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Understanding Mixers From a Switching Perspective

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Mixers are essential building blocks in communications equipment, converting baseband information to a transmitted frequency, and converting a received signal to baseband for recovery of its information

Mixers are important components for frequency conversion, signal detection and phase detection. Often, it is the performance of the mixer that establishes limits for the overall noise figure or intercept point of a communication system. This tutorial offers a review of mixers from a specific perspective—switching (also referred to as commutation).

This a good time to review these circuits. Digital signal processing has shortened the RF/microwave path between front end and baseband in today's receivers. Sometimes, that path includes little more than a bandpass filter followed by two mixer/detectors that deliver I and Q signals to the baseband processor. Without the usual IF filter to provide additional selectivity, the performance of the mixer has an even greater effect on the receiver's ability to reject unwanted signals.

Mixing as an Analog Function

As a review, let's look at an ideal analog mixer, which performs the function of multiplication between two inputs (Figure 1). Analog mixing implements the following trigonometric identity:

$$\cos(A)\cos(B) = 1/2[\cos(A+B) + \cos(A-B)]$$

where A and B represent the two input frequencies, $2\pi f_a t$ and $2\pi f_b t$ (or $\omega_a t$ and $\omega_b t$). The mixer output comprises two frequencies, which are the sum and difference of the two input frequencies. In a practical system, the two inputs (the desired signal and a local oscillator) are sufficiently separated in frequency to allow one or the other of the output frequencies to be selected by filtering. In an ideal system, the selected output is an exact replica of the desired signal, shifted up or down in frequency by an amount equal to the local oscillator frequency.

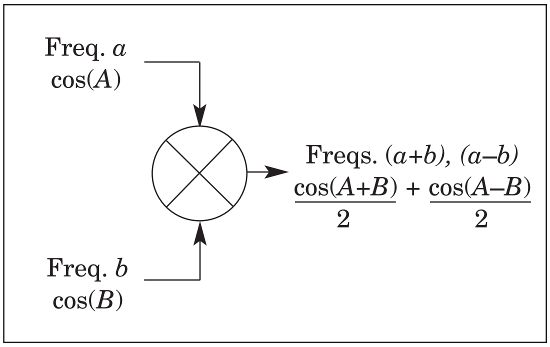

Figure 1 · Analog mixers implement the multiplication function, as illustrated here.

It is easy to understand how any deviation from perfect linearity will result in unwanted signals at the output. Non-linearities can generate harmonics of the input signals, which are also multiplied, with sum and difference frequencies appearing at the output. If the input is modulated, harmonics of the modulation sidebands create further spurious signals at the output. Like the desired modulation sidebands, these spurious products of modulation are adjacent to the desired frequency, so they cannot be removed by filtering.

High-linearity analog circuits require class A bias to handle sufficient amplitude for the expected range of signal levels. With predictable signal levels, linear mixers are practical and easily implemented as typical RFICs. Integration also offers the advantages of active baluns and on-chip buffers. However, to achieve high dynamic range, these circuits consume a lot of power relative to the signal levels, since high level signal handling can be achieved only with high quiescent current. This may result in unacceptably high power consumption and heat dissipation.

Mixing With Switches

Many of the difficulties in implementing high dynamic range mixer circuits can be overcome using a switching topology. Figure 2 is an illustration of switching action, using two square waves for simplicity. The top waveform is the signal, which is switched by the center waveform, representing the local oscillator. The bottom waveform is the output, a train of pulses with periods equivalent to the various frequencies resulting from mixer action.

This diagram is not ideal for illustrating a switching mixer, but it does show how the various mixing products are generated by switching action. Remember that a square wave includes the fundamental frequency and odd harmonics, so a wide range of products are created in this scenario. Among the output frequencies are the sum and difference, as expected—periods ($T_1 + T_2$) and ($T_1 — T_2$).

Intuitively, we can compare a switching mixer to a switch-mode power amplifier—both alternate between a low loss through-path and a high-impedance off state. Power dissipation (loss) is reduced in an amplifier, and signal-handling is improved in a mixer.

To explain differently: With an ideal switch, the ON state will be "linear," passing the input directly to the output. In the OFF state, no signal is present and, thus, no distortion products can be present. With fast ON-OFF and OFF-ON transition periods, low on-resistance in the switches and minimal nonlinearities in other components, very high performance can be achieved.

Figure 3 is the equivalent circuit of a switching mixer, using the common ring topology and showing the active devices as ideal switches plus their associated on and off resistances, R_{on} and R_{off}. The diode ring version was analyzed nearly 40 years ago by Walker [1], and the FET switch version was described in 1986 by Oxner [2].

For a switching mixer with ideal elements, the optimum conversion loss in dB is [3]:

$$L_C = 10 \log (4/\pi^2) = 3.92 \text{ dB}$$

The total loss consists of: a) the result of the fundamental being split into the sum and difference frequency outputs (3 dB); and b) the sum of the mixing products resulting from the harmonics of the local oscillator switching frequency. Of course, a practical mixer has non-ideal components, and the conversion loss will be greater.

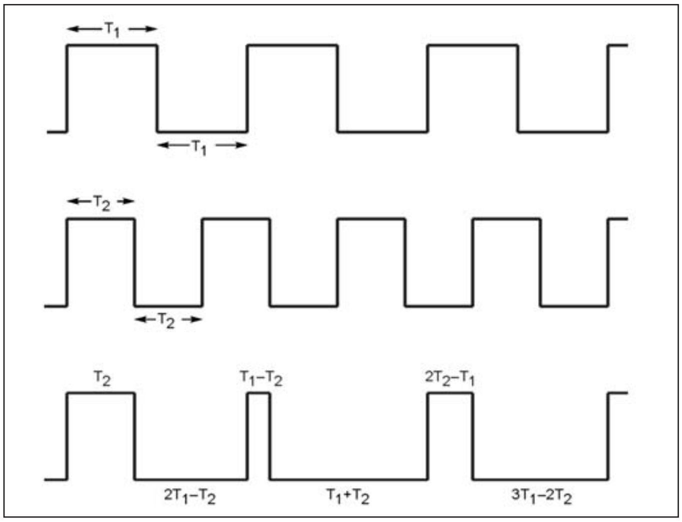

Figure 2 · The "signal" (top) is switched by the "local oscillator" (middle), creating the various outputs, some of which are included on the bottom waveform.

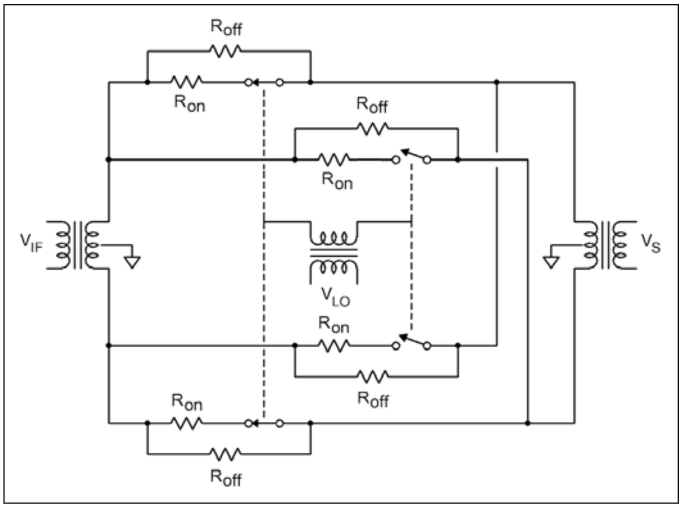

Figure 3 · Circuit diagram of a ring mixer, showing the switching components and their associated finite on and off resistances. (After Oxner (2))

Intermodulation Distortion

In brief, the causes of intermodulation distortion are the various non-linearities that occur in when non-ideal components are used in practical circuit. For a switching mixer, these include:

- Improper termination of the ports. which allows re-entry of reflected signals into the mixer.
- Discontinuity in switching action at zero-crossing due to the voltage drop in diodes and gate voltage threshold of FET switches.
- Modulation of R_{on} in the switching devices by high signal levels.

· Finite rise and fall times, which can create discontinuities and imbalance.

Also, in a balanced mixer, any variation in the components will unbalance the circuit, allowing even-order products to appear at the output.

Because switching mixers rely on fast rise and fall times, Walker [1] derived the following expression to predict the improvement in the relative intermodulation performance (in dB) as a function of LO rise/fall time:

$$\text{Relative IMD} = 20\log\left[\frac{\left[t_r\omega_{LO}\dfrac{V_S}{V_{LO}}\right]^2}{8}\right]$$

where t_r is the rise/fall time of V_{LO}, ω_{LO} is the local oscillator frequency, V_S is the peak signal voltage and V_{LO} is the peak-to-peak local oscillator voltage.

This expression illustrates that IMD improvements occur if the signal voltage is reduced, the LO voltage is increased, the LO frequency is lower ("low-side injection") and if the rise/fall time is reduced.

In practice, each of these factors has its limitations. Lower V_S degrades the signal-to-noise ratio, higher V_{LO} increases power consumption and LO frequency often cannot be changed. Depending on the frequency of operation and the devices being used, rise and fall time may be improved, and has been the focus of significant work.

Summary

This tutorial has presented basic information on mixers as switching circuits. This type of analysis can lead to very high dynamic range implementations, and there are volumes of information on the development and application of high performance switching mixers. We plan to present some of that work in future articles.

References

1. H.P. Walker, "Sources of Intermodulation in Diode-Ring Mixers," *The Radio and Electronic Engineer*, Vol 46, No. 5, May 1967.

2. E. Oxner, "A Commutation Double Balanced Mixer of High Dynamic Range," *Proceedings of RF Technology Expo '86*. Also in *Proceedings of RF Expo East 1986,* and *RF Design*, February 1986.

3. Oxner, Eq. (10)