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RF Signal Chain Discourse—Part 2: Essential Building Blocks

Anton Patyuchenko, Field Applications Engineer

Discrete and integrated components represent functional building blocks underpinning RF signal chains across all application domains. In Part 1 of our discourse we considered the main properties and performance metrics used for their characterization. To achieve the desired performance, however, an RF system engineer must also have a solid understanding of a broad variety of RF components, the choice of which will determine the overall performance of the complete RF signal chain in the final application.

Part 2 of our discourse will detail a concise overview of the key types of different components used in a typical RF signal chain, depicted in its generic form in Figure 1. We will limit our discussion to most common RF integrated circuits (ICs), relying on the classification criteria relevant for the signal chain definition on a system level. This assessment includes RF amplifiers, frequency generation ICs, frequency multipliers and dividers, mixers, filters, and switches, as well as attenuator and detector components, and it can serve as an RF system designer's guide to select the right building blocks for the target application.

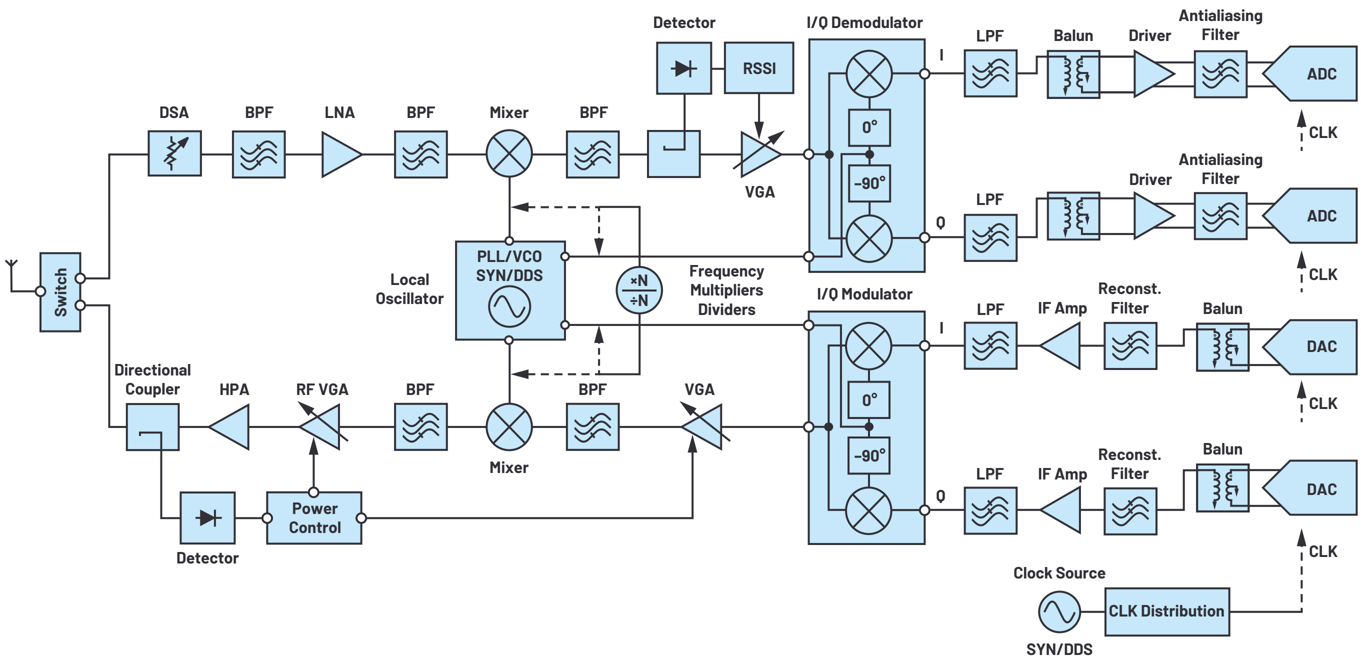


Figure 1. A generic RF signal chain.

RF Amplifiers

The key function of an amplifier is to increase the level of an input signal to produce a greater signal at the output. The main attribute of any RF amplifier is its gain, which describes the ratio of the output power to the input power. However, an optimum amplifier design is always a trade-off between its gain, noise, bandwidth, efficiency, linearity, and other performance parameters. Considering these characteristics as the main classification criteria, we can distinguish between various types of amplifiers designed to offer performance optimized for specific application scenarios.

Low noise amplifiers (LNAs) are optimized to increase the level of low power signals without introducing significant noise. The noise figure (NF) of a good LNA can be less than 1 dB in the sub-GHz range and a few dB at higher frequencies. Since the overall noise figure of a signal chain is dominated by its first stages, LNAs are often used at the front end of a receiver to maximize its sensitivity. On the contrary, power amplifiers (PAs) are usually used in the output stages of a transmit signal chain. They are optimized for power handling to deliver high output power with high efficiency while maintaining low heat dissipation.

High IP3, or high linearity amplifiers, share similar characteristics with PAs as they offer a high dynamic range performance. However, this type of amplifier is optimized for linearity and preferred to PAs in applications where signals with high peak-to-average power ratios are used. For instance, in communication systems relying on vector modulated signals, high linearity amplifiers allow minimization of distortions, which is critical for achieving low bit error rates.

Variable gain amplifiers (VGAs) address high dynamic range applications, too, but with a wide range of signal levels. VGAs accommodate signal variations by gain regulation to control transmit or adjust received signal amplitude. Digitally controlled VGAs are chosen if the control parameters are available on a data bus and a stepwise gain adjustment is not critical for the application. An analog controlled VGA is the solution of choice when digital control data is not available, or the application cannot tolerate the step disturbance. VGAs are often used for automatic gain control (AGC) or for compensation of gain drift due to variations in temperature or characteristics of other components.

LNAs, PAs, VGAs, and other types of RF amplifiers can also be classified as wideband amplifiers if they are designed to operate over a broad range of frequencies (up to several octaves). Such amplifiers offer wideband amplification with a moderate gain, which is often needed in front-end stages of the main signal path in broadband applications. Wideband amplifiers often rely on distributed amplifier circuit designs and offer a large gain-bandwidth product, usually at the cost of efficiency and noise.

Some RF amplifiers also belong to the general category of driver amplifiers (or just drivers). A driver is an amplifier used to control another component such as the second amplifier, mixer, converter, or other element in a signal chain. The main function of the driver amplifier is to regulate certain operational parameters to ensure optimum operational conditions for the attached component. Driver amplifiers do not necessarily have to be designed to drive a specific component, but any RF amplifier regardless of its type can be considered a driver if its use case suggests fulfillment of a driving function. Similarly, we can also recognize the general category of buffer amplifiers (or just buffers), which are used to prevent the signal source from being affected by the load. For instance, buffer amplifiers are often utilized to isolate a local oscillator from a load to minimize the undesired impact of the load impedance variations on the performance of the oscillator.

Considering a classical superheterodyne architecture, in the broad category of RF amplifiers we can also distinguish local oscillator (LO) and intermediate frequency (IF) amplifiers. The main difference between these amplifiers is their functional purpose in the signal chain. The LO amplifiers are used in the LO path to ensure the required LO drive level for a mixer (they are usually called LO drivers or LO buffers), while the IF amplifiers are designed to operate at lower frequencies, which makes them a solution of choice for the intermediate frequency stages of a signal chain.

A gain block is another general type of amplifier that can be used in RF, IF, or LO signal paths, as it provides good gain flatness and return loss. Its design often incorporates internal matching and biasing circuits, which simplify its integration into a signal chain by requiring a minimal number of external components. Gain block amplifiers can serve both general-purpose as well as specific needs covering various frequencies, bandwidths, gains, and output power levels.

The broad diversity of RF amplifiers is certainly not limited to only those discussed in this article. Based on amplifier characteristics we can recognize many other types of RF amplifiers that offer different combinations of performance characteristics—for example, limiting amplifiers deliver stable compressed output power over a wide input power range, low phase noise amplifiers are optimized for high signal integrity applications, and logarithmic amplifiers are typically in essence RF-to-DC converters fulfilling the RF detection function (see the section "RF Detectors"), just to name a few. The summary of the key amplifier types we have discussed in this discourse is given in Table 1.

Table 1. Summary of Some Key Types of RF Amplifiers

Amplifier Type	Distinguishing Features
Low Noise Amplifier	Amplifies low power signals introducing minimum noise
Power Amplifier	Delivers high output power with high efficiency
High IP3 Amplifier	Provides high linearity performance for signals with high crest factor
Variable Gain Amplifier	Handles a wide range of signal levels by offering adjustable gain
Wideband Amplifier	Operates over a wide range of frequencies
Driver Amplifier	Regulates operational conditions for the attached component
Buffer Amplifier	Minimizes effects of load impedance variations on the signal source
Gain Block	Offers good gain flatness and return loss, requiring minimum external components
Limiting Amplifier	Delivers stable compressed output power across a wide input range
Low Phase Noise Amplifier	Offers minimum additive phase noise

RF amplifiers can also be classified based upon other criteria such as their features, operational modes (amplifier classes), assembly, or process technology, which extends their full classification beyond the scope of this article. However, in this section we have considered some of the most common categories of RF amplifiers adapted in the industry for the definition of RF signal chain architectures.

Frequency Generation ICs

Frequency generation components can serve a variety of different functions in an RF signal chain including frequency conversion, waveform synthesis, signal modulation, and clock signal generation. Depending on the target use case of an IC there are a few performance criteria that govern its choice including the output frequency range, spectral purity, stability, and the tuning speed. There is a broad selection of frequency generation components optimized for various use cases, among which are voltage controlled oscillator (VCO), phase-locked loop (PLL), integrated frequency synthesizer, translation loop, and direct digital synthesis (DDS) ICs.

A voltage controlled oscillator (VCO) produces an output signal whose frequency is controlled by an external input voltage. A VCO's core can be based on different types of resonators. Single-core VCOs using high quality resonators offer a low phase noise performance over a limited frequency range, whereas the oscillators designed for lower quality target a wideband operation with mediocre noise characteristics. Multiband VCOs using several switched high quality resonator circuits offer an alternative solution by providing wideband operation and low phase noise performance, which is, however, achieved at the expense of a slower tuning speed limited by the time required to switch between different cores. VCOs are usually used in conjunction with phase-locked loops.

A phase-locked loop (PLL) or PLL synthesizer is a circuit that ensures the stability of a VCO output frequency required in many frequency synthesis and clock recovery applications. As depicted in Figure 2a, a PLL incorporates a phase detector that compares a divide-by-N version of the VCO frequency to the reference frequency and uses this difference output signal to adjust the DC control voltage applied to the tuning line of the VCO. This allows for instantaneous correction of any frequency drift and thus maintains stable operation of the oscillator. A typical PLL IC includes an error detector—a phase frequency detector (PFD) with a charge pump—and a feedback divider (see dashed line area in Figure 2a), and it still requires an additional external loop filter, a reference frequency, and a VCO to form a complete feedback system for stable frequency generation. The realization of this system can be significantly simplified by using synthesizer ICs featuring an integrated VCO.[1]

Synthesizers with integrated VCO combine a PLL and a VCO in a single package and require only an external reference and a loop filter to realize the desired function. An integrated PLL synthesizer is a versatile solution with a broad spectrum of digital control settings for accurate frequency generation. It may often include integrated power splitters, frequency multipliers, frequency dividers, and tracking filters to permit up to several octaves of frequency coverage beyond the fundamental range of the integrated VCO. Intrinsic parameters of all these components determine output frequency range, phase noise, jitter, lock time, and other characteristics representing overall performance of the synthesizer circuit.

A translation loop is another type of synthesizer solution based on the PLL concept but implemented using a different approach. As shown in Figure 2b, it uses an integrated downconversion mixing stage instead of an N-divider in the feedback loop to set the loop gain to 1 and minimize the in-band phase noise. Translation loop ICs (see the dashed line area in Figure 2b) are designed for highly jitter sensitive applications and, in combination with an external PFD and an LO, enable a complete frequency synthesis solution offering an instrument-grade performance in a compact form factor.

A direct digital synthesis (DDS) IC is an alternative to integrated PLL synthesizers, and realized using a different concept. The basic DDS architecture is schematically depicted in Figure 2c. It is a digitally controlled system that includes a highly accurate reference frequency representing a clock signal, a numerically controlled oscillator (NCO) creating a digital version of the target waveform, and a digital-to-analog converter (DAC) delivering the final analog output. DDS ICs offer rapid hopping speeds, fine tuning resolution of the frequency and phase, and low output distortion, which makes them an ideal solution for applications where superior noise performance and high frequency agility are of primary importance.[2]

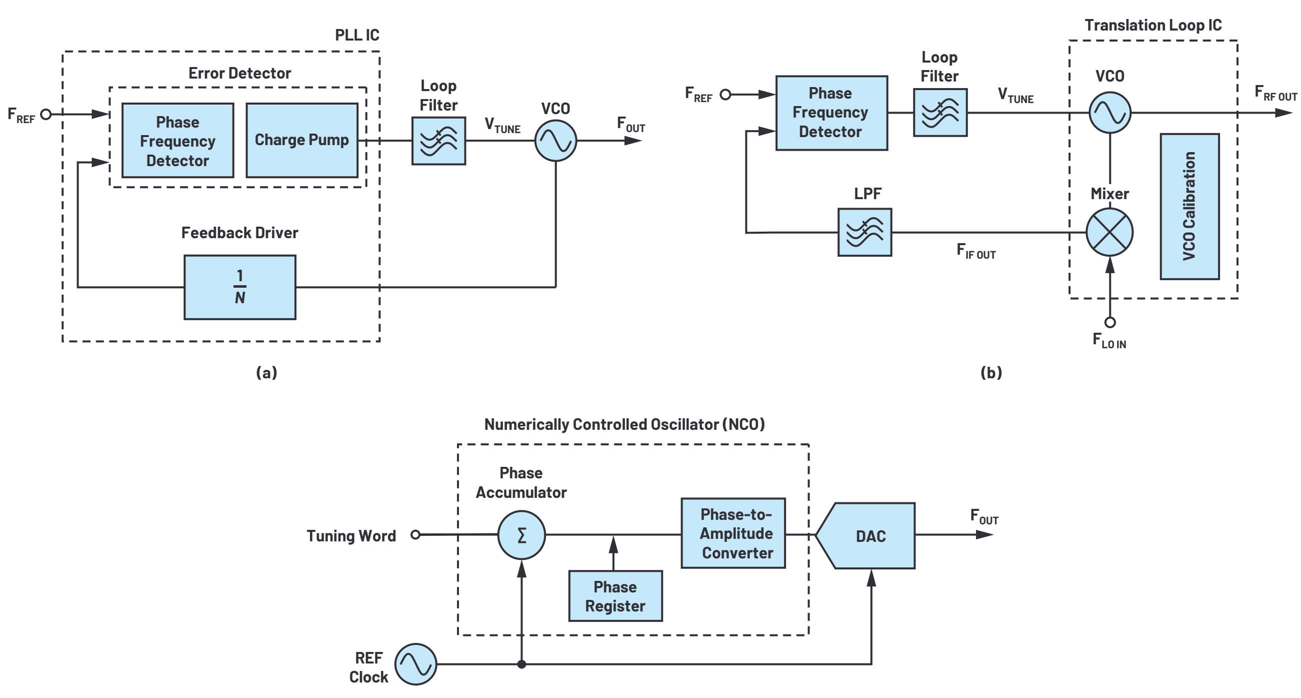


Figure 2. Simplified block diagrams of the (a) phase-locked loop, (b) translation loop, and (c) direct digital synthesizer.

Frequency generation components find their use in a broad range of applications that impose different requirements on their performance. For example, communication systems require low in-band noise to maintain low error vector magnitude (EVM), spectrum analyzers rely on local oscillators with fast lock time to realize rapid frequency sweep, and high speed converters need a low jitter clock to ensure high SNR performance.

Frequency Multipliers

Frequency multipliers enable the generation of higher frequencies when fundamental frequency oscillators cannot be used to cover the desired range. These components exploit nonlinear properties of their elements to produce an output signal whose frequency is a harmonic of an input signal. Depending on the order of the target output harmonic, we can distinguish between doublers, triplers, and quadruplers as well as multipliers of higher orders.

Different types of nonlinear elements used to achieve frequency multiplication allow us to distinguish between passive multipliers relying on diode circuits and active multipliers utilizing transistors. Active multipliers require an external DC bias, but they offer a number of significant advantages over passive devices including conversion gain, lower input drive levels, and better suppression of the fundamental and spurious frequencies.

Frequency multiplier ICs are widely used, particularly in conjunction with VCOs, in PLL synthesizer designs or as a part of a local oscillator signal path, offering a simple and inexpensive solution to increase frequencies. However, all types of frequency multipliers suffer from the same disadvantage: they degrade phase noise by at least 20log(N) dB, where N is a multiplication factor. For example, a doubler will increase the phase noise level by at least 6 dB, which can be critical in high speed converter clocking and other phase noise and jitter sensitive applications.[3]

Frequency Dividers and Prescalers

Frequency dividers transform a higher input frequency into a lower output frequency. Nowadays the great majority of these types of components are digital circuits realized using binary counters or shift registers. They are widely incorporated in clock distribution circuits and PLL synthesizer designs, finding their use in many applications. Frequency dividers can have a fixed divide ratio (such dividers are also known as prescalers) or a programmable divide ratio. Frequency division by a divide ratio of N improves the phase noise of the output signal by 20log(N) dB. However, this improvement is limited by the additive phase of a frequency divider itself, which originates within its active circuitry and adds up to its output. A good frequency divider has low additive phase, which, along with a low harmonic content, belongs to some of its key characteristics.

RF Mixers

An RF mixer in its basic form is a 3-port component that uses a nonlinear or time-varying element to produce an output signal containing the sum and difference frequencies of two input signals. We can generally distinguish between passive and active mixers. Passive mixers use a diode element, or a FET transistor operated as a switch, while active mixers rely on transistor-based circuits to achieve frequency conversion. Passive mixers can offer wide bandwidth and high linearity performance, do not require an external DC bias, and have generally better noise figure than active mixers. However, passive mixers exhibit conversion loss and depend upon high LO input power, as opposed to active mixers that provide gain and require significantly lower LO drive levels. Alternative designs realized as a downconverter or upconverter can combine a passive mixer core and an active circuitry to achieve conversion gain without compromising on NF and linearity.[4]

Mixer ICs can come in a variety of different designs, the most basic being the single-ended (or unbalanced). A conceptual topology of a diode-based single-ended mixer is shown in Figure 3a. Single-ended mixers use only one nonlinear element to accomplish frequency conversion, which provides a simple solution but limited performance due to poor isolation between the ports and high level of spurs. Balanced mixer designs overcome those limitations by utilizing symmetrical properties of their circuits. Depending on the degree of symmetry, balanced mixers can be classified into single balanced, double balanced, and triple balanced. Single balanced mixers (see Figure 3b) consist of two unbalanced mixers combined with either 90° or 180° hybrid. This type of mixer provides high LO-RF isolation, suppression of RF or LO signal, and rejection of even LO harmonics in the output. Further improvement in performance can be achieved with various types of double balanced mixers. A common example, shown in Figure 3c, uses four Schottky diodes in a quad ring configuration with hybrids placed at both RF and LO ports. Double balanced mixers offer high overall performance, which makes them a widely used type of RF mixer IC, as they provide good port-to-port isolation, rejection of both RF and LO frequencies, and suppression of all even RF and LO harmonics.[5] Higher isolation and linearity can be achieved with triple balanced mixers. This type of mixer combines two double balanced designs, forming a higher degree of symmetry to optimize the frequency conversion process, however, at the cost of a significantly increased circuit complexity.

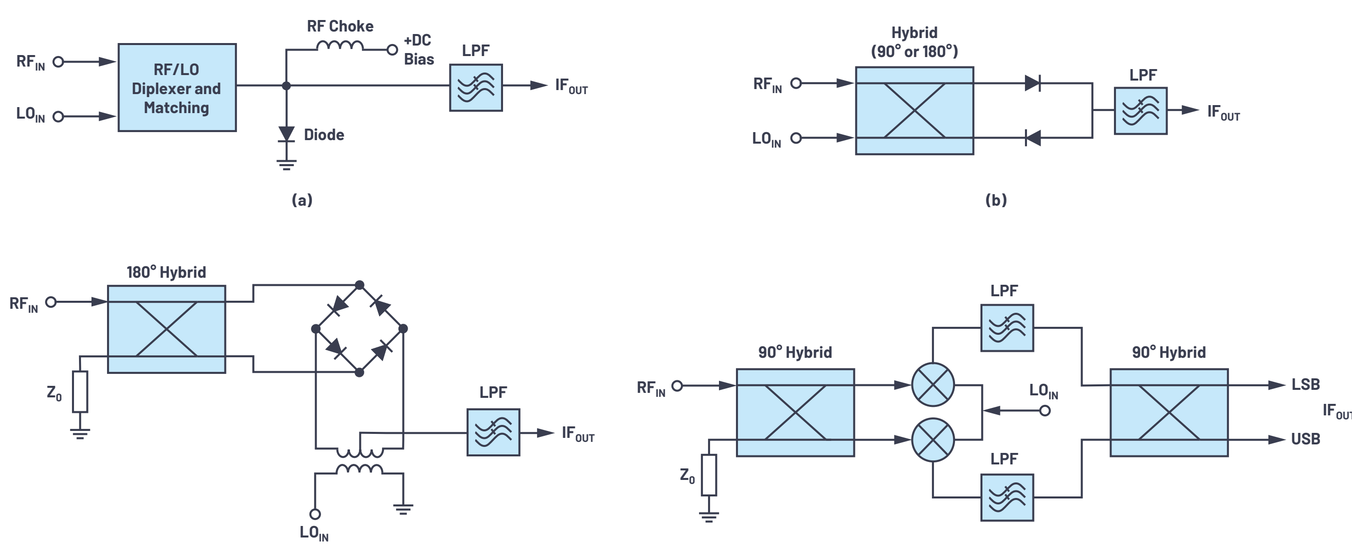


Figure 3. Conceptual topology of a (a) single-ended, (b) single balanced, (c) double balanced, and (d) image reject mixer.

In-phase quadrature (I/Q) mixers represent a separate category of balanced designs. I/Q mixers exploit phase cancellation to eliminate unwanted image signals without external filtering. An ordinary I/Q mixer can usually be operated as an image reject mixer (IRM) in a downconversion mode (see Figure 3d) or as a single sideband (SSB) mixer in an upconversion mode. The I/Q mixers featuring integrated buffer and driver amplifiers are designed for one of the two operational modes only, which classifies them into I/Q downconverters and I/Q upconverters. These mixers are closely related to another type of frequency conversion ICs known as I/Q modulators and I/Q demodulators. I/Q modulators and I/Q demodulators offer a high impedance differential baseband interface designed to be used with data converters, which makes them ideally suited for direct conversion transceiver applications. In particular, they constitute the core of modern highly integrated RF transceiver ICs.[6]

Another common example of a mixer type that we should briefly mention is a subharmonic mixer. It incorporates a subharmonically pumped local oscillator, providing a simple solution for the realization of high frequency RF designs using lower LO frequencies without an external frequency multiplier.

There are many other types of RF mixer implementations relying on active and passive technologies. RF mixer ICs can use sophisticated architectures incorporating various components including PLL/VCO, amplifiers, frequency multipliers, attenuators, and detectors in one package, and provide digital interface to control their functionality.

RF Filters

RF filter ICs find their use in virtually every RF application to select the desired frequencies in the spectrum content, which usually also includes unwanted spurious components generated within a nonlinear signal chain and out-of-band signals originating from outside. The key function of the filter is thus to provide a minimum attenuation for pass-band frequencies of interest, and a maximum attenuation for stop-band frequencies to suppress undesired signals. Common types of filter frequency responses depicted in Figure 4 include a low-pass filter (LPF), high-pass filter (HPF), band-pass filter (BPF), and band-reject filter or band-stop filter (also called a notch filter if its stop band is narrow).

Most RF applications require filtering across multiple frequency bands, which can be realized using switched filter banks. This type of solution, which incorporates switches and fixed bandwidth filters in one module, can be designed to deliver excellent performance in terms of stop-band rejection, linear dynamic range, and switching speeds. However, conventional switched filter banks have limited band selection capabilities, and they are typically large and costly. Compact tunable filter ICs featuring continuous analog or digital tuning function overcome those limitations, which makes them an attractive alternative to switched fixed filter banks for multiband operation in many applications. Analog tunable filters provide voltage control for adjustment of center and/or cutoff frequencies, whereas the desired characteristic of digital tunable filters can be configured via digital control interface. Tunable filters can offer exceptional pass-band characteristics, good stop-band rejection, wide tuning ranges, and fast settling times to meet the demanding requirements of a broad range of today's RF applications.

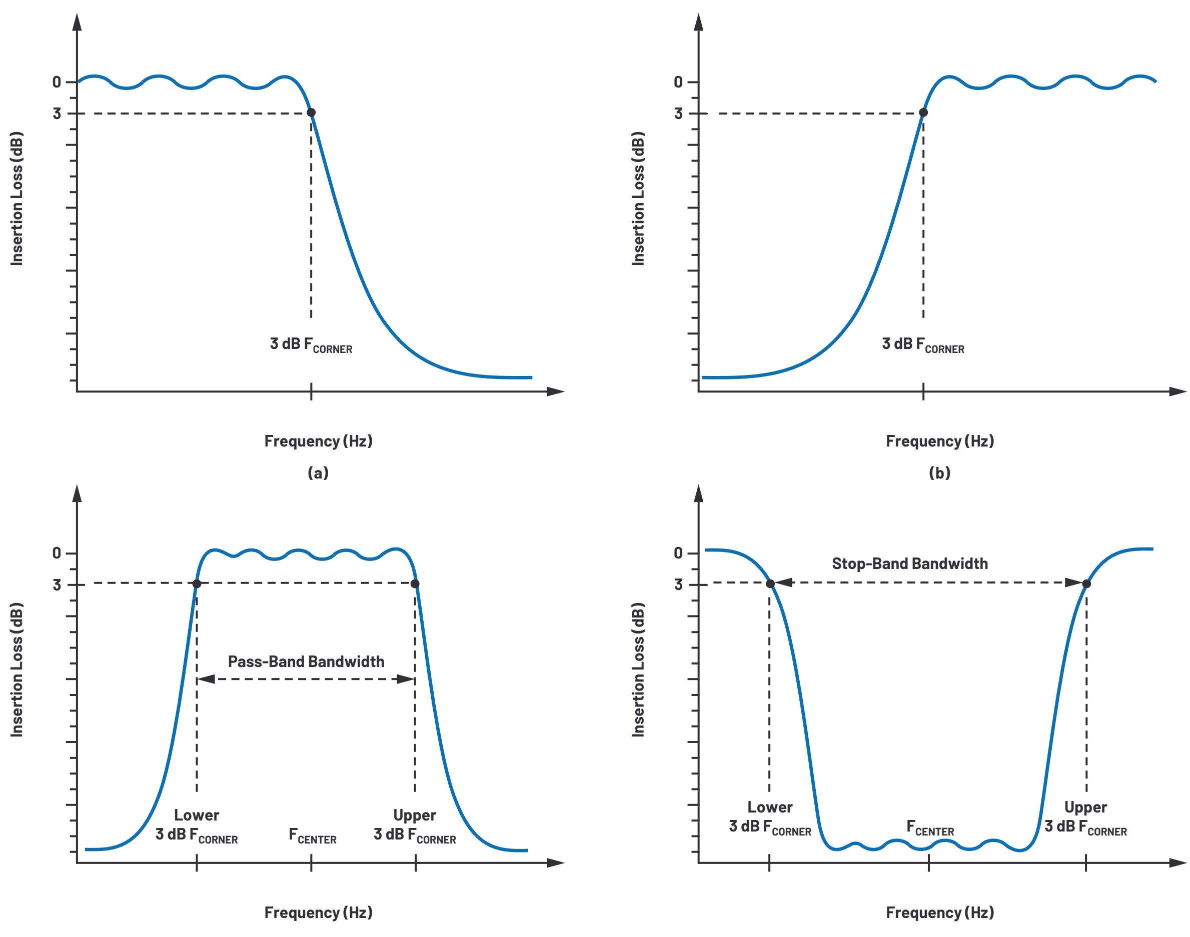
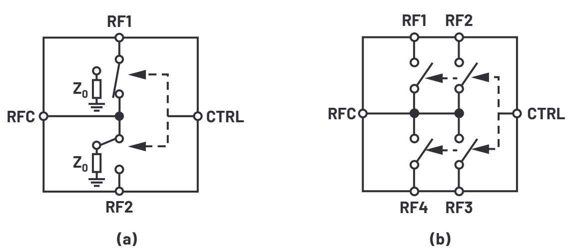


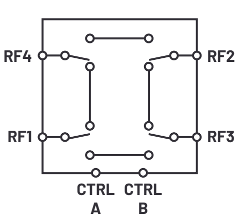
Figure 4. Filter frequency responses: (a) low-pass filter, (b) high-pass filter, (c) band-pass filter, and (d) band-stop filter.

RF Switches

An RF switch is a control component used to route high frequency signals through the signal chain. Its key function can be realized with different types of switching elements including PIN diodes, FET transistors, or micromachined cantilever beams. Depending on how the switching elements are arranged, the switch design can have a different number of poles (separate circuits controlled by the switch) and throws (separate output paths the switch can adopt for each pole). Single-pole, n-throw (SPnT) switches route signals from one input to n outputs. For example a single-pole, single-throw (SPST) switch connects one input to one output providing a simple on-off functionality, a single-pole, double-throw (SPDT) switch toggles one input with two outputs (see Figure 5a), and a single-pole, four-throw (SP4T) switch routes the input signal to four output paths (see Figure 5b). RF switches can also have multiple poles, and this type of switch is called a transfer switch (see Figure 5c). The most common example is a double-pole, double-throw (DPDT) configuration with two separate circuits that can be connected to one of the two output paths.

RF switch designs can have more complex topologies combining multiple switches of a lower order. These ICs are known as switch matrix or crosspoint switches. They provide flexible routing of RF signals between multiple inputs and multiple outputs.





Control Input		Signal Path State			
CTRL A	CTRL B	RF4 RF2	RF1 RF3	RF4 RF1	RF2 RF3
Low	High	On	On	Off	Off
High	Low	Off	Off	On	On

(c)

Figure 5. Examples of RF switches: (a) absorptive SPDT, (b) reflective SP4T, and (c) control transfer switch with a truth table example. (Note: RFC = RF common port, CTRL = control voltage port).

Regardless of the switch configuration, we can generally distinguish between reflective switches and absorptive switches (also known as nonreflective or terminated switches). The main difference between them is that the absorptive switches incorporate a matched load used to terminate output ports in off-state to minimize voltage standing-wave ratio (VSWR) (see Figure 5a). This feature allows the absorptive switches to maintain good return loss in both switch modes, which is something reflective switches cannot offer. However, this advantage of absorptive switches comes at the cost of their lower power handling capability and higher circuit complexity compared to reflective switches.

RF switch ICs can be implemented in a number of different technologies including silicon-based semiconductors CMOS and SOI, compound semiconductors GaAs and GaN, and microelectromechanical systems (MEMS).[7,8] Each technology offers various trade-offs between key performance specifications such as frequency range, power handing capability, isolation, insertion loss, switching speed, and settling time. For example, GaAs is preferrable for high temperature performance, GaN is widely used in high power applications, and the silicon-based process prevails in settling time, integration capabilities, lower frequency characteristics, and higher ESD robustness.[7] The alternative MEMS technology offers a micromechanical relay in a small chip scale package. It uniquely enables DC precision performance with high linearity and power, trading off switching speed, finite cycle lifetimes, and hot-switching limits.

RF Attenuators

An RF attenuator reduces the strength of RF signals, and thus fulfills the opposite function of an amplifier. It is a control component used to adjust gain and balance signal levels in the signal chain. RF attenuator ICs are typically absorptive (transmission-type) devices. We can generally distinguish between fixed attenuators, which have an unchanging attenuation level, and variable attenuators, which allow its adjustment. Variable attenuator ICs featuring a set of discrete attenuation levels are called digital step attenuators (DSAs), and they are usually employed for coarse signal calibration, which is limited by the predetermined attenuation step size. For fine signal control, voltage variable attenuators (VVAs) are used. As opposed to DSAs, VVAs offer continuous adjustment of the attenuation level, which can be set to any value within the given range. All types of RF attenuators should deliver flat attenuation performance with good VSWR across the operational frequency range, while the DSAs must also ensure glitch-free operation to reduce signal distortions during state transitions.[7]

RF Detectors

An integrated RF detector in its basic form is a 2-port device providing an output voltage signal proportional to the RF signal power applied to its input. As opposed to discrete diode-based detector implementations, integrated RF detectors offer a number of out-of-the-box advantages including stable output voltage over wide temperature range, easier device calibration, and a buffered output for a direct interface with an ADC.[9] Most common RF detector ICs are scalar detectors utilized for a broad variety of applications where measurement of RF signal power magnitude is required. The main types of scalar detectors include rms power detectors, logarithmic detectors, and envelope detectors.

RMS power detectors provide an accurate rms representation of the real signal power applied to the RF input. There are rms detectors with a linear response, whose rms output is a linear-responding DC voltage, and logarithmic rms detectors with a "linear in dB" response, whose output voltage changes by the same amount for every dB change in true RF input power. Both types of rms detectors are ideally suited for waveform independent power measurement of complex modulated signals with high crest factor changing over time in applications that do not require fast response time performance. They are typically used for average power monitoring, transmitter signal strength indication (TSSI), received signal strength indication (RSSI), and automatic gain control (AGC).

Logarithmic detectors (also known as logarithmic amplifiers) convert an input RF signal to an accurate log-linear DC output voltage. Log detectors offer a very high dynamic range operation. This is achieved using a successive compression approach, which relies on a cascade of limiting amplifiers coupled to detectors whose outputs are summed at the output stage of the cascaded topology. As the input power increases, successive amplifiers move into saturation one by one, thus creating an approximation of the logarithm function. Log detectors are very well suited for high dynamic range applications including RSSI and RF input protection.

[A successive detection logarithmic video amplifier (SDLVA)] is a special type of logarithmic detector that offers flat frequency response and superior rise/fall and delay times, which makes it the solution of choice for applications demanding very high speed performance including instantaneous frequency measurement, direction finding receivers, and electronic intelligence applications.

Envelope detectors (also known as peak detectors or AM detectors) provide a baseband output voltage proportional to the instantaneous amplitude of the RF input signal. Envelope detector ICs are usually realized using fast switching Schottky diodes, which makes them an ideal solution for lower dynamic range applications requiring very fast response times. Typical applications of envelope detectors include efficiency enhancing envelope tracking in PA bias control, PA linearization, fast excessive RF power protection, high resolution pulse detection, and LO leakage correction of I/Q modulators.

Apart from scalar detectors, we can also recognize another category of integrated detectors known as vector power measurement ICs. They offer extended capabilities going beyond scalar power measurement functionality.[10] Vector power measurement detectors can measure multiple parameters of a signal including its magnitude, phase, and traveling direction along the transmission path (forward and reverse). This type of device is an ideal solution for inline measurement of scattering parameters in numerous applications including antenna tuning in wireless transmitters, built-in test in modular systems, and materials analysis.

Conclusion

In the second part of our RF signal chain discourse we discussed and classified some of the key RF ICs representing essential building blocks of a typical RF signal chain. However, in this overview we have only scratched the surface of the multifaceted diversity of types and forms of RF components. Increasing complexity of RF systems requires more complete signal chain solutions, which results in development of numerous IC designs consolidating multiple functional blocks in the same package or on one die. These devices can integrate mixers, PLLs, VCOs, amplifiers, detectors, and other components to deliver significantly advanced functionality in a compact form factor and offer simpler designs, reduced power consumption, lower cost, and shorter development cycles.

Analog Devices provides the broadest portfolio of RF integrated circuits in the industry, covering the complete frequency spectrum from DC to beyond 100 GHz and fitting nearly all of the functional blocks in a signal chain.[11] The widest array of ADI offerings spans from amplifiers, mixers, filters, and other standard IC components, all the way through mixed-signal analog front ends and system-in-package (SiP) solutions, which are fully tested and verified as complete subsystems. ADI products deliver best-in-class performance and address the most demanding requirements across a wide variety of RF applications ranging from communication and industrial systems, all the way up to test and measurement equipment and aerospace systems. To support RF engineers in the development process of these applications ADI provides not only RF ICs but also an entire ecosystem including design tools, rapid prototyping platforms, Circuits from the Lab® reference designs, EngineerZone® technical forums, and world-class technical support.

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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.