From cellular phones to two-way pagers to wireless Internet access, the world is becoming more connected, even though wirelessly. No matter the technology, these devices are basically simple radio transceivers (transmitters and receivers). In the vast majority of cases the receivers and transmitters are a variation on the superheterodyne radio shown in Figure 9.1 for the receiver and Figure 9.2 for the transmitter.

The basic concept of operation is as follows. For the receiver, the signal from the antenna is amplified in the radio frequency (RF) stage. The output of the RF stage is one input of a

![Figure 9.1: Basic superheterodyne radio receiver](image)
mixer. A local oscillator (LO) is the other input. The output of the mixer is at the intermediate frequency (IF). The concept here is that it is much easier to build a high gain amplifier string at a narrow frequency band than it is to build a wideband, high gain amplifier. Also, the modulation bandwidth is typically very much smaller than the carrier frequency. A second mixer stage converts the signal to the baseband. The signal is then demodulated (demod). The modulation technique is independent from the receiver technology. The modulation scheme could be amplitude modulation (AM), frequency modulation (FM), phase modulation, or some form of quadrature amplitude modulation (QAM), which is a combination of amplitude and phase modulation.

To put some numbers around it, let us consider a broadcast FM signal. The carrier frequency is in the range of 98–108 MHz. The IF frequency is almost always 10.7 MHz. The baseband is 0 Hz–15 kHz. This is the sum of the right and left audio frequencies. There is also a modulation band centered at 38 kHz that is the difference of the left and right audio signals. This difference signal is demodulated and summed with the sum signal to generate the separate left and right audio signals.

On the transmit side the mixers convert the frequencies up instead of down.

These simplified block diagrams neglect some of the refinements that may be incorporated into these designs, such as power monitoring and control of the transmitter power amplifier as achieved with the “Tru-Power” circuits.

As technology has improved, we have seen the proliferation of IF sampling. Analog-to-digital converters (ADCs) of sufficient performance have been developed which allow the sampling of the signal at the IF frequency range, with demodulation occurring in the digital domain. This allows for system simplification by eliminating a mixer stage.

In addition to the basic building blocks that are the subject of this chapter, these circuit blocks often appear as building blocks in larger application specific integrated circuits (ASIC).
9.1 Mixers

9.1.1 The Ideal Mixer

An idealized mixer is shown in Figure 9.3. An RF (or IF) mixer (not to be confused with video and audio mixers) is an active or passive device that converts a signal from one frequency to another. It can either modulate or demodulate a signal. It has three signal connections, which are called ports in the language of radio engineers. These three ports are the RF input, the LO input, and the IF output.

A mixer takes an RF input signal at a frequency $f_{\text{RF}}$, mixes it with a LO signal at a frequency $f_{\text{LO}}$, and produces an IF output signal that consists of the sum and difference frequencies, $f_{\text{RF}} \pm f_{\text{LO}}$. The user provides a bandpass filter that follows the mixer and selects the sum ($f_{\text{RF}} + f_{\text{LO}}$) or difference ($f_{\text{RF}} - f_{\text{LO}}$) frequency.

Some points to note about mixers and their terminology:

- When the sum frequency is used as the IF, the mixer is called an upconverter; when the difference is used, the mixer is called a downconverter. The former is typically used in a transmit channel, and the latter in a receive channel.

- In a receiver, when the LO frequency is below the RF, it is called low side injection and the mixer a low side downconverter; when the LO is above the RF, it is called high side injection, and the mixer a high side downconverter.
Each of the outputs is only half the amplitude (one-quarter the power) of the individual inputs; thus, there is a loss of 6 dB in this ideal linear mixer. (In a practical multiplier, the conversion loss may be greater than 6 dB, depending on the scaling parameters of the device. Here, we assume a mathematical multiplier, having no dimensional attributes).

A mixer can be implemented in several ways, using active or passive techniques.

Ideally, to meet the low noise, high linearity objectives of a mixer we need some circuit that implements a polarity-switching function in response to the LO input. Thus, the mixer can be reduced to Figure 9.4, which shows the RF signal being split into in-phase (0°) and antiphase (180°) components; a changeover switch, driven by the LO signal, alternately selects the in-phase and antiphase signals. Thus reduced to essentials, the ideal mixer can be modeled as a sign-switcher.

In a perfect embodiment, this mixer would have no noise (the switch would have zero resistance), no limit to the maximum signal amplitude, and would develop no intermodulation between the various RF signals. Although simple in concept, the waveform at the IF output can be very complex for even a small number of signals in the input spectrum. Figure 9.6 shows the result of mixing just a single input at 11 MHz with an LO of 10 MHz.

The wanted IF at the difference frequency of 1 MHz is still visible in this waveform, and the 21 MHz sum is also apparent. How are we to analyze this?

We still have a product, but now it is that of a sinusoid (the RF input) at $\omega_{RF}$ and a variable that can only have the values +1 or -1, that is, a unit square wave at $\omega_{LO}$. The latter can be expressed as a Fourier series.

$$S_{LO} = 4/\pi \left\{ \sin \omega_{LO} t - 1/3 \sin 3\omega_{LO} t + 1/5 \sin 5\omega_{LO} t - \cdots \right\}$$

(9.1)

Thus, the output of the switching mixer is its RF input, which we can simplify as $\sin \omega_{RF} t$, multiplied by the above expansion for the square wave, producing:
Now expanding each of the products, we obtain:

\[
S_{IF} = \frac{4}{\pi} \left\{ \sin \omega_{RF} t \sin \omega_{LO} t - \frac{1}{3} \sin \omega_{RF} t \sin 3\omega_{LO} t \\
+ \frac{1}{5} \sin 5\omega_{RF} t \sin 5\omega_{LO} t - \cdots \right\} 
\]  
(9.2)

or simply

\[
S_{IF} = \frac{2}{\pi} \left\{ \sin (\omega_{RF} + \omega_{LO}) t + \sin (\omega_{RF} - \omega_{LO}) t - \frac{1}{3} \sin (\omega_{RF} + 3\omega_{LO}) t \\
- \frac{1}{3} \sin (\omega_{RF} - 3\omega_{LO}) t \\
+ \frac{1}{5} \sin (\omega_{RF} + 5\omega_{LO}) t + \frac{1}{5} \sin (\omega_{RF} - 5\omega_{LO}) t - \cdots \right\} 
\]  
(9.3)

The most important of these harmonic components are sketched in Figure 9.5 for the particular case used to generate the waveform shown in Figure 9.6, that is, \(f_{RF} = 11\) MHz and \(f_{LO} = 10\) MHz. Because of the \(2/\pi\) term, a mixer has a minimum 3.92 dB insertion loss (and noise figure) in the absence of any gain.

Note that the ideal (switching) mixer has exactly the same problem of image response to \(\omega_{LO} - \omega_{RF}\) as the linear multiplying mixer. The image response is somewhat subtle, as it does not
immediately show up in the output spectrum; it is a latent response, awaiting the occurrence of the “wrong” frequency in the input spectrum.

### 9.1.2 Diode-ring Mixer

For many years, the most common mixer topology for high performance applications has been the diode-ring mixer, one form of which is shown in Figure 9.7. The diodes, which may be silicon junction, silicon Schottky-barrier, or gallium–arsenide (GaAs) types, provide the essential switching action. We do not need to analyze this circuit in great detail, but note in passing that the LO drive needs to be quite high—often a substantial fraction of 1 W—in order to ensure that the diode conduction is strong enough to achieve low noise and to allow large signals to be converted without excessive spurious nonlinearity.

Because of the highly nonlinear nature of the diodes, the impedances at the three ports are poorly controlled, making matching difficult. Furthermore, there is considerable coupling between the three ports; this, and the high power needed at the LO port, make it very likely that there will be some component of the (highly distorted) LO signal coupled back toward the antenna. Finally, it will be apparent that a passive mixer such as this cannot provide conversion gain; in the idealized scenario, there will be a conversion loss of $2/\pi$ (as Eq. 9.4 shows), or 3.92 dB. A practical mixer will have higher losses, due to the resistances of the diodes and the losses in the transformers.

Users of this type of mixer are accustomed to judging the signal-handling capabilities by a “Level” rating. Thus, a Level-17 mixer needs +17 dBm (50 mW) of LO drive and can handle
an RF input as high as +10 dBm (±1 V). A typical mixer in this class would be the Mini-Circuits LRMS-1 H, covering 2–500 MHz, having a nominal insertion loss of 6.25 dB (8.5 dB maximum), a worst-case LO–RF isolation of 20 dB, and a worst-case LO–IF isolation of 22 dB (these figures for an LO frequency of 250–500 MHz). The price of this component is approximately $10.00 in small quantities. Even the most expensive diode-ring mixers have similar drive power requirements, high losses, and high coupling from the LO port.

The diode-ring mixer not only has certain performance limitations, but also is not amenable to fabrication using integrated circuit (IC) technologies, at least in the form shown in Figure 9.7. In the mid-1960s it was realized that the four diodes could be replaced by four transistors to perform essentially the same switching function. This formed the basis of the now-classical bipolar circuit shown in Figure 9.8, which is a minimal configuration for the fully balanced version. Millions of such mixers have been made, including variants in complementary-MOS (CMOS) and GaAs. We will limit our discussion to the bipolar junction transistor (BJT) form, an example of which is the Motorola MC1496, which, although quite rudimentary in structure, has been a mainstay in semi-discrete receiver designs for about 25 years.

The active mixer is attractive for the following reasons:

- It can be monolithically integrated with other signal processing circuitry.
- It can provide conversion gain, whereas a diode-ring mixer always has an insertion loss. (Note: active mixers may have gain. The Analog Devices’ AD831 active mixer, for example, amplifies the result in Eq. 9.4 by π/2 to provide unity gain from RF to IF.)
- It requires much less power to drive the LO port.
- It provides excellent isolation between the signal ports.
- Is far less sensitive to load matching, requiring neither diplexer nor broadband termination.
Using appropriate design techniques it can provide trade-offs between third-order intercept (3OI or IP3) and the 1 dB gain-compression point ($P_{1\text{dB}}$), on the one hand, and total power consumption ($P_D$) on the other. (That is, including the LO power, which in a passive mixer is “hidden” in the drive circuitry.)

### 9.1.3 Basic Operation of the Active Mixer

Unlike the diode-ring mixer, which performs the polarity-reversing switching function in the voltage domain, the active mixer performs the switching function in the current domain. Thus the active mixer core (transistors Q3–Q6 in Figure 9.8) must be driven by current-mode signals. The voltage-to-current converter formed by Q1 and Q2 receives the voltage-mode RF signal at their base terminals and transforms it into a differential pair of currents at their collectors.

A second point of difference between the active mixer and diode-ring mixer, therefore, is that the active mixer responds only to magnitude of the input voltage, not to the input power; that is, the active mixer is not matched to the source. (The concept of matching is that both the current and the voltage at some port are used by the circuitry which forms that port.) By altering the bias current, $I_{EE}$, the transconductance of the input pair Q1–Q2 can be set over a wide range. Using this capability, an active mixer can provide variable gain.

A third point of difference is that the output (at the collectors of Q3–Q6) is in the form of a current, and can be converted back to a voltage at some other impedance level to that used at the input; hence, it can provide further gain. By combining both output currents...
(typically, using a transformer) this voltage gain can be doubled. Finally, it will be apparent that the isolation between the various ports, in particular, from the LO port to the RF port, is inherently much lower than can be achieved in the diode-ring mixer, due to the reversed-biased junctions that exist between the ports.

Briefly stated, though, the operation is as follows. In the absence of any voltage difference between the bases of Q1 and Q2, the collector currents of these two transistors are essentially equal. Thus, a voltage applied to the LO input results in no change of output current. Should a small DC offset voltage be present at the RF input (due typically to mismatch in the emitter areas of Q1 and Q2), this will only result in a small feedthrough of the LO signal to the IF output, which will be blocked by the first IF filter.

Conversely, if an RF signal is applied to the RF port, but no voltage difference is applied to the LO input, the output currents will again be balanced. A small offset voltage (due now to emitter mismatches in Q3–Q6) may cause some RF signal feedthrough to the IF output; as before, this will be rejected by the IF filters. It is only when a signal is applied to both the RF and LO ports that a signal appears at the output; hence, the term doubly balanced mixer.

Active mixers can realize their gain in one other way: the matching networks used to transform a 50Ω source to the (usually) high input impedance of the mixer provide an impedance transformation and thus voltage gain due to the impedance step up. Thus, an active mixer that has loss when the input is terminated in a broadband 50Ω termination can have “gain” when an input matching network is used.

### 9.2 Modulators

*Modulators* (sometimes called *balanced modulators*, *doubly balanced modulators*, or even on occasions *high level mixers*) can be viewed as *sign-changers*. The two inputs, X and Y, generate an output W, which is simply one of these inputs (say, Y) multiplied by just the sign of the other (say, X), that is $W = Y \times \text{sign}(X)$. Therefore, no reference voltage is required. A good modulator exhibits very high linearity in its signal path, with precisely equal gain for positive and negative values of Y, and precisely equal gain for positive and negative values of X. Ideally, the amplitude of the X input needed to fully switch the output sign is very small; that is, the X-input exhibits a comparator-like behavior. In some cases, where this input may be a logic signal, a simpler X-channel can be used.

As an example, the AD8345 is a silicon RFIC quadrature modulator, designed for use from 250 to 1,000 MHz. Its excellent phase accuracy and amplitude balance enable the high performance direct modulation of an IF carrier (Figure 9.9).