40.1 Introduction

A signal is usually defined by a time-varying function carrying some sort of information. Such a function most often represents a time-changing electric or magnetic field, whose propagation can be in free space or in dielectric materials constrained by conductors (waveguides, coaxial cables, etc.). A signal is said to be periodic if it repeats itself exactly after a given time \( T \) called the period. The inverse of the period \( T \), measured in seconds, is the frequency \( f \) measured in hertz (Hz).

A periodic signal can always be represented in terms of a sum of several (possibly infinite) sinusoidal signals, with suitable amplitude and phase and having frequencies that are integer multiples of the signal frequency. Assuming an electric signal, the square of the amplitudes of such sinusoidal signals represents the power in each sinusoid and is said to be the power spectrum of the signal. These concepts can be generalized to a nonperiodic signal; in this case, its representation (spectrum) will include a continuous interval of frequencies, instead of a discrete distribution of integer multiples of the fundamental frequency. The representation of a signal in terms of its sinusoidal components is called Fourier analysis. The (complex) function describing the distribution of amplitudes and phases of the sinusoids composing a signal is called its Fourier transform (FT). The Fourier analysis can be readily generalized to functions of two or more variables; for instance, the FT of a function of two (spatial) variables is the starting point of many techniques of image processing.

A typical way to analyze a time-dependent electric signal, then in the so-called time domain, is through an oscilloscope. The set of signals on this instrument is arranged such that signal's amplitude voltage on a vertical scale, while the horizontal scale is continuously updated to account for the evolution of the time.

The spectrum analyzer, instead, is said to operate in the frequency domain because it allows one to measure the harmonic content of an electric signal, that is, the power of each of its spectral components. In this case, the vertical scales read powers available in each pre-into bandwidth, centered at the frequency reported in the horizontal scale. The two domains are mathematically well defined, and
through the FT algorithm, it is not too difficult to switch from one response to the other. Their graphical, easily perceivable representation is shown in Figure 40.1 where the two responses are shown lying on orthogonal planes. It is trivial to say that the easiest way to make a Fourier analysis of an electric signal is to have it displayed on a spectrum analyzer. Many physical processes, when detected by appropriate sensors, generate (electric) signals whose nature is not deterministic, but rather stochastic, or even of true random origin, like noise. Such signals can also be analyzed in terms of FT, although in a statistical sense only.

A time signal is said to be band limited if its FT is nonzero only in a finite interval of frequencies, say \((F_{\text{max}} - F_{\text{min}}) = B\), being the bandwidth. Usually, this is the case; then, an average frequency \(F_0\) can be defined. Although the definition is somewhat arbitrary, a (band-limited) signal is referred to as radio frequency (RF) if \(F_0\) is in the range 100 kHz to 1 GHz and as a microwave signal in the range 1-1000 GHz. The distinction is not fundamental theoretically, but it has very strong practical implications in instrumentation and spectral measuring techniques. A band-limited signal can be described further as narrowband, if \(B/F_0 << 1\), or wideband otherwise.

The first step in performing a spectral analysis of a narrowband signal is generally the so-called heterodyne downconversion: it consists in the mixing ("beating") of the signal with a pure sinusoidal signal of frequency \(F_1\), called local oscillator (LO). In principle, mixing two signals of frequency \(F_0\) and \(F_1\) in any nonlinear device will result in a signal output containing the original frequencies as well as difference \((F_0 - F_1)\) and the sum \((F_0 + F_1)\) frequencies and all their harmonic (multiple) frequencies. In the practical case, the best mixer devices are selected in order to exhibit an almost pure quadratic transfer function with the output including only the frequencies \((F_0 - F_1)\) and \(2F_0\), \(2F_1\), \(F_0 + F_1\), \(F_0 - F_1\). The first term (called the intermediate frequency or IF) will be easily separated from the others, which have a much higher frequency, by a proper termination and filtering of the mixer output. The bandwidth of the IF signal will be the same as the original bandwidth \(B\); however, to preserve the original information fully in the IF signal, stringent limits must be imposed on the LO signal, because any deviation from a pure sinusoidal law will show up in the IF signal as added phase and amplitude noise, corrupting the original spectral content. The process of downconverting a (band-limited) signal is generally necessary to perform spectral analysis in the very high-frequency (microwave) region, to convert the signal to a frequency range more easily handled by the following analyzing hardware and software.

When the heterodyne process is applied to a wideband signal (or whenever \(F_1 > F_{\text{min}}\), "negative" frequencies will appear in the IF signal. This process is called double sideband mixing, because a given IF bandwidth \(B\) (i.e., \((F_1 + B)/2\)) will include two separate bands of the original signal, centered at \(F_1 + IF\)
("upper" sideband) and \( f_1 - 1f \) ("lower" sideband). \( T \) is form of mixing is obviously undesirable in spectrum analysis, and input filters are generally necessary to split a wideband signal in several narrowband signals before downconversion. Alternatively, special mixers can be used that can deliver the upper and lower sidebands to separate IF output ports. A band-limited signal in the frequency interval \( (f_{\text{max}} - f_{\text{min}}) = B \) is said to be converted to baseband when the LO is placed at \( f_1 = f_{\text{min}} \), so that the band is converted to the interval \( (B - 0) \). Modern digital circuits are best matched to this case, being essentially limited on the maximum working frequency. Here, it is possible to employ analog-to-digital converters (ADCs) to get a discrete numerical representation of the analog signal, and the spectral analysis is then performed numerically, either by direct computation of the FT (generally via the fast Fourier transform, FFT, algorithm) or by computation of the signal autocorrelation function, which is directly related to the square modulus of the FT via the Wiener–Khinchin theorem. Considering that the ADC must sample the signal at least at the Nyquist rate (i.e., at twice the highest frequency present) and with adequate digital resolution, this process is feasible and practical only for frequencies (bandwidths) less than a few hundreds of megahertz. Also, the possibility of a real-time analysis with high spectral resolution may be limited by the availability of very fast digital electronics and special-purpose computers. The digital approach is the only one that can provide extremely high spectral resolution, up to several hundred thousand channels.

### 40.2 Practical Approach to Spectrum Analysis

Spectrum analysis is normally done in order to verify the harmonic content of oscillators, transmitters, frequency multipliers, etc., or the spurious components of amplifiers and mixers [1]. Other specialized applications are possible, such as the monitoring of radio-frequency interference (RFI), electromagnetic interference (EMI), and electromagnetic compatibility (EMC). These applications, as a rule, require an antenna connection and a low-noise, external amplifier. Which are then the specifications to look for in a good spectrum analyzer? First, we would suggest evaluating what are the critical parameters that are most relevant for your application. Then identify what is the instrument performance that has to drive the selection of the industrial product that best matches your needs.

Here follows a list of the typical characteristics of a spectrum analyzer:

1. It should display selectable, both wide and narrow, bands of the EM radio spectrum with amplitude power and frequency readable with good accuracy.
2. Its selectivity should range, in discrete steps, from few hertz to megahertz so that sidebands of a selected signal can be spotted in details as well as monitored in the spectral environment where that signal is immersed in.
3. It should possess a very wide dynamic range, so that signals differing in amplitude six to eight orders of magnitude can be observed at the same time on the same view of the display.
4. Its sensitivity must be compatible with the measurements to be taken. As already mentioned, specialized applications may require external wideband, low-noise amplifiers, and an antenna connection.
5. The type of power supply (mains or battery), weight, and dimensions should be compatible with the type of operation, fixed or portable, you want to have.
6. Phase noise stability of the LO shall be carefully verified before attempting to reach your ultimate target in spectral resolution measurements.
7. Consider your data logger requirements: the capability of direct driving a plotter or a printer, archive data on external memory devices, and finally the interface protocol that will allow controlling your spectrum analyzer, from a personal computer (PC).
8. Analog and/or digital averaging and other special functions can extend the measuring capabilities in dedicated measuring configurations.
9. Periodic calibration of the unit by an authorized center will guarantee that your results could be traced to international standards, along the operating life of the instrument.

A block diagram of a commercial spectrum analyzer is shown in Figure 40.2.
Figure 40.2 shows that we are confronted with a radio-receiver-like superhet with a wideband input circuit. The horizontal scale of the instrument is driven by a ramp generator, which is also applied to the voltage-controlled LO [2].

A problem arises when dealing with a broadband mixing configuration like the one shown earlier, namely, avoiding receiving the image band.

The problem is successfully tackled here by upconverting the input band to a high-valued IF. An easily designed input low-pass filter, not shown in the block diagram for simplicity, will now provide the necessary rejection of the unwanted image band.

Nowadays, with the introduction of YIG band-pass filters, tunable over very wide input bands, upconversion is not always necessary. Traces of unwanted signals may, however, show up on the display although at very low level (less than −80 dBc) even on good analyzers.

A block diagram of a commercial spectrum analyzer exploiting both the mentioned principles is shown in Figure 40.3. This instrument includes a very important feature that greatly improves its performance: the LO frequency is no longer coming from a free-running source but rather from a synthesized unit referenced to a very stable quartz oscillator. The improved quality of the LO both in terms of its own noise and frequency stability optimizes several specifications of the instrument, such as frequency determining accuracy, finer resolution on display, and reduced noise in general.

Further, a stable LO generates stable harmonics that can then be used to widen the input-selected bands up to the millimeter region. As already stated, this option requires external devices, for example, a mixer-amplifier as shown in Figure 40.4a and b.

The power reference on the screen is the top horizontal line of the reticle. Due to the very wide dynamic range foreseen, the use of a log scale (e.g., 10 dB/square) seems appropriate. Conventionally, 1 mW is taken as the zero reference level: accordingly, dBm are used throughout.

The noise power level present on the display without an input signal connected (noise floor) is due to the input random noise multiplied by the IF amplifier gain. Such a noise is always present and varies with input frequency, IF selectivity, and analyzer sensitivity (in terms of noise figure).

The “on display dynamic range” of the analyzer is the difference between the maximum compression-free level of the input signal and the noise floor. As a guideline, the dynamic range of a good instrument could be of the order of 70–90 dB.

An input attenuator, always available on the front panel, allows one to apply more power to the analyzer while avoiding saturation and nonlinear readings. The only drawback is the obvious sensitivity loss.
When kept calibrated over the specified warranty periods, modern spectrum analyzer can exhibit measurement uncertainties of a fraction of a dB and Hertz resolutions up to a few GHz.

When more accurate measurement of power sources, with slow time variations, is needed, the suggestion is to use a bolometer instead of a spectrum analyzer. An erratic signal pattern on display and a fancy level indication may be caused by the wrong setting of the “scan time” knob. It must be realized that high-resolution observation of a wide input band requires the proper scanning time. An incorrect parameter setting yields wrong readings, but usually an optical alarm is automatically switched on to
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warn the operator. In any case, never forget that pulsed signal, in particular even when repeated with very low duty cycles, cannot be represented with fidelity by a frequency swept spectrum analyzer.

The knowledge of the noise floor level allows a good valuation of the noise temperature, \( T_n \) (and therefore of the sensitivity), of the analyzer, a useful parameter on many occasions. The relations involved are as follows.

The Nyquist relation states that

\[
P = k \times T_n \times B
\]

where

- \( P \) is the noise floor power level read on the display (W)
- \( k \) is the Boltzmann constant = \( 1.38 \times 10^{-23} \text{ (J/K)} \)
- \( B \) is the passband of the selected IF (Hz)

Therefore,

\[
T_n = \frac{P}{k \times B}
\]

Usually, engineers prefer to quote the noise figure of receivers. By definition, we can write

\[
N = \left( \frac{T_n}{T_0} \right) + 1
\]

where

- \( N \) is the noise factor
- \( T_0 = 290 \text{ K} \)
- \( F \) (noise figure) = \( 10 \log N \)

A typical \( F \) for a good spectrum analyzer is of the order of 10–20 dB.

It must be said, however, that the "ultimate sensitivity" of the spectrum analyzer will depend not only on its noise floor but also on the setting of other parameters like the video filter, the IF bandwidth, the insertion of averaging functions, the scan speed, and the type of transfer function of the detector used.

As a rough estimate, a noise floor level of ~130–140 dBm is very frequently met by a good instrument.

Another criterion to select a spectrum analyzer is a good "IMD dynamic range," that is, the tendency to create spurious signals by intermodulation due to saturation.

This figure is generally quoted by the manufacturers, but it is also easily checked by the operator by injecting two equal amplitude sinusoidal signals at the input socket of the analyzer. The frequency separation between the two should be at least a couple of "resolution bandwidths," that is, the selected IF bandwidth. As the input levels increase, spurious lines appear at the sum and difference frequencies and spacing of the input signals.

The range in decibels between the nonoverloaded input signals on display and the barely noticeable spurious lines is known as the "spurious free dynamic range," shown graphically in Figure 40.5a, where the third-order "intercept point" is also graphically determined. If input power is increased, higher-order spurious signals appear, as shown in Figure 40.5b. The input connector of most spectrum analyzers is of the 50 \( \Omega \) coaxial type. Past instruments invariably used \( N \)-type connectors because of their good mechanical and electric behavior up to quite a few gigahertz. Today, type SMA or type K connectors are preferred.

External millimeter wave amplifiers and converters use waveguide input terminations. As is discussed in the next section, multipurpose analyzers are available where power meter, frequency
counter, tracking generator, etc., can all be housed in the same cabinet. The economic and practical convenience of these units must be weighed on a case-by-case basis.

Finally, we mention that spectrum analyzers are available equipped with AM and FM detectors to facilitate their use in the RFI monitoring applications in order to identify the name of the interferer.

40.3 Selecting Correct Spectrum Analyzers for Specific Purposes

Several manufacturers offer a large number of spectrum analyzer models; the choice may be made on the basis of application field (i.e., CATV, mobile telephony, R-LAN, service, surveillance, and R&D), performance (resolution bandwidth, frequency range, accuracy, battery operation, etc.), or cost. Very often, the newest RF models exhibit also the signal analyzer function, intended as some kind of characterization in the time domain, by computing the FFT of the signal under test, that is, baseband modulation and phase noise.

In addition, it is important to know that most spectrum analyzers need some accessories generally not furnished as a standard: for example, a connectorized, coaxial, microwave cable is always required; a directional coupler, power divider, or handheld sampler antenna may be very useful to pick up the signals; and a PC is useful to collect, store, reduce, and analyze the data.

There are six main families of RF and microwave spectrum analyzers.

40.3.1 Family 1

The bench instruments are top performance but also large, heavy, and the most expensive class, intended for metrology, certification, factory reference, and radio surveillance done by government and military institutions.

Their operating frequencies span from a few tens of hertz to RF (i.e., 2.9 GHz), or up to the microwave region (i.e., 26.5 GHz), or even reach millimeter wavelengths (i.e., 40–67 GHz). Their class of instruments includes lower-noise figures, approximately 20–25 dB at medium frequencies that can be decreased down to 10–15 dB with an integrated preamplifier. The synthesized LO has a good phase noise (typically 10 dB better than general-purpose spectrum analyzers) for precise, accurate, and stable measurement.

Also, this class of instruments can be integrated with plug-in instruments like a power meter (for more accurate power measurements), a frequency counter (for accurate frequency measures), or a tracking generator (for network analysis and mixer testing).

An interface to a computer (and printer) such IEEE-488, USB, and in particular LAN is now standard in all units. Now, even the front panel acts as the remote control terminal for the instrument inside. Optical encoders, up and down push buttons, and the digital keyboard have substituted for all old analog or mechanical input switches. The output display is now typically a colorful at LED monitor, with greater advantages for a clearer and much more detailed view. Having inside powerful, state-of-the-art
microprocessor controllers, RAM memories, and plug-in cards for storing data, all sort of statistical and mathematical analysis can be implemented in many different measuring configurations, each stored for later usage with a single press of recovery functions. Among the most appreciated and qualified trademarks, we mention Agilent [3] and Rohde & Schwarz [4]. Indicative prices are between $50,000 and $100,000.

40.3.2 Family 2

Less-expensive bench instruments, the workhorse class of spectrum analyzers, portable and lightweight, are associated with a synthesized LO that includes a frequency range from a few kilohertz up to the RF region (i.e., 2.9 GHz), microwave region (i.e., 26.5 GHz), or near millimeter wavelengths (i.e., 40–50 GHz). A typical noise figure of 30 dB is good enough to ensure most measurements. A large number of filters down to a few hertz of resolution are offered; digital filters are preferable to analog ones, because they give a faster refresh rate of the trace on the display. The kind of spectrum analyzer nearly always has the capability to extend the frequency range up to millimeter and submillimeter wavelengths with an external mixer. One of the most important features for a spectrum analyzer in this class is the quality of the LO; it should be synthesized phase-locked loop (PLL) to achieve stability, precision, accuracy, and low phase noise. Demodulation is also an important feature to listen to AM and FM on the loudspeaker and to display complex modulations onto the screen, which is often required by people working on surveillance, TV, and mobile telephone. The interface to a computer such as IEEE-488/USB/LAN is standard in a large number to display TV pictures or complex modulations onto the screen, which is often required by people working on surveillance, TV, and mobile telephone. The interface to a computer such as IEEE-488 or RS232 is standard in a large number of spectrum analyzers and allows the remote control and data reading, storing, and manipulation.

This kind of instrument may integrate a tracking generator, a frequency counter, and other instruments that can transform the spectrum analyzer into a compact, full-featured RF and microwave laboratory. Agilent [3], Anritsu [5], IFR [6], Rohde & Schwarz [4], and Tektronix [7] are the leader companies in the market. Prices typically span from $30,000 to $75,000.

40.3.3 Family 3

The entry level, a more economical class of spectrum analyzer, is intended for field use or for one specific application. If your need is mainly EMI/EMC, CATV, mobile telephone, or surveillance, perhaps you do not need the extreme stability of a synthesized LO, and a frequency range up to 2 GHz may be enough; however, if you need some special functions such as “quasi-peak detector” or “occupied bandwidth measurement,” two functions that originate from a combination of a mathematical treatment with some legislative requirements, you can find on the shelf what you need in a dedicated instrument. Manufacturers are the same, while costs typically run from around $10,000 to $35,000.

40.3.4 Family 4

Handheld spectrum analyzers are very popular nowadays, being low cost, with a high level of performance for their deep usage of the newest digital processing techniques. Frequency coverage up to 43 GHz, and just a few kilograms of weight, can satisfy a large number of users in general fields and in particular when it is required to make a measurement in outdoor open spaces. Agilent [3], Anritsu [5], Rohde & Schwarz [4], Tektronix [7], and some minor companies of such units from $5,000 to $45,000, according to their specific performance.

40.3.5 Family 5

The most economical class of spectrum analyzer, with prices around $2000–$6000, includes instruments that perform only the basic functions with a limited frequency range and filter availability.
They are intended for service, for general-purpose measurements (i.e., IP3, harmonic distortion), or for certification in EM I/EMC measurements. One of the most popular is HAM EG [8] and RIGOL [9].

In this class are some special spectrum analyzers that come on a PC board. Such spectrum analyzers are generally cheap (typically $2000-4000), with a frequency range up to 2 GHz, and may include PLL LOs, tracking generators, and other advanced characteristics. The input is through a coaxial connector on the board, the output and the control are done by a virtual instrument running on the PC.

Other unusual RF spectrum analyzers working in conjunction with a PC and worth noting are the instruments for EM I/EMC measurements and reduction in power lines and power cords. For this type of instrument, the core is not the hardware but the software that performs the measurement according to international standards and may guide the engineer to meet the required compatibility.

40.3.6 Family 6

Many modern applications require “modal analysis,” for example, at acoustic frequencies in mechanical systems. All devices have moving parts, like wheels, axles, and ropes so they can be applied to cars as well as civil elevators, just as the most common examples. These applications require industrial qualifications based on a deeper knowledge of their dynamical properties to avoid dangerous resonances and dissipative losses and finally improve their efficiencies.

Extremely low-frequency spectrum analyzers, with resolutions down at the millihertz level, are quite common. They are very cheap (with respect to the RF spectrum analyzers), being made of only digital hardware, acquiring the input signal in the time domain, and then computing the frequency spectrum by dedicated FFT processors. In this case, the dynamic range can be raised a few decades, ranging up to 90-110 dB. The tracking generator is generally built in, as well as many anti-aliasing input filtering choices.

40.4 Advanced Applications

Completely new families of integrated circuits now offer unprecedented functionalities. For example, off-the-shelf components now make analog-to-digital conversions up to a few giga samples per second with a large dynamic range (of 48 dB, meaning 8 bits of resolution or even more). Such a huge amount of data can only be handled by an extremely fast processing system equipped with field programmable arrays (FPGAs) or graphics processing units (GPUs).

Fundamental research like radio astronomy has found a great benefit from these technological developments opening new possibilities in advanced spectrum analysis applications. Autocontrollers, with a typical frequency resolution of ~5/25 kHz, have been extensively used in radio astronomy. Their performance is well documented; the autocorrelation function is computed online and recorded. Later, the FFT of the function is computed offline in order to get the power spectrum.

As a matter of fact, the FPGA represents a medium-/high-cost approach to the state of the art of very high-performance silicon engines. FPGA advantages are low power consumption at high clock rates and easy reconfiguration for different very high computing demanding projects. They are limited to only linear and pipelined elaboration, under PC control for final data storage.

Fully dedicated applications allow quickly implementing even very complex algorithms on the FPGA chips. FPGA huge processing power is a result that comes out from combining the unattained velocity of the hardware together with the extremely high flexibility of the software, with the benefit of low power consumption per clock rate.

Current FPGA applications demonstrate the capability of processing more than 500 MHz bandwidth with up to 1,000,000 channels using polyphase filter banks (PFBs) in real time.

Here follows a simple block diagram of a high-resolution spectrum analyzer powered by FPGA using the PFB and the FFT engine blocks: our configuration is capable to synthesize in real time several hundred million frequency channels over an input band of 500 MHz [10].
A block diagram of a high-resolution spectrum analyzer is shown in Figure 40.6.

Another state-of-the-art low-cost approach for spectrum analysis is based on GPU; this is a dedicated microprocessor conceived to off-load and accelerate 3D or 2D graphics rendering, made available from its associated CPU. This kind of powerful engine is primarily used in workstations, game consoles, etc. Due to their highly parallel structure, modern GPUs are more effective than standard CPUs for implementing a wide range of complex algorithms.

Their main advantages are high computing power, suitable to drive directly data parallel computing, and easy programmability with little overhead in standard C language and with runtime configurations, scalable on different GPU clusters. In conclusion, a GPU offers an extremely powerful tool as the "number crunching" machine that is requested for the huge FFT computations needed for reaching top performance in spectrum analysis with high frequency resolution and over large bandwidths. The block diagram of a high-resolution spectrum analyzer is illustrated in Figure 40.6.

References