# RF receiver mixers

**In the first of three articles explaining rf mixers, Joe Carr looks at their operation and demonstrates the basic single-ended diode-mixing configuration.**

Mixer circuits are used extensively in radio frequency electronics Applications include frequency translators – in radio receivers – demodulators limiters, attenuators phase detectors and frequency doublers

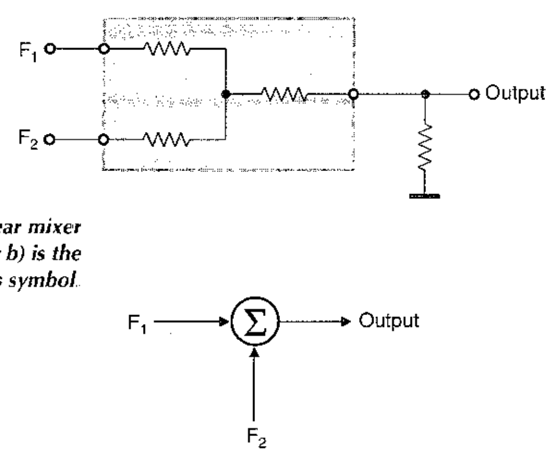



*Fig. 1a) The basic linear mixer is actually a summer; b) is the linear mixer's symbol.*

There is a number of different approaches to mixer design. Each of these approaches has advantages and disadvantages, and these factors are critical to the selection process

## Linear *versus* non-linear mixers

The word 'mixer' is used to denote both linear and non-linear circuits. And this situation is unfortunate because only the non-linear is appropriate for the rf mixer applications listed above.

So what's the difference? The basic linear mixer is actually a summer circuit, as shown in **Fig. 1a)** Its schematic symbol is shown in Fig **1b)** Some sort of combiner is needed. In the case shown, the combiner is a resistor network. There is no interaction between the two input signals, $F_1$ and $F_2$. They will share the same pathway at the output, but otherwise do not affect each other This is the action one expects of microphone and other audio mixers.

If you examine the output of the summer on a spectrum analyser **Fig. 2**, you will see the spikes representing the two frequencies, and nothing else other than noise.

The non-linear mixer is shown in **Fig. 3a)**, and the circuit symbol in Fig **3b)**

While the linear mixer is a summer, the non-linear mixer is a multiplier. In this particular case, the non-linear element is a simple diode, such as a 1N4148 or similar devices

Mixing action occurs when the non-linear device, such as diode $D_1$, exhibits impedance changes over cyclic excursions of the input signals. In order to achieve switching action one signal must be considerably higher than the other. It is commonly assumed that a 20dB or more difference is necessary.

Whenever a non-linear element is added to the signal path a number of new frequencies will be generated If only one frequency is present, then we would still expect to see its harmonics. For example, $F_1$ and $nF_1$ where $n$ is an integer. But when two or more frequencies are present a number of other products are also present. The output frequency spectrum from a non-linear mixer is,

$$\pm F_o = mF_1 \pm nF_2 \qquad (1)$$

### Detecting receiver radiation

There is a number of possibly apocryphal legends from World War II of receiver local-oscillator radiation back through the antenna circuit being responsible for an enemy detecting the location of the receiver, so this effect is rather important.

One such legend is from British airborne radar history. According to one source of doubtful authority, German submarines sailing on the surface learned to listen for Beaufighter centimetric radars using a receiver that was poorly suppressed

The aircrews then learned that they could locate the submarine with just the radar's receiver tuned to listen for the submarine receiver's local oscillator. Anyone with first hand knowledge of this matter please let me know.

where $F_O$ is the output frequency for a specific $(m,n)$ pair, $F_1$ and $F_2$ are the applied frequencies and $m$ and $n$ are integers or zero, i.e. 0, 1, 2, 3...

There will be a unique set of frequencies generated for each $(m,n)$ ordered pair. These new frequencies are called mixer products or intermodulation products. **Figure 4** shows how the output would look on a spectrum analyser. The original signals $F_1$ and $F_2$ are present, along with an array of mixer products arrayed at frequencies away from $F_1$ and $F_2$.

The implication of equation (1) is that there will be a large number of $(m,n)$ frequency products in the output spectrum. Not all of them will be useful for any specific purpose, and may well cause adverse effects.

So why do we need mixers? There are other ways to generate various frequencies, so why a frequency translator such as a heterodyne mixer?

The principal answer is that the mixer will translate the frequency, and in the process transfer the modulation of the ...ginal signal. So, when an amplitude-modulated signal is received, and then translated to a different frequency in the receiver, the modulation characteristics of the AM signal convey to the new frequency essentially undistorted. Those of you who know that there is no such thing as a 'distortionless' circuit, please refrain from snickering. Perhaps the most common use for mixers, in this regard, is in radio receivers.

## The receiver mixer

The vast majority of radio receivers made since the late twenties have been superheterodynes. The process of heterodyning is the translation of one frequency to another by the use of a mixer and local oscillator, or LO, **Fig. 5a)**.

The antenna picks up a radio signal of frequency $F_{RF}$, and mixes it with a local oscillator signal $F_{LO}$. This produces a number of new frequencies in the spectrum defined by equation (1), but those of principal interest are the cases where (m,n)=(1,1), i.e. the *sum* and *difference* frequencies $F_{RF}+F_{LO}$ and $F_{FR}-F_{LO}$.

An intermediate-frequency filter will select one of these second-order products, and the other is rejected. Why would ...ceiver designers use this approach?

The principal reason is that it is very much easier to design the receiver using this approach. It is much easier to provide the gain and selectivity filtering needed to make the receiver work properly at a single frequency. This frequency, regardless of whether the sum or difference product is used, is called the intermediate frequency, or IF, or $F_{IF}$. The high gain stages, and the bandpass filtering, are all provided in the IF stages.

At one time, it was universally the practice to select the difference frequency, but today the sum frequency is often selected. It is quite common to find high-frequency short-wave receivers with a dual conversion scheme in which $F_{RF}$ is first up-converted to the sum frequency, and then a new mixer down-converts it to a lower second intermediate frequency.

In the remainder of this article, $F_1$ and $F_2$ will be expressed much of the time as $F_{RF}$ and $F_{LO}$ in view of the receiver being the most common use for mixer devices.

The sum or difference second-order products are selected for the IF, but the other frequencies don't simply evaporate. They can cause serious problems. But more of that later.

## ...mple diode mixer

...igure **5b)** shows a block diagram circuit for a simple form of mixer. Although not terribly practical in most cases, the circuit has been popular in a number of receivers in the high uhf and microwave regions since World War II.

The two input signals are the rf and local oscillator. The oscillator signal is at a very much higher level than the rf signal. It is used to switch the diode in and out of conduction, providing the non-linearity that mixer action requires.

There are three filters shown in this circuit. The rf and local oscillator filters are used for limiting the frequencies that can be applied to the mixer. In the case of the rf port it is other radio signals on the band that are being suppressed

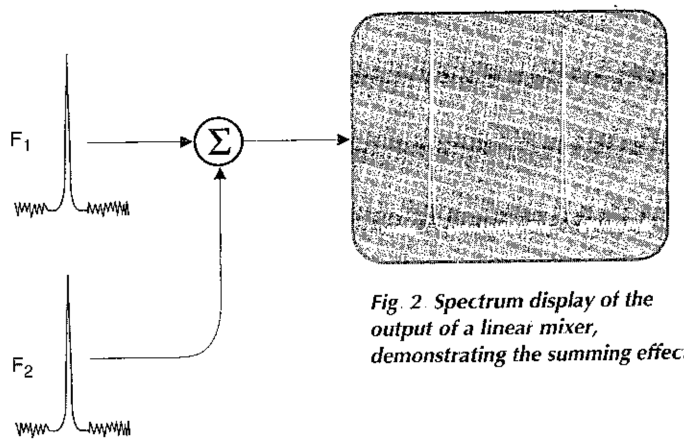



*Fig. 2. Spectrum display of the output of a linear mixer, demonstrating the summing effect.*

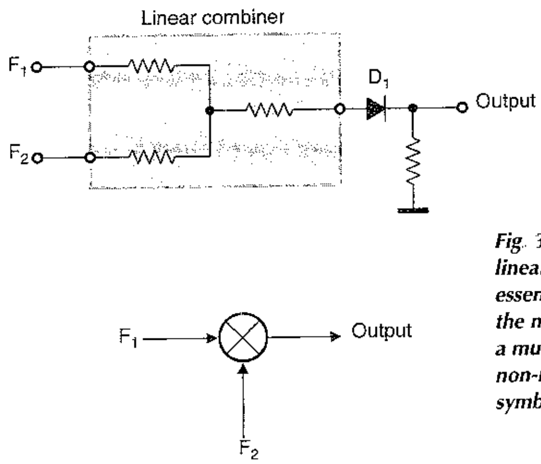



*Fig. 3a) Unlike the linear mixer, which is essentially a summer, the non-linear mixer is a multiplier; b) is the non-linear mixer's symbol.*

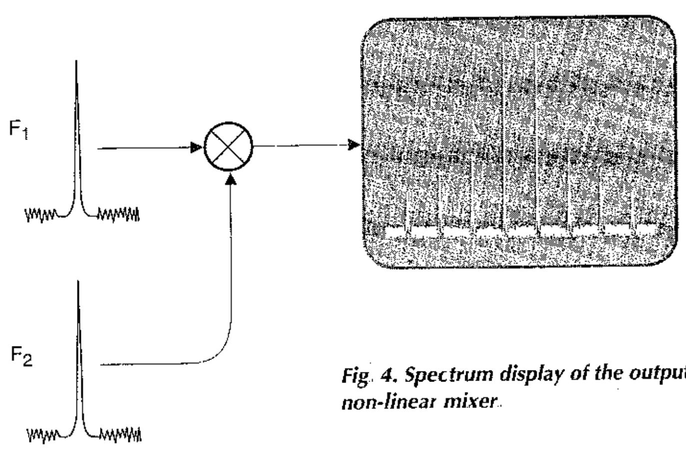
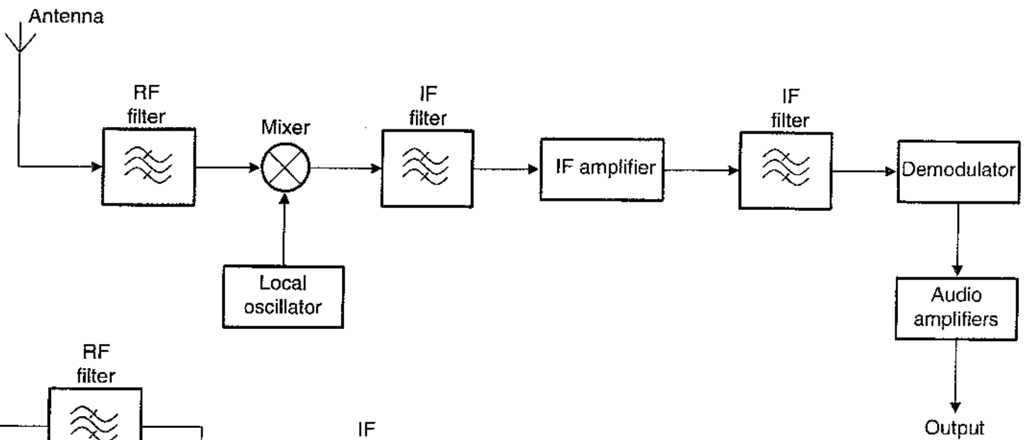



*Fig. 4. Spectrum display of the output of a non-linear mixer.*



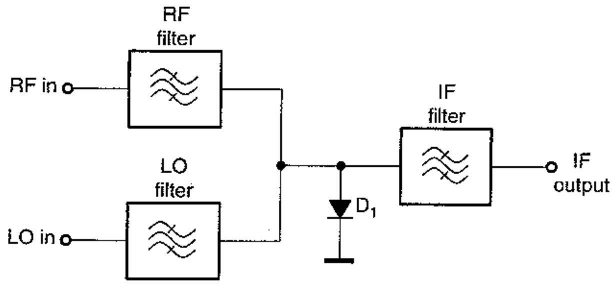




*Fig. 5a) Block diagram of a superheterodyne receiver; b) basic single-ended unbalanced mixer circuit.*

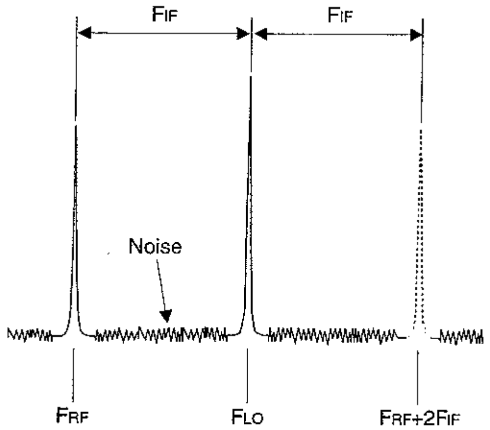



*Fig. 6. Image frequency for high-side injection mixer. Image response is due to the fact that two frequencies satisfy the criteria for the intermediate frequency.*

In the case of the local oscillator it is oscillator noise and harmonics that are suppressed.

The rf filter also serves to reduce any oscillator energy that may be transmitted back towards the rf input. Take a look at the panel entitled, 'Detecting receiver radiation' for more on this.

## The question of 'balance'

One of the ways of classifying mixers is whether or not they are unbalanced, single balanced or double balanced. Although there are interesting aspects of each of these categories, the important aspect for the moment is how they affect the output spectrum.

**Unbalanced mixers**. Both $F_{RF}$ and $F_{LO}$ appear in the output spectrum, and there may be poor LO-RF and RF-LO port isolation. Their principal attraction is low cost.

**Single-balanced mixers**. Either $F_{RF}$ or $F_{LO}$ is suppressed in the output spectrum, but not both. In other words, if $F_{RF}$ is suppressed, $F_{LO}$ will be present, and *vice versa*.

The single balanced mixer will also suppress even order local-oscillator harmonics, $2F_{LO}$, $4F_{LO}$, $6F_{LO}$, etc. High LO-RF isolation is provided, but LO-IF isolation must be provided by external filtering.

**Double-balanced mixers**. Both $F_{RF}$ and $F_{LO}$ are suppressed in the output. The single-balanced mixer will also suppress even order local-oscillator and rf harmonics, $2F_{LO}$, $2F_{RF}$, $4F_{LO}$, $4F_{RF}$, $6F_{LO}$, $6F_{RF}$, etc.). High port-to-port isolation is provided.

## Spurious responses

The IF section of a receiver will use one of the second-order products in order to convert $F_{RF}$ to $F_{IF}$. Ideally, the receiver would only respond to the single radio frequency that meets the need. Unfortunately, reality sometimes rudely intervenes, and certain spurious responses might be noted.

A spurious response in a superheterodyne receiver is any response to any frequency other than the desired $F_{RF}$, and which is strong enough to be heard in the receiver input. Most of these 'spurs' are actually mixer responses, although overloading the rf amplifier can cause some responses as well.

The mixer responses may or may not be affected by premixer filtering of the rf signal. Candidate spur frequencies include any that satisfy the following equation,

$$F_{spur} = \frac{nF_{LO} \pm nF_{IF}}{m} \qquad (2)$$

## Image

The image response of a mixer is due to the fact that two frequencies satisfy the criteria for $F_{IF}$.

**Figure 6** shows how the image response works. The frequency that satisfies the image criteria depends on whether the local oscillator is high-side injected, in which case $F_{LO}>F_{FR}$, or low-side injected, when $F_{LO}<F_{RF}$.

In the high-side injection case (m,n)=(1,–1) shown in Fig 6, the image appears at $F_{RF}+2F_{IF}$. If low-side injection, (m,n)=(–1,1), is used, then the image is at $F_{RF}-2F_{IF}$. The image always appears on the opposite side of the LO from the RF, so will be $F_{LO}+F_{IF}$ for high-side injection and $F_{LO}-F_{IF}$ for low-side injection.

Consider an actual example based on an AM broadcast-band receiver. The IF is 455kHz, and the receiver is tuned to $F_{RF}$ of 1000kHz.

The usual procedure on AM broadcast-band receivers is high-side injection, so,

$$F_{LO}=F_{RF}+F_{IF}=1000\text{kHz}+455\text{kHz}=1455\text{kHz}$$

The image frequency appears at,

$$F_{RF}+2F_{IF}=1000\text{kHz}+(2(455\text{kHz})=1910\text{kHz}$$

Any signal on or near 1910kHz that makes it to the mixer rf input port will be converted to 455kHz along with the desired signals.

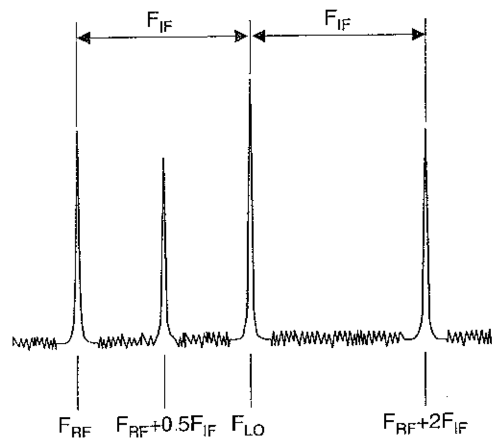



*Fig. 7. Another set of images occurs when (m,n) is (2,-2) the low side or (-2,2) for the high side – so-called half-IF response.*

The problem is complicated by the fact that it is not just actual signals present at the image frequency, but noise as well. The noise applied to the mixer input is essentially doubled if the receiver has any significant response at the image frequency.

Pre-mixer filtering is needed to reduce the noise. Receiver designers also specify high intermediate frequencies in order to move the image out of the passband of the rf pre-filter.

**Half-IF.** Another set of images occurs when $(m,n)$ is (2,–2) for low-side or (–2,2) for high side. This image is called the *half-IF image*, and is illustrated in **Fig. 7**. An interesting aspect of the half-IF image is that it is created by internally generated harmonics of both $F_{RF}$ and $F_{LO}$. For our AM broadcast-band receiver where $F_{RF}$=1000kHz, $F_{LO}$=1450kHz and $F_{IF}$=450kHz, then the half-IF frequency is 1000+(450/2)=1222.5kHz.

**IF feedthrough.** If a signal from outside passes through the mixer to the IF amplifier, and happens to be on a frequency equal to $F_{IF}$, then it will be accepted as a valid input signal by the IF amplifier. The mixer RF-IF port isolation is critical in this respect.

## High-order spurs

Thus far we have considered only the case where a single radio frequency is applied to the mixer. But what happens when two radio frequencies – $F_{RF1}$ and $F_{RF2}$ – are applied simultaneously? This is the actual situation in most practical receivers. There is a large number of higher order responses – i.e. where $m$ and $n$ are both greater than 1, defined by $mF_{RF1} \pm nF_{RF2}$.

The worst case is usually the $2F_{RF1}-F_{RF2}$ and $2F_{RF2}-F_{RF1}$ third-order products because they fall close to $F_{RF1}$ and $F_{RF2}$ and may be within the device passband.

Although any of the spurs may prove difficult to handle in some extreme cases, the principal problems occur with the third-order difference products of two rf signals applied to the rf port of the mixer, $2F_{RF1}-F_{RF2}$ and $2F_{RF2}-F_{RF1}$.

**Figure 8** illustrates this effect for our AM broadcast band-receiver. Suppose two signals appear at the mixer input: $F_{RF1}$=1000kHz and $F_{RF2}$=1020kHz. This combination is highly likely in the crowded AM broadcast band!

The third-order products of these two signals hitting the mixer are 980kHz and 1040kHz, and appear close to $F_{RF1}$ and $F_{RF2}$. If the pre-mixer filter selectivity is not sufficiently narrow to suppress the unwanted radio frequency, then the receiver may respond to the third-order products as well as the desired signal.

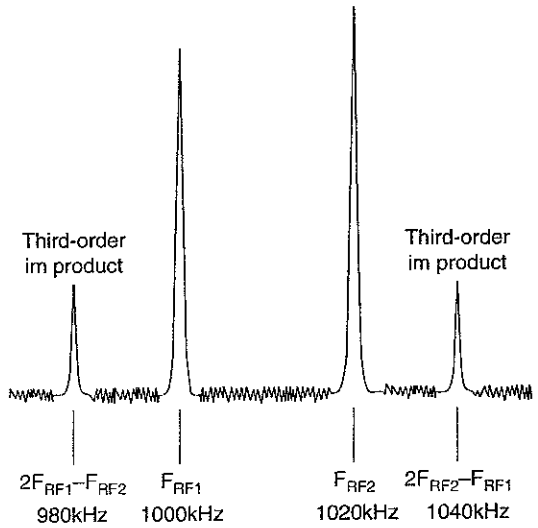



*Fig. 8. Third-order products close to test signals.*

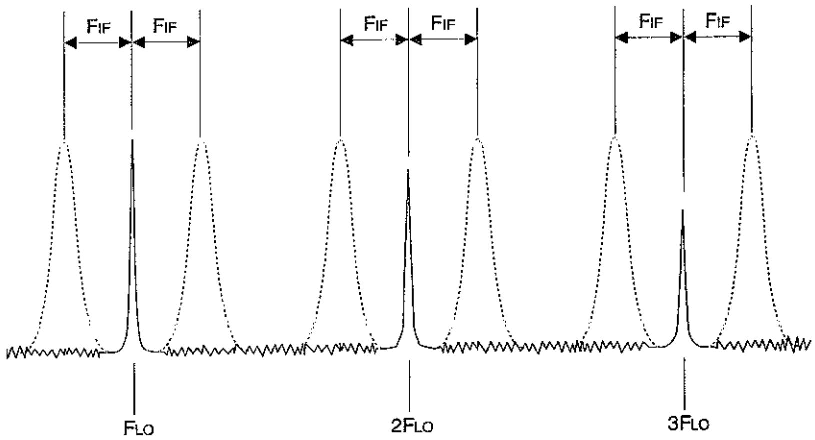



*Fig. 9. Noise balance deteriorates if local-oscillator harmonics are present.*

**LO harmonic spurs.** If the harmonics of the local oscillator are strong enough to drive mixer action, then signal clustered at $\pm F_{IF}$ from each significant harmonic will also cause mixing. **Figure 9** shows this effect. The passband of the pre-mixer filter is shown as dotted line curves at $F_{LO} \pm F_{IF}$, $2F_{LO} \pm F_{IF}$ and $3F_{LO} \pm F_{IF}$.

**LO noise spurs.** All oscillators have noise close to the LO frequency. The noise may be due to power supply noise modulating the LO, or it may be random phase noise about the LO. In either case, the noise close to the LO, and within the limits imposed by the IF filter, will be passed through the mixer to the IF amplifier. ■

**What's next?**

In part two of this three-part series on rf mixers, Joe looks at intermodulation distortion, third-order intercept point, mixer losses, noise figure and noise balance, and gets into actual circuits by considering the single-ended unbalanced active mixer circuit.