Mixer Technology For Advanced Communications, Part 1: Mixer Basics

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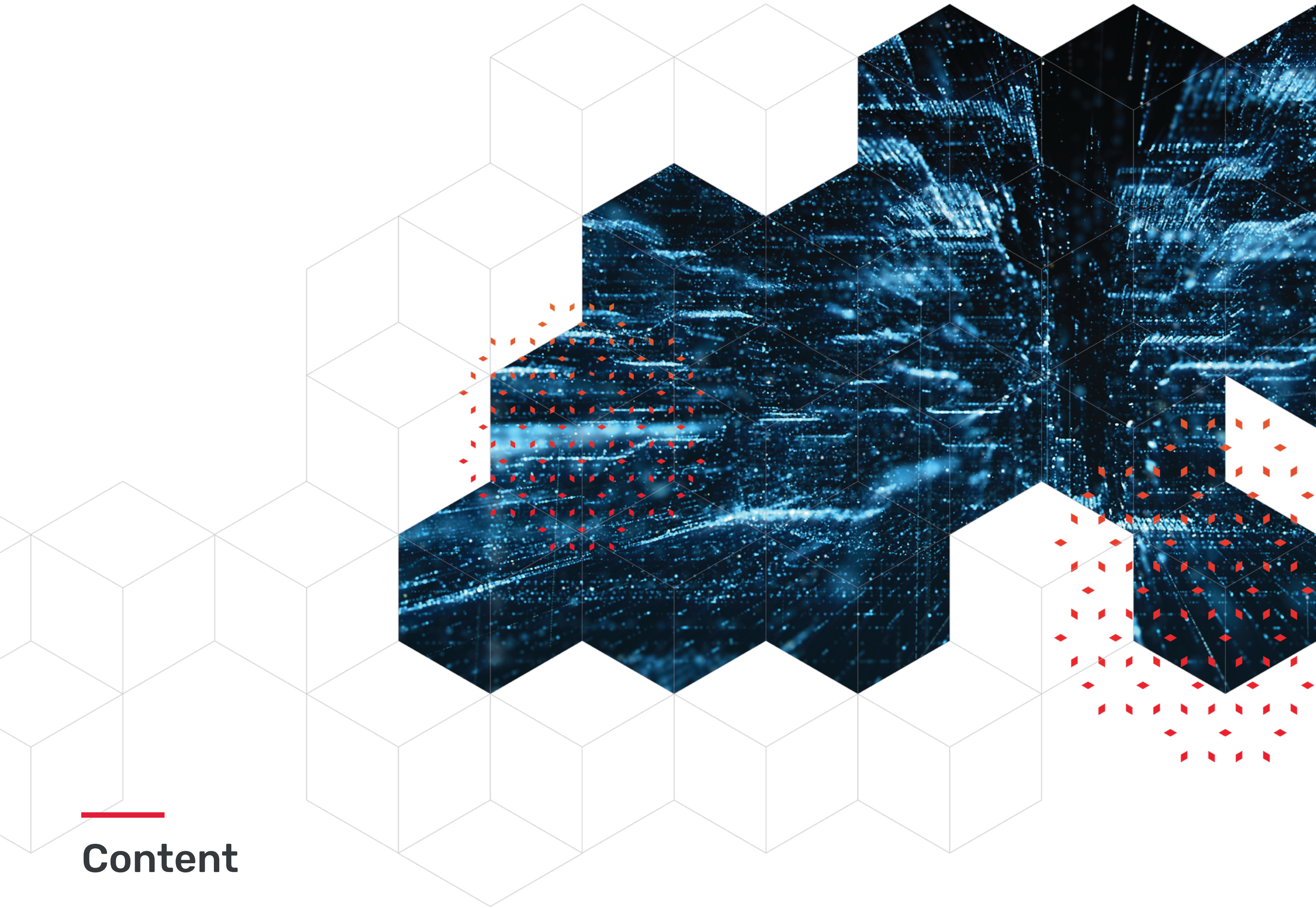


Content

Mixer Technology For Advanced Communications, Part 1: Mixer Basics

Introduction

Mixers are a fundamental component of wireless communications, and their design constraints become increasingly stringent with the demands of next-generation systems such as 5G and 6G. To meet these requirements, RF designers must optimize networks to support ever-increasing data rates while addressing challenges such as signal losses at millimeter-wave frequencies and the noise susceptibility of high-order QAM schemes in OFDM systems.

This white paper is Part 1 of a two-part series on mixer design for advanced communications systems. It introduces the core principles of mixers, including their role, common topologies, and the use of I/Q mixers in modern applications.

Part 2 will expand on this foundation, covering practical design and simulation in Cadence Microwave Office software and demonstrating how the Visual System Simulator works with Microwave Office to perform system-level simulations for receivers and transmitters.

By first establishing this foundation, you can better understand the critical role mixers play in enabling reliable, high-performance communication systems. A clear grasp of their principles and topologies sets the stage for tackling the more advanced design and simulation techniques explored in the second part of this series.

Mixers: An Overview

The Role Mixers Play In The Rf Frontend

Mixers are used in the receiver signal chain to shift frequencies by down-converting the incoming radio frequency (RF) signal to an intermediate frequency (IF), which can then be amplified and demodulated with digital signal processing (DSP) techniques **(Figure 1)**. Downconversion also provides practical benefits, such as managing gain requirements. Many receivers need gains of tens of decibels (dB), and attempting to achieve this in a single frequency stage can create the risk of feedback and oscillation. Distributing the gain across multiple stages mitigates this risk.

In a transmitter, the mixer enables upconversion from IF to RF. These microwave systems operate at frequencies ranging from 1 GHz to 100 GHz. Mixers are used because direct digital generation of modulated RF at such frequencies is generally beyond current signal processing capabilities .

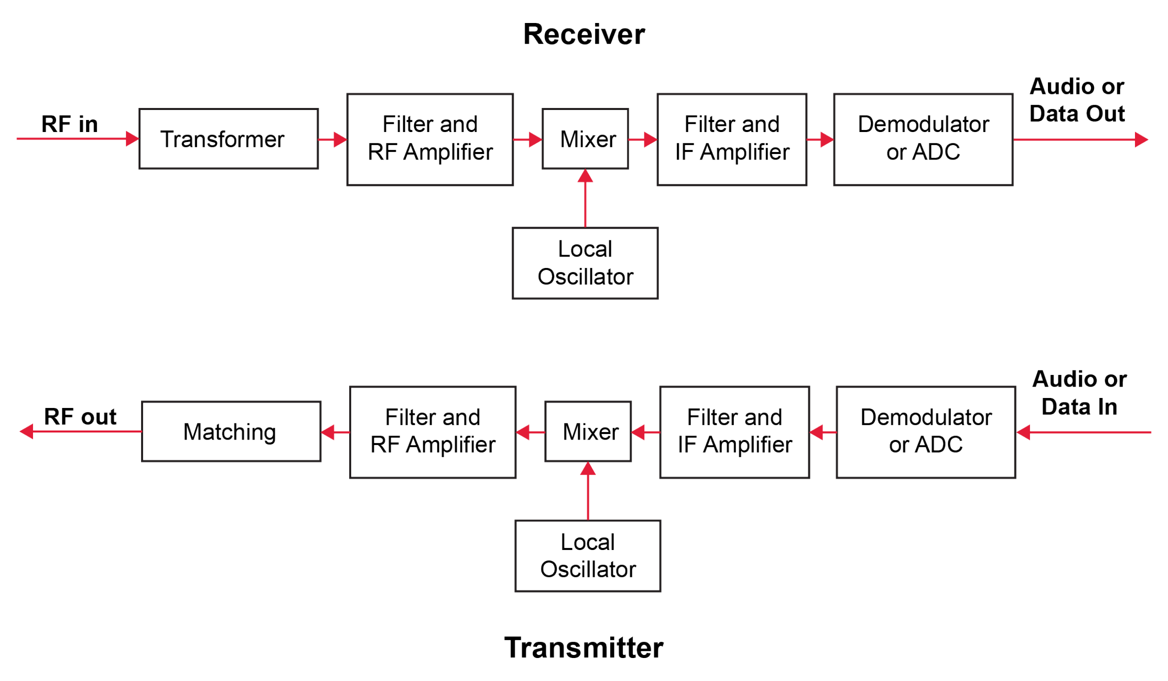
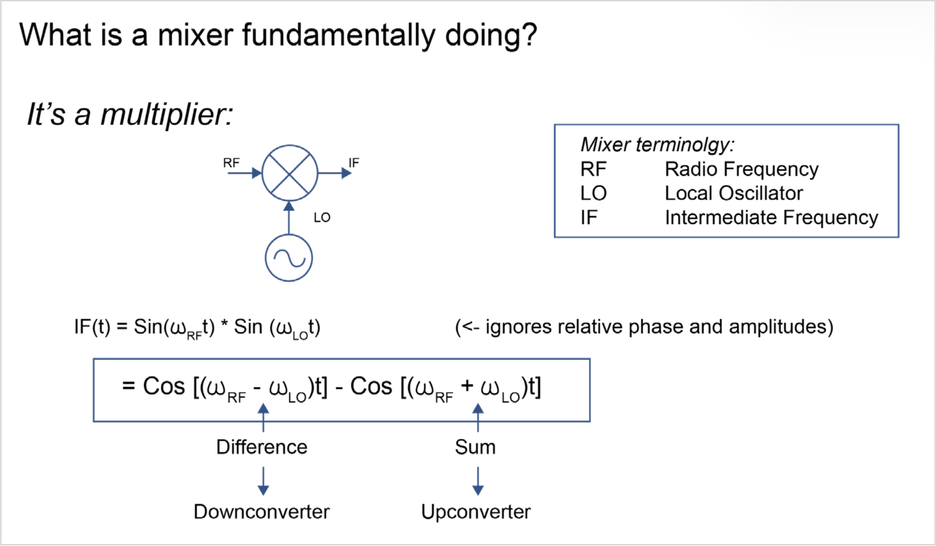


Figure 1: *Receiver and transmitter block diagram. Source: AWR RF ebook*

Mixers In A Nutshell

At their core, mixers function as multipliers. Multiplying two ac signals produces both sum and difference frequency components **(Figure 2)**. For upconversion in a transmitter, the mixer passes the sum component and filters out the difference (low frequency) component. For downconversion in a receiver, the mixer passes the difference component and filters out the sum (high frequency) component.



What is a mixer fundamentally doing?

It's a multiplier:

Mixer terminolgy:

RF	Radio Frequency
LO	Local Oscillator
IF	Intermediate Frequency

IF(t) = Sin(ω_{RF}t) * Sin (ω_{LO}t) (<- ignores relative phase and amplitudes)

$$= \text{Cos}\ [(\omega_{RF} - \omega_{LO})t] - \text{Cos}\ [(\omega_{RF} + \omega_{LO})t]$$

Difference → Downconverter

Sum → Upconverter

Figure 2: *Multiplication of two oscillating signals yields both a sum (upconversion) and difference (downconversion) component. Source: Cadence*

In electrical circuits, a switch is used to achieve frequency multiplication. **Figure 3** a shows an idealized RF switch, where the signal is gated (turned on and off) to control the flow of the RF signal. A square wave drives the switch, toggling it on (1) and off (0), thereby multiplying the signal by the square wave to produce an output containing both sum and difference frequencies.

Illustrated in Figure 3b, the electronic equivalent of a switch is a diode. When the RF input and local oscillator (LO) signals are applied to the diode, it is driven into rectification, provided that the (usually much larger) LO signal has sufficient amplitude. This behavior approximates that of the idealized switch shown in Figure 3a: during the positive cycle of the LO signal, the diode is on, and during the negative cycle, it is off.

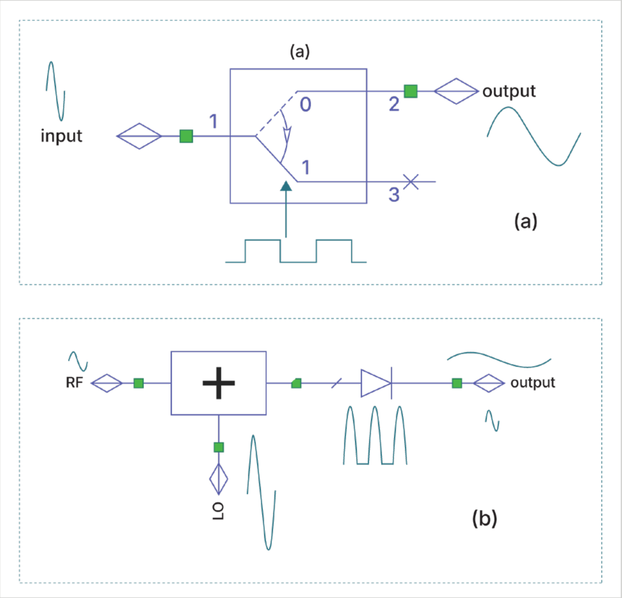


Figure 3: *(a) Ideal switch turned on and off to multiply the input signal with a square wave. This can be applied electronically with a (b) diode that is turned on and off with the LO frequency, offering both the sum and difference frequency components at the output.*

At the diode's output, the signal comprises two components derived from the input signals—the sum frequency and the difference frequency. An appropriate filter can then be used to isolate either component.

However, this analogy omits a critical consideration: diodes are inherently nonlinear, and when two frequency components are applied, the mixing process generates additional intermodulation (IMD) products alongside the desired sum and difference frequencies. Balanced circuit designs can help suppress these distortion products, thereby reducing filtering requirements.

Additional device characteristics also affect mixer design. For example, diodes include a series resistance preceding the ideal diode component, which contributes to the overall noise figure (NF) of the mixer.

It is important to note that most mixers function well in either direction: a signal can be injected at the IF to produce RF output, or at the RF to produce IF output. External factors, such as filtering or other topological features, determine the mixer's specific functionality, i.e., upconversion or downconversion.

Realizing Mixers: GaAs Or CMOS

Mixers can be implemented in several ways:

- Discrete components within multi-chip modules (MCMs)
- RFICs, typically fabricated with CMOS processes (Si or SiGe)
- MMICs, using compound semiconductors such as gallium arsenide (GaAs) or gallium nitride (GaN)

In these implementations, an entire receiver or transmitter can be integrated onto a single microwave substrate and packaged for production.

As with other microwave circuits, compound III–V semiconductors support transistors with very high electron mobility. GaAs substrates are commonly used for mixers operating up to millimeter-wave frequencies, while indium phosphide (InP) can support operation into the terahertz (THz) range. CMOS processes are also employed, often leveraging advanced nodes—such as 65 nm, 32 nm, and 22 nm—to achieve microwave and millimetre-wave performance.

Diode Mixer Topologies

Figure 4 shows the three principal mixer topologies: single-ended or unbalanced, single-balanced (180o coupler or 90° coupler), and double-balanced.

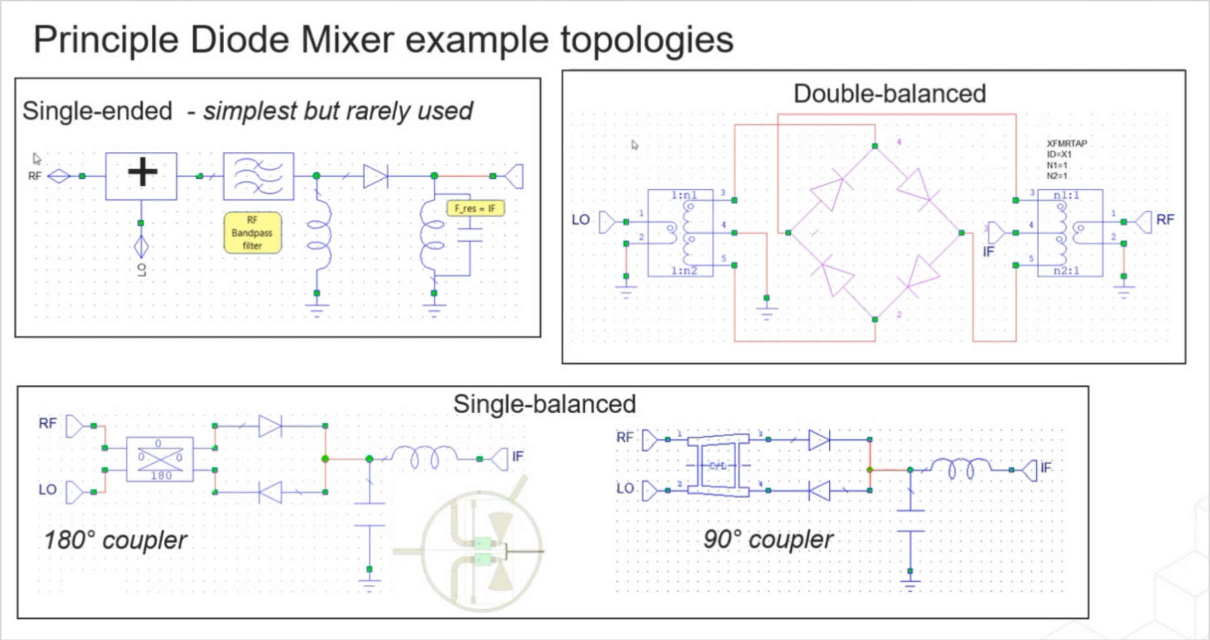


Figure 4: *Principal diode mixer topologies. Source: Cadence*

The single-ended mixer is the simplest topology and closely resembles the diode analogy shown in Figure 3. Depicted in Figure 4, the LO signal is combined with the RF signal, passed through a diode and then through a filter. The filter primarily serves as a DC block, removing the rectified current's DC component. The circuit allows circulating DC to pass through ground, into the first inductor, through the diode, and into the second inductor. The low-pass filter (LPF) at the output then extracts the IF for downconversion. This topology provides no inherent isolation and is therefore seldom used outside of terahertz frequencies, where forming controllable components is challenging.

The single-balanced mixer utilizes either a 90° (quadrature) hybrid coupler or a 180° hybrid coupler to provide inherent isolation between the LO and RF ports. This isolation is critical, as it minimizes the leakage of LO signals back through the RF port. After passing through the coupler, the signals traverse the two diodes and are combined. The two diodes provide inherent DC isolation while allowing a path for circulating DC current. An LPF at the output then extracts the IF. The 180° coupler topology requires longer transmission line elements to achieve the full 180° phase shift, whereas the 90° coupler requires shorter lines but provides less isolation.

The double-balanced mixer is widely used at lower RF frequencies due to its high inherent isolation, with the LO isolated from both the RF and IF ports. However, implementation becomes more challenging at higher frequencies, as the design relies on transformers.

Diode or Transistor?

The semiconductor switch may be implemented using either a diode or a transistor, employing topologies similar to those described previously. Schottky diode–based mixers are often deployed on GaAs substrates due to their simplicity, cost-effectiveness, compact size, and reliable performance. Transistors, such as GaAs FETs or CMOS devices, can also be used. The use of transistors has grown with advancements in MMIC and RFIC technologies, which facilitate high-volume manufacturing and integration.

Transistors are inherently three-terminal nonlinear elements, providing natural isolation between the RF and LO ports, such as the gate and drain. Typically, the FET is operated passively—without a drain–source bias—using the channel conductance as a variable resistor. This approach offers several benefits, including unconditional stability and the suppression of nearly all induced flicker (1/f) noise. In a passive mixer, like a resistive ring topology, the output signal typically exhibits lower power than the input signals. This limitation is addressed in active mixers, which provide improved isolation; however, they introduce higher noise levels.

The Gilbert cell **(Figure 5)** is a widely used example of a four-quadrant multiplier, also known as a double-balanced active FET mixer. In this topology, two single-balanced mixers are cross-coupled at their outputs to minimize RF and LO feedthrough. The Gilbert cell is prevalent in RFICs and is typically implemented using silicon technologies, such as CMOS.

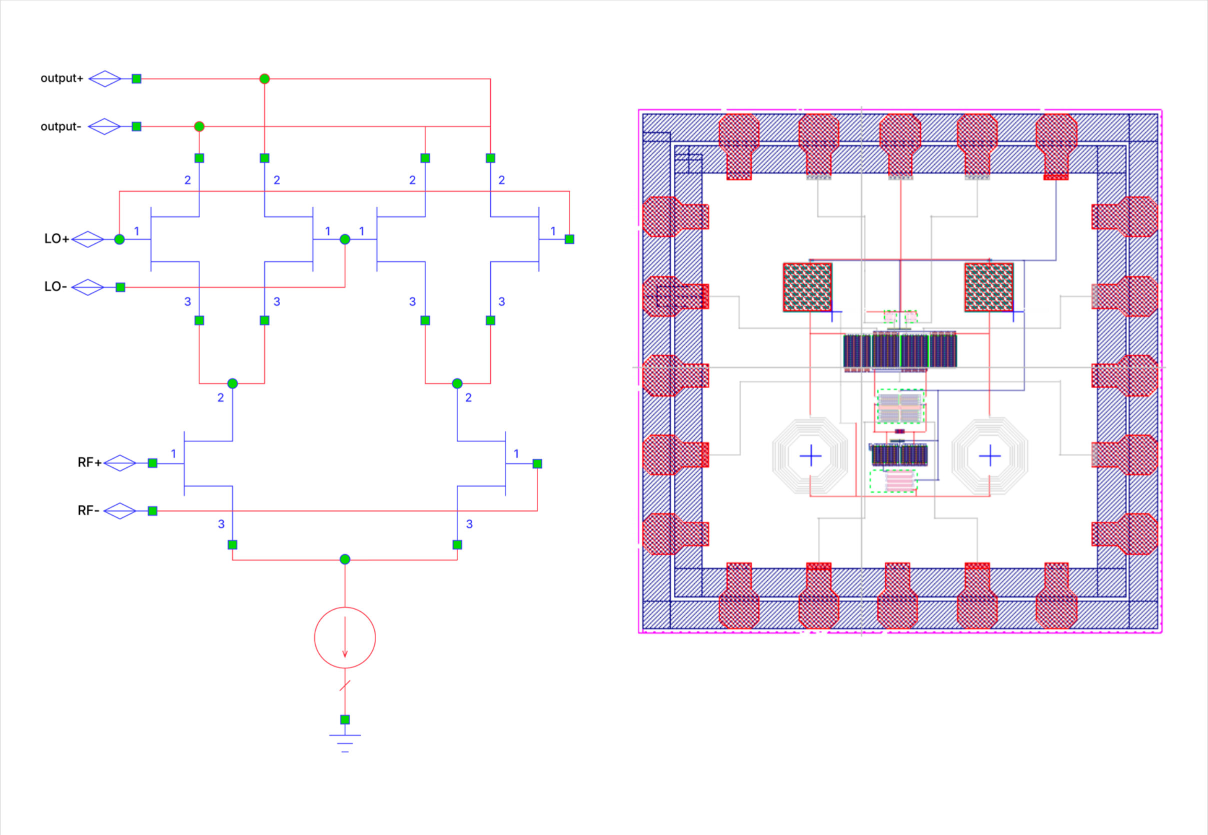


Figure 5: *Typical Gilbert cell mixer topology schematic and layout in RFIC. Source: Cadence*

Mixers For 5g And Beyond

Developing next-generation cellular systems to meet global data demands has been a complex task for mobile network operators (MNOs). The success of 5G in achieving low latency, high capacity, broad availability, and seamless mobility is driven by innovations such as millimeter-wave spectrum utilization through small cells, MIMO base stations, and low-Earth orbit (LEO) satellites. Techniques like carrier aggregation (CA) and dynamic spectrum sharing (DSS) further enhance spectrum efficiency to support high-throughput, low-latency connections.

6G is expected to heavily integrate AI and machine learning for network optimization, resource management, and security, reflecting global trends toward autonomous network functionality. Achieving this will require the use of higher sub-THz frequencies (e.g., 100–300 GHz) and high-performance chipsets capable of executing AI algorithms efficiently.

There is a wide array of mixer topologies available for RF design. In modern communications systems, mixers increasingly need to support larger bandwidths to accommodate higher modulation densities and wider transmit-signal carrier bandwidths. Understanding these emerging system requirements highlights the critical role of mixers in the RF signal chain.

A detailed analysis of key mixer parameters—including conversion gain (CG), linearity (P1dB and IIP3), noise figure (NF), isolation, dynamic range, and bandwidth—is essential for optimizing receiver and transmitter performance.

SSB Upconversion And IR Downconversion

As a fundamental principle, mixing always produces two frequency components: the sum and the difference of the input frequencies.

- $F_{LO} + F_{IN}$
- $F_{LO} - F_{IN}$

A critical aspect of mixer design is the suppression of unwanted frequency components in the output spectrum. During upconversion, mixing produces an undesired sideband, while in downconversion, an image frequency may exist that, when mixed, results in the same intermediate frequency (IF) **(Figure 6)**.

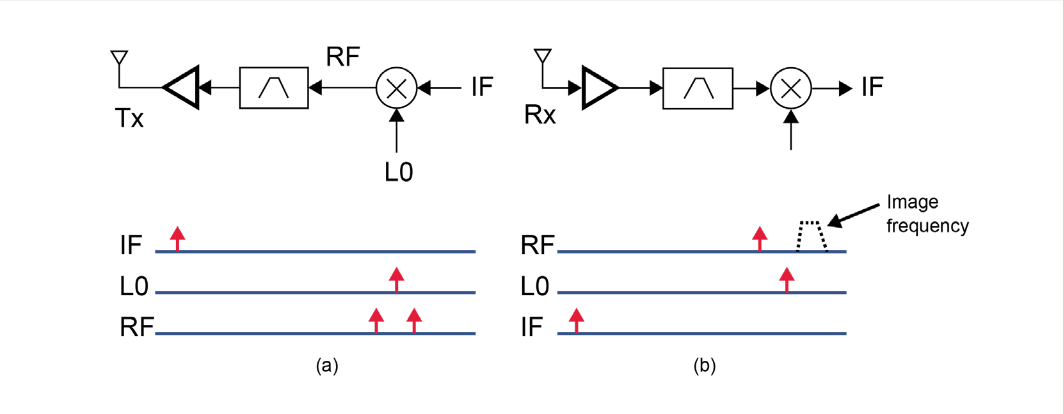


Figure 6: *: Two sidebands occur in mixers during upconversion (a), where one is removed. Downconversion (b) usually involves a sneaky image frequency in the RF, which, when mixed, will produce the same IF, causing problematic interference. Source: RF Integrated Circuit Design*

For upconversions, both $\mathbf{F_{RFa} = F_{LO} + F_{IF}}$ **and** $\mathbf{F_{RFb} = F_{LO} - F_{IF}}$ appear at the **RF** output. One of these components can be filtered out after the mixer in the transmitter to remove the unwanted sideband. This suppression can also be implemented by design within the mixer itself, as in a single-sideband (SSB) mixer.

For downconversion, the desired intermediate frequency, $\mathbf{F_{IF} =|F_{LO}-F_{RF}|}$, can be preserved, while the component, $\mathbf{F_{IF}=F_{LO}+F_{RF}}$, can be readily filtered out. However, the output will also contain a mixer image frequency that is equidistant **($\mathbf{F_{image}}$)** from the **LO** frequency **($\mathbf{F_{LO}}$)**, where:

$$F_{image} = F_{LO} - F_{IF} \text{ or } 2 * F_{LO} - F_{RF}$$

The $\mathbf{2*F_{LO}-F_{RF}}$ product is particularly problematic, as it often falls inside the passband of the bandpass preselection filter commonly used in downconverters (see Figure 1). This image frequency can then mix with the LO to generate the same intermediate frequency as the desired signal.

For example, a downconversion using a 1.1 GHz LO and a 1.5 GHz RF input generates a 400 MHz IF signal. However a signal at 700 MHz on the RF input also generates a 400MHz IF signal; this 700MHz is the Image Frequency. It has the potential to mask the desired signal, and therefore must be suppressed. This image can be filtered out prior to the mixer in the receiver; however, such filtering limits broadband operation. The image-reject (IR) mixer overcomes this limitation by handling image suppression internally through a phasing technique. Fundamentally, both IR and SSB mixers are implemented as I/Q mixers.

I/Q Mixers

Modern communication systems, including advanced cellular networks (4G and beyond) and contemporary Wi-Fi standards, typically use in-phase and quadrature (I/Q) modulation schemes such as QAM, orthogonal frequency-division multiplexing (OFDM), or phase-shift keying (PSK). I/Q transmission helps mitigate unwanted IMD products by using both sidebands to modulate the RF signal, eliminating the need to filter out undesired images or sidebands.

I/Q mixers, also called I/Q modulators and demodulators, use two mixers of any type, such as single-balanced or double-balanced, where each receives the LO signal but with 90° of phase separation, via quadrature hybrid couplers.

In receivers, this configuration separates the downconverted signal into its two orthogonal components, in-phase (I) and quadrature (Q), allowing designers to measure both amplitude and phase relative to the transmitted signal. By demodulating to produce the I and Q components, these mixers inherently provide image rejection, eliminating the need for sharp, high-order, or complex filtering. As shown in **Figure 7**, the I and Q components can be sent directly to analog-to-digital converters (ADCs) in direct-conversion downconverter—or receiver—architectures.

Conversely, in a SSB upconverter—or transmitter—architectures, the analog I and Q components are created from digital signals using digital-to-analog converters (DACs).

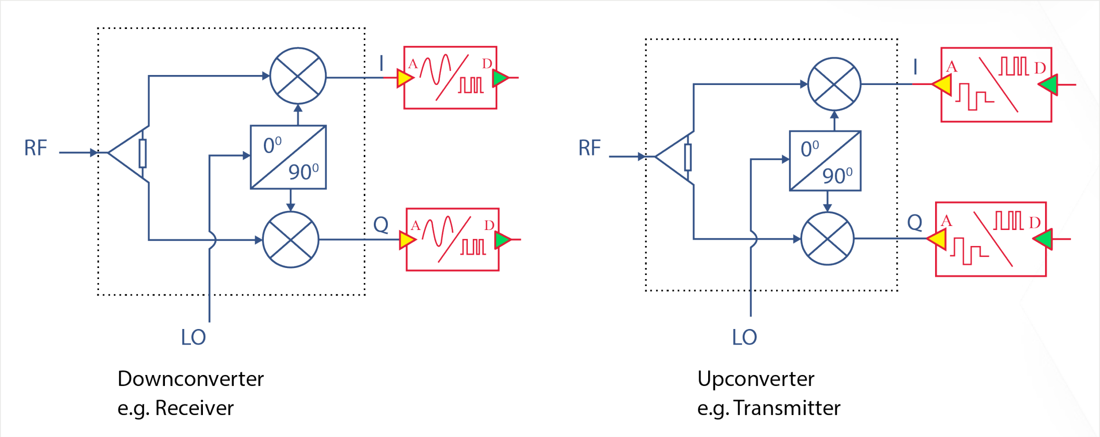


Figure 7: *Simplified block diagram of an I/Q downconverter (demodulator) and I/Q upconverter (modulator). Source: Cadence*

This approach is ideal for modern telecommunication systems that can directly process I and Q data, reducing solution complexity, size, and cost. However, I/Q mismatch and LO leakage must be addressed, as they can substantially degrade error vector magnitude (EVM). Additionally, high mixer linearity helps optimize power consumption by enabling a smaller power amplifier (PA) stage in transmitters.

For receivers using demodulation schemes where separate I & Q signals are not required, and wideband image rejection is required, a configuration known as an IR mixer can be used. This is an I/Q mixer with an additional hybrid coupler **(Figure 8)**, which enables analog selection of the desired sideband at the output by choosing the appropriate hybrid coupler output.

Similarly, for a single-sideband (SSB) upconverter where the input is a one signal rather than separate I & Q components, the configuration in Figure 8 allows determination of the desired Sideband output by choice of hybrid coupler input.

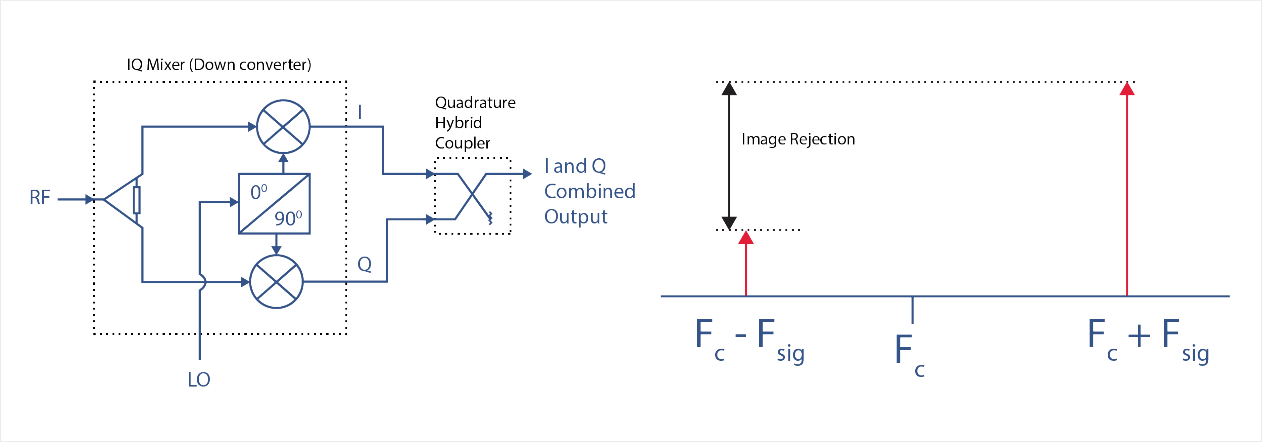


Figure 8: *An I/Q mixer will use phasing to select the SSB operation. Source: Cadence*

Conclusion

Mixers are essential components in RF and millimeter-wave communications, utilizing nonlinear circuit elements such as diodes or transistors to generate sum and difference frequencies. A key challenge in mixer design is the unwanted generation of IMD products. While some IMD products can be filtered out, others lie inside the signal filter passband, requiring single-sideband (SSB) suppression for upconverters and IR for downconverters. IR/SSB mixers are derived from the I/Q mixer topology, which processes I/Q signals and uses an additional quadrature hybrid coupler to achieve effective IR or SSB suppression. I/Q mixers are fundamental to advanced communication systems, as nearly all modern architectures employ some form of I/Q modulation.

As discussed in this paper, mixers can be implemented in numerous configurations, but the tradeoffs among conversion loss or gain, NF, linearity, dynamic range, and isolation are not always immediately clear without simulation. Part 2 of this series will address mixer design and simulation using Microwave Office and demonstrate system-level optimization with Visual System Simulator.

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