610 kHz. Note that the telescopic whip antenna is not a good match for these low frequencies, but some reception might still be possible.

Experiment to see if the FieldFox can pick up cell phone transmission. The specific frequency depends upon the phone type and the service provider. Some common frequencies to try are 800 MHz, 850 MHz, 1700 MHz, 1900 MHz, or 2100 MHz. AT&T and Verizon both use 850 MHz for voice. Make a note of the power levels and signal bandwidth used by these transmissions as a reference. For the reception in the 800 MHz to 900 MHz range, the short, flexible BNC antenna works best.

Since cell phone transmissions are usually brief, using the Run/Hold button is useful to temporarily capture a signal so that you can measure it later with the marker after the transmission ends.

FieldFox Fundamentals Parts List — Lessons 1 through 6

FieldFox Fundamentals Lessons 1 through 6 require a FieldFox handheld analyzer and the parts listed in the table below. Additionally, Lesson 2 requires a Keysight MXG RF analog signal generator used to generate CW, AM, and FM signals.

These lessons are for the FieldFox N9914A 6.5 GHz analyzer. However, you can substitute the N9914A with any of the following models: N9913/15/16/17A, N9918A with adaptors, N9950/51/52A with adaptors, or N991xB.

You can use other MXG signal generators; an A Series is simpler to use than a B Series, as the AM modulation scheme is different between the A and B Series. The lesson is applicable for the A Series.

Item	Description	Manufacturer	Mfr. part no.	Vendor	Vendor part no.	Qty
C1	SMA (m) to SMA (m) coaxial cable assembly, RG58C/U, 50 ohm, 18 in. long			L-com	CCS58A-1.5	2
C2	Type-N (m) to BNC (f) coaxial adapter, 50 ohm			L-com	AXA-NMBF	2
C3	Type-N (m) to SMA (f) coaxial adapter, 50 ohm			L-com	AXA-NMSF	2
C4	SMA (f) to SMA (f) coaxial adapter, knurled middle			L-com	BA23	2
C5	SMA (m) to SMA (m) coaxial adapter, Au			L-com	BA22	2
C6	SMA (m) to SMA (m) to SMA (m) coaxial T adapter			L-com	BA18	2
C7	SMA (m) terminator, 50 ohm			L-com	BTS5M	2
C8	SMA (f) terminator, 50 ohm			L-com	BTS5F	2
D1	Center-loaded telescoping whip antenna with BNC (m) connector, 19 in. long			RadioShack	20-006	1
D2	800 MHz scanner antenna with BNC (m) connector			RadioShack	20-283	1
D7	SMA coaxial attenuator, 10 dB, DC to 6 GHz, 50 ohm			Mini-Circuits	VAT-10+	1
D8	SMA coaxial bandpass filter, 70 MHz, (63 to 77 MHz), 50 ohm			Mini-Circuits	SBP-70+	1
D9	SMA coaxial power splitter/combiner, 2-way, 90°, 50 ohm, 80 to 120 MHz			Mini-Circuits	ZMSCQ-2-120+	1

Item	Description	Manufacturer	Mfr. part no.	Vendor	Vendor part no.	Qty
D10	SMA coaxial bi-directional coupler, 50 ohm, 50 W, 10 to 600 MHz			Mini-Circuits	ZFBDC20-62HP+	1
C9	SMA male shorting cap, Au	Amphenol Connex	132331_	Digi-Key	ACX2070-ND	1
A1	SMA (f) PCB jack, 50 ohm, 3 GHz, PTFE, Zn alloy/Au plated	TE Connectivity	5-1814832-1	Digi-Key	A97594-ND	1
A2	SMA (f) PCB jack, 50 ohm, 3 GHz, PTFE, brass/Ni plated	Linx Technologies	CONSMA001	Digi-Key	CONSMA001-ND	1
A3	Thumbwheel trimpot, 500 ohm, 0.5 W, PC pin, cermet, single turn, top adjust	Bourns	3352T-1-510LF	Digi-Key	3352T-501LF-ND	1
A4	Resistor, 100 ohm, 1/4 W, 1%, axial lead metal film, 100 ppm/C	Yageo	MFR-25FBF52-100R	Digi-Key	100XBK-ND	1
A5	Capacitor 22 pF, 100 V, 5%, radial lead ceramic disk, C0G-NP0	Vishay	D220J20C-0GH63L6R	Digi-Key	1429PH-ND	1
A6	DIP8 machine pin socket, 0.100 pitch, 0.300 spacing, 30 µin Au plated	Mill-Max Mfg. Corp.	110-13-308-41-001000	Digi-Key	ED56083-ND	1
A7	Hook up wire, 22 AWG, solid, tinned Cu, black 300 V PVC insulated, 100 ft. spool	Alpha Wire	3051/1 BK005	Digi-Key	A3051B-100-ND	1

Item	Test equipment	Manufacturer	Mfr. part no.	Vendor	Vendor part no.	Qty
T1	FieldFox handheld analyzer • Option 233: Spectrum analyzer • Option 210: VNA transmission/reflection • Option 211: VNA full 2-port S-parameters	Keysight	N9914A		N9914A	1
T2	MXG RF analog signal generator	Keysight	N5181A		N5181A	1

Professor Bruce Darling, from the University of Washington's Electrical Engineering Department, created this application note in collaboration with Keysight Technologies' handheld team. The content complements an introductory course in undergraduate electromagnetics.

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