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RF Signal Chain Discourse: Properties and Performance Metrics

Anton Patyuchenko, Field Applications Engineer

Introduction

It was not so long ago from the historical perspective, at the dawn of the 20th century, that the RF engineering underpinning any RF signal chain was a new emerging discipline. Today RF technology and radio frequency devices are so deeply ingrained in our lives that it is inconceivable how modern civilization could survive without them. There are countless examples of societal spheres that are heavily reliant on RF signal chains, which is the focus of our discourse.

However, before we delve into it, we need to understand what the term RF actually means. At first glance, this may seem like an easy question. We all know that RF stands for radio frequency, and a common definition ties this term to a specific range of frequencies extending from MHz to GHz portions of the electromagnetic spectrum. Yet, if we take a closer look at its acknowledged definitions and compare them, we come to realize that all of them define the actual boundaries of the RF portion of the spectrum differently. This becomes even more puzzling in light of the fact that we may often encounter a broader usage of this term in other contexts unrelated to specific frequencies at all. Then what is RF?

A consistent basis for its definition conveying more than one sense can be established by focusing on the distinguishing features of the RF, which include phase shift, reactance, dissipation, noise, radiation, reflections, and nonlinearity.[1] This basis represents a modern all-inclusive definition that does not rely on a single aspect or specific numerical values to distinguish RF from other terms. The term RF can be applied to any circuit or a component sharing a number of these features that underlie its definition.

Now that we have set the context for our discussion, we can move on to its main subject and consider the RF signal chain depicted in its generic form in Figure 1. Its representation uses a distributed-elements circuit model to account for the phase shift across the circuit, which is not negligible at shorter RF wavelengths, making the lumped circuit approximation inapplicable to these types of systems. An RF signal chain may include a broad variety of discrete components such as attenuators, switches, amplifiers, detectors, synthesizers, and other RF analog parts, along with high speed ADCs and DACs as well. All these components are combined to serve a specific application whose overall indicative performance will be determined by the composite performance of its constituent discrete parts.

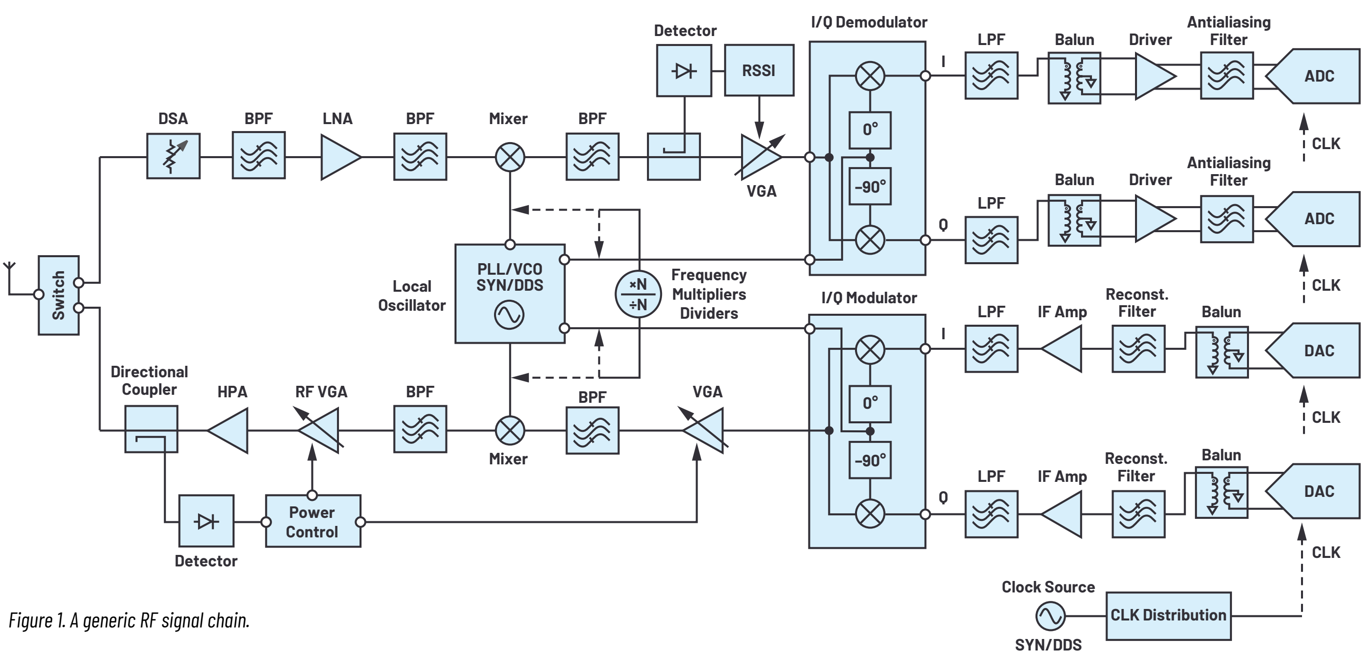

Figure 1. A generic RF signal chain.

Therefore, in order to design a system that would meet specific requirements imposed by the target application, an RF system engineer must attain a substantial system-level perspective and have consistent understanding of the key notions and principles underlying it. The importance of this knowledge has motivated the creation of this discourse, which consists of two parts. The goal of the first part is to provide a concise guidance on the main properties and metrics used to characterize RF devices and quantify their performance. The goal of the second part is to give a well-structured overview of a broad range of individual components and their types that can be used to develop RF signal chains for desired applications. In this article, we will focus on the first part of our discourse and consider the main properties and performance metrics associated with RF systems.

Introduction to RF Terminology

There is a wide range of specifications used for characterization of complete RF systems and their discrete building blocks. Depending on the application or use case, some of these characteristics might be of primary importance while the others are instead less critical or irrelevant. It is certainly not possible to perform a full comprehensive analysis of such a complex subject within the scope of this article. Nevertheless we will attempt to give a concise yet comprehensive overview of the most common RF performance aspects by following the common thread that should shape their complex constellation into a balanced and easy to understand guide to properties and characteristics of RF systems.

Fundamental Properties

Scattering matrix (or S-matrix) is the basic term one needs to know to describe the behavior of an RF system. An S-matrix allows us to represent even the most complex RF network as a simple N-port black box. A common example of a 2-port RF network (for example, an amplifier, filter, or attenuator) is shown in Figure 2, where V_n^+ is a complex amplitude of the voltage wave incident on port n, and V_n^- is a complex amplitude of the voltage wave reflected from port n.[2] When all its ports are terminated in matched loads, we can describe this network by the scattering matrix which elements, or S-parameters, quantify how RF energy propagates through the system in terms of a relationship between these voltage waves. Let us now use S-parameters to express the main properties of a typical RF network.

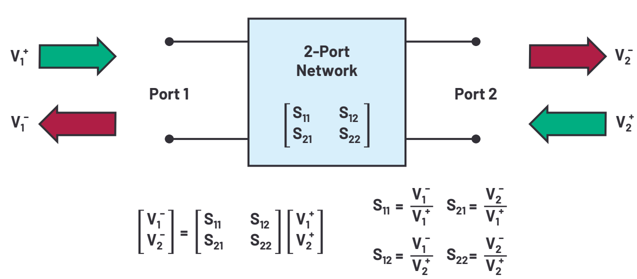

Figure 2. A 2-port network described by its S-matrix.

S_{21} is equivalent to the transmission coefficient from Port 1 to Port 2 for the case when the network is matched (S_{12} can be defined similarly). Its magnitude $|S_{21}|$ in logarithmic scale describes the ratio of the output power to the input power, which is known as gain or scalar logarithmic gain. This parameter is the key attribute of an amplifier and other RF systems in which it can take also negative values. Negative gain indicates intrinsic or mismatch losses usually expressed by its reciprocal quantity known as insertion loss (IL), which is a typical attribute of attenuators and filters.

If we now consider the incident and reflected waves at the same port, we can define S_{11} and S_{22} as shown in Figure 2. These terms are equivalent to the reflection coefficient |Γ| at the corresponding port for the case when the other port is terminated in matched load. Using Equation 1, we can relate the magnitude of the reflection coefficient to return loss (RL):

$$RL = -20\ log(|\Gamma|) \tag{1}$$

Return loss describes a ratio of the power incident on the port to the power reflected back to the source. Depending at which port we estimate this ratio, we can distinguish between input and output return loss. Return loss is always a non-negative quantity that indicates how well the input or output impedance of the network is matched to the impedance seen at the port toward the source.

It is important to note that this simple relation of the IL and RL to the S-parameters is valid only for the case when all ports are matched, which is the main condition for the definition of S-matrix that describes the network itself. If the network is not matched it will not change its intrinsic S-parameters, but it may certainly change the reflection coefficients seen at its ports as well as the transmission coefficients between them.[2]

Frequency Range and Bandwidth

All these fundamental quantities that we have just described will continuously change across the frequency range, which is the basic characteristic common to all RF systems. It defines the frequencies at which these systems are operable and brings us to one more crucial performance measure—bandwidth (BW).

Although this term may refer solely to signal properties, some of its forms are used to describe RF systems that process these signals. In its general definition, bandwidth defines a range of frequencies confined by a certain criterion. However, it may have different meanings that vary depending on the specific application context. To make our discourse more complete, let us give brief definitions to some variations of its meaning:

- 3 dB BW is a span of frequencies at which signal power level is above half its maximum value.
- Instantaneous BW (IBW), or real-time BW, defines the maximum continuous bandwidth that a system is able to generate or acquire without retuning.
- Occupied BW (OBW) is a range of frequencies containing a specified percentage of the total integrated signal power.
- Resolution BW (RBW) in its general meaning describes the minimum separation between two frequency components that can still be resolved. For instance, in spectrum analyzer systems, it is the frequency span of the final filter stage.

These are just a few examples of various types of bandwidth definitions; however, regardless of its meaning, the bandwidth of an RF signal chain is largely determined by its analog front end as well as the sampling rate and bandwidth of a high speed analog-to-digital or digital-to-analog converter.

Nonlinearities

It needs to be mentioned that characteristic properties of an RF system vary not only across different frequencies, but also across different power levels of a signal. The fundamental properties we described in the beginning of this article are typically expressed using small signal S-parameters, which do not account for nonlinear effects. However, in a general case, a continuous increase in power level passing through an RF network often results in more pronounced nonlinear effects, ultimately degrading its performance.

When we talk about an RF system or a component with good linearity, we usually mean that the key metrics describing its nonlinear performance meet the requirements of our target application. Let us consider some of these key metrics that are commonly used to quantify nonlinear behavior of RF systems.

The first parameter we should consider defines the point at which a common device transitions from linear into nonlinear mode: the output 1 dB compression point (OP1dB). This is the output power level at which the gain of a system decreases by 1 dB. This is an essential characteristic of any power amplifier that sets operation of the device toward the level of saturation defined by the saturated output power (P_{SAT}). Power amplifiers generally belong to the final stages of a signal chain, and therefore these parameters usually define the output power range of an RF system.

Once the system is in a nonlinear mode, it starts distorting a signal, producing spurious frequency components, or spurs. Spurs are measured relative to the level of a carrier signal in dBc, and they can be classified into harmonics and intermodulation products (see Figure 3). A harmonic is a signal found at integer multiples of the fundamental frequency (for example, H1, H2, H3 harmonics), whereas the intermodulation products are signals that appear when two or more fundamental signals are present in a nonlinear system. If the first fundamental signal is at the frequency f_1 and the second is at f_2, then second-order intermodulation products are found at their sum and difference frequencies $f_1 + f_2$ and $f_2 - f_1$ as well as $f_1 + f_1$ and $f_2 + f_2$ (the latter are already known to us as H2 harmonics). The combination of the second-order intermodulation products and the fundamental signals results in third-order intermodulation products, two of which ($2f_1 - f_2$ and $2f_2 - f_1$) are especially critical since they are close to the original signals and therefore are not easy to filter. The output spectrum of a nonlinear RF system with spurious frequency components represents intermodulation distortion (IMD), which is an important term describing nonlinearity of the system.[2]

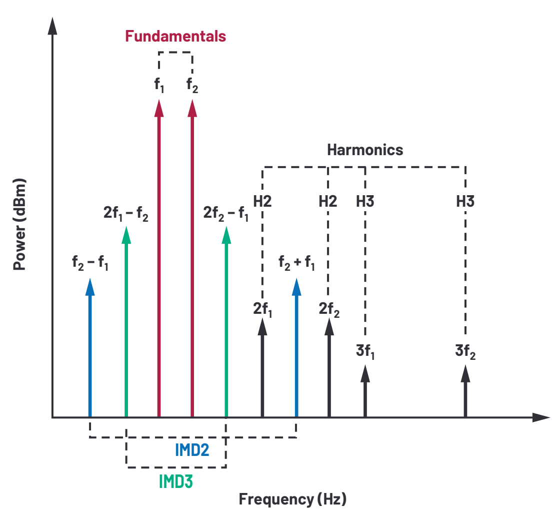

Figure 3. Harmonics and intermodulation products.

Spurious components associated with the second-order intermodulation distortion (IMD2) and third-order intermodulation distortion (IMD3) cause interference to the desired signals. The key figure of merit used to quantify the level of its severity is the intercept point (IP). We can distinguish the second-order (IP2) and third-order (IP3) intercept points. As depicted in Figure 4, they define hypothetical points for the input (IIP2, IIP3) and output (OIP2, OIP3) signal power levels at which the power of the corresponding spurious components would reach the same level of fundamental components. Although the intercept point is a purely mathematical concept, it is the paramount measure of RF system tolerance to nonlinear effects.

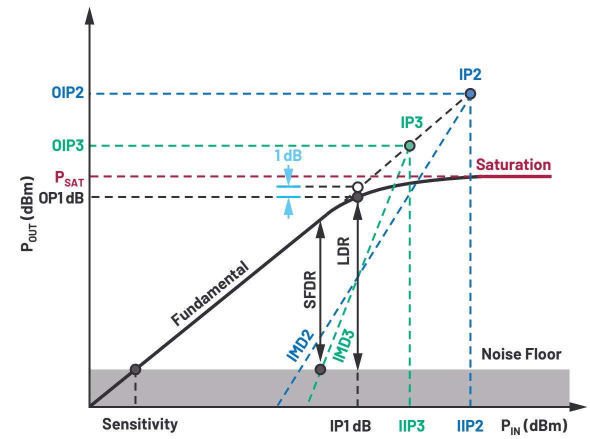

Figure 4. Definition of nonlinear characteristics.

Noise

Let us now consider another important attribute inherent to every RF system—noise. This term describes a fluctuation in an electrical signal that encompasses many different aspects. Depending on its spectrum and the way it affects a signal and mechanisms generating it, the noise can be categorized into many different types and forms. However, despite the existence of many different variations of noise sources, we do not need to delve into their physical properties in order to describe their ultimate impact on system performance. We can rely on a simplified noise model of a system that uses a single theoretical noise generator described by the key figure of merit known as noise figure (NF). It quantifies the degradation of the signal-to-noise ratio (SNR) caused by the system and defined as the logarithmic ratio of SNR at the output to that at the input. Noise figure expressed in a linear scale is called noise factor. This is the key attribute of any RF system that can govern its overall performance.

In the case of a simple linear passive device, the noise figure is equal to its insertion loss defined by $|S_{21}|$. In more complex RF systems consisting of multiple active and passive components, described by their individual noise factors, F_i, and power gains, G_i, the noise cascades down the signal chain according to the Friis formula (assuming that the impedances are matched at each stage):

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}} \qquad (2)$$

From this we can conclude that the first two stages in an RF signal chain are the main contributors to the overall noise figure of the system. This is why the components with the lowest noise figure, such as low noise amplifiers, are used at the front ends of receiver signal chains.

If we now consider devices or systems used specifically for signal generation, for characterization of their noise performance, it is more common to refer to signal properties affected by their noise sources. These properties are phase jitter and phase noise, which are interrelated terms indicating signal stability in time (jitter) and frequency domain (phase noise). Which one is preferred depends usually on the application—for instance, in RF communications it is common to use the term phase noise, while in digital systems we will often see the term jitter. Phase jitter defines small fluctuations in the phase of a signal, while the phase noise describes its spectral representation, which is characterized by the noise power level relative to the carrier contained in 1 Hz bandwidth at various offsets from the carrier, and considered to be uniform across this bandwidth (see Figure 5).

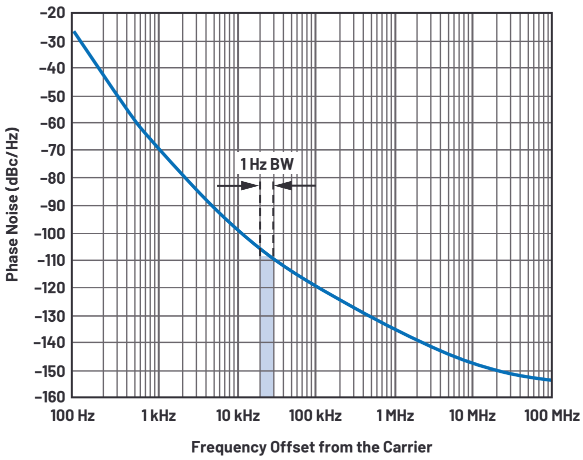

Figure 5. An example of a phase noise characteristic.

Multifold Derivatives

The most important figures of merit that we have considered so far underlie a broad range of derivative parameters utilized for performance quantification of RF signal chains in various application domains. For example, the combination of the terms noise and spurious results in the definition of the term dynamic range (DR). It describes the operating range for which a system has desirable characteristics. As shown in Figure 4, if this range is limited at the low end by noise and at the high end by the compression point, we talk about the linear dynamic range (LDR); and if its high end is defined by the maximum power level for which intermodulation distortion becomes unacceptable, we talk about the spurious-free dynamic range (SFDR). It should be noted that, depending on the application, actual definitions of the terms LDR and SFDR may vary.[2]

The lowest signal level that a system can handle to produce an output signal with a specified SNR defines another important characteristic typical for receiver systems known as sensitivity. It depends primarily on the system noise figure and signal bandwidth. The noise inherent to the receiver limits its sensitivity as well as other system specifications. For instance, phase noise or jitter in data communication systems will result in deviation of the constellation points in the eye diagram from their ideal locations, degrading the system's error vector magnitude (EVM) and contributing to higher bit error rate (BER).

Conclusion

There are numerous properties and performance metrics that can be used for the characterization of RF signal chains. They address different system aspects, and their importance and relevance may vary from one application to another. Although it is not possible to consider all of them in one article, substantial understanding of the fundamental characteristics discussed in this part of our discourse will allow an RF engineer to easily translate them into some of the key requirements and specifications of the target application whether it is a radar, communication, measurement, or any other RF system.

Analog Devices addresses the most demanding requirements of RF applications with the industry's broadest portfolio of RF, microwave, and millimeter wave solutions coupled with deep system design expertise. The widest range of discrete and fully integrated ADI solutions from antenna to bits unlocks the entire spectrum from DC to beyond 100 GHz and offers best-in-class performance, enabling multifaceted RF and microwave designs in communications, test and measurement instrumentation, industrial, and aerospace & defense applications.

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[2] David M. Pozar. *Microwave Engineering*, 4th Edition. Wiley, 2011.

About the Author

Anton Patyuchenko received his Master of Science in microwave engineering from the Technical University of Munich in 2007. Following his graduation, Anton worked as a scientist at German Aerospace Center (DLR). He joined Analog Devices as a field applications engineer in 2015 and is currently providing field applications support to strategic and key customers of Analog Devices specializing in RF applications. He can be reached at anton.patyuchenko@analog.com.