UHF RECEIVERS

An ultra-high frequency (UHF) receiver receives radio signals with input frequencies between 300 MHz and 3000 MHz. Radio waves in this part of the spectrum usually follow line-of-sight paths and penetrate buildings well. The natural radio environment is significantly quieter at UHF than at lower frequencies, making receiver noise performance more important. UHF antennas are small enough to be attractive for vehicular and hand-held applications, but are not as directional or expensive as microwave antennas. Many radio services use UHF, including land mobile, TV broadcasting, and point-to-point. The point-to-point users are rapidly disappearing, and the greatest current interest in receiver design centers on cellular and personal communications system (PCS) applications in bands from 800 MHz to 950 MHz and 1850 MHz to 1990 MHz.

UHF receiver design was once a specialized field incorporating parts of the lumped-circuit techniques of radio frequency (RF) engineering and the guided-wave approach of microwave engineering. Recent trends in circuit integration and packaging have extended RF techniques to the UHF region, and there are few qualitative distinctions between UHF receivers and those for lower frequencies. UHF receivers differ from their lower-frequency counterparts primarily by having better noise performance and by being built from components that perform well at UHF.

UHF RECEIVER OPERATION

The Role of a UHF Receiver in a Radio Communications System

Radio frequency communications systems exist to transfer information from one source to a remote location. Figure 1 is a system block diagram of a simple radio communications system. A transmitter takes information from an external source, modulates it onto an RF carrier, and radiates it into a radio channel. The radiated signal grows weaker with distance from the transmitter. The receiver must recover the transmitted signal, separate it from the noise and interference that are present in the radio channel, and recover the transmitted information at some level of fidelity. This fidelity is measured by a signal to noise ratio for analog information or by a bit error rate for digital information.

Receiver Characteristics

The following characteristics describe receiver performance:

- *Sensitivity* is a measure of the weakest signal that the receiver can detect. The ideal receiver should be capable of detecting very small signals. Internally generated noise and antenna performance are the primary factors limiting the sensitivity of UHF receivers.
- *Selectivity* describes the receiver's ability to recover the desired signal while rejecting others from transmitters operating on nearby frequencies.
- *Stability* is the receiver's ability to remain tuned to the desired frequency over time with variations in supply voltage, temperature, and vibration, among others.
- *Dynamic range* is a measure of the difference in power between the strongest signal and the weakest signal that the receiver can receive.
- *Image rejection* measures the receiver's ability to reject images, incoming signals at unwanted frequencies that can interfere with a wanted signal.
- *Spurious response protection* measures the receiver's freedom from internally generated unwanted signals that interfere with the desired signal.

The Superheterodyne Architecture

The most widely used receiver topology is the superheterodyne or superhet. A block diagram of this topology is shown in Fig. 2. It provides amplification both at the incoming radio frequency and at one or more intermediate frequencies. The incoming signal from the channel passes through the preselector filter, RF amplifier, and image filter, where it is applied to the mixer. The mixer combines the incoming signal with the local oscillator (LO) waveform to generate output at the sum and difference of the signal and LO frequencies. The LO frequency can be above or below the signal frequency. If the LO frequency is above the signal frequency, the receiver uses high-side injection. If the LO frequency is below the signal frequency, the receiver uses low-side injection. The intermediate frequency (IF) filter selects either the sum or the difference and rejects the other. The selected frequency is termed the intermediate frequency (IF), and the IF amplifier provides additional gain at this frequency. The detector/demodulator extracts the transmitted information from the IF waveform. Some superhet architectures use two or more intermediate frequencies in succession to simplify the requirements placed on the filters. The mixing process is sometimes called *conversion.* A receiver with one intermediate frequency is a single-conversion receiver, and a receiver with two intermediate frequencies is a dual-conversion receiver. Unless explicitly stated otherwise, examples in this article refer to single-conversion receivers.

While other receiver architectures exist, the superheterodyne has many advantages. Distributing the amplifier gain between the RF and IF frequencies makes it less difficult to prevent unwanted oscillation. The receiver is tuned to a wanted input frequency by selecting the frequency of the LO. The IF filter can have a fixed center frequency, so its characteristics like bandwidth and delay can be optimized. It does not have to be retuned when the receiver is tuned to a new channel.

Weak Signal Performance. At UHF, internally generated noise limits the weakest signal that can be detected. The noise generated by the RF amplifier is amplified by all the stages in the receiver so that it determines the receiver sensitivity. Low-noise, high-gain RF amplifiers produce the greatest sensitivity. There is often a trade-off between sensitivity

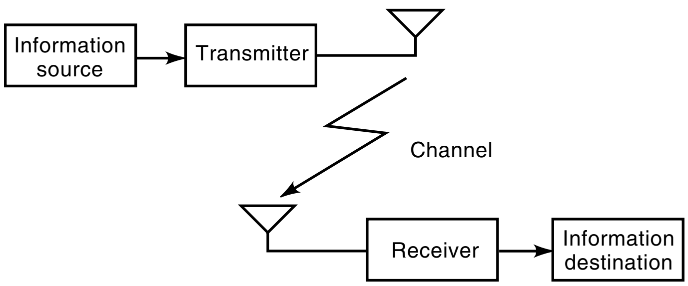

Figure 1. Block diagram of a UHF communications system showing the role of the receiver.

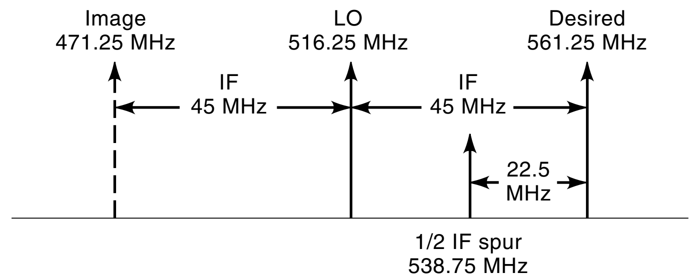

Figure 3. The frequency relationship between the desired signal, the local oscillator signal, and the image signal for a TV receiver with a 45 MHz intermediate frequency. Note that the image and the desired signal frequencies are symmetric about the local oscillator frequency.

and strong signal performance, since a high-gain RF amplifier can overload the mixer with a strong signal.

Images

The mixing or frequency conversion process introduces unwanted and spurious responses. The most important unwanted response is called an image. The image frequency and the wanted frequency are symmetrical about the LO frequency. Any unwanted signal at the image frequency that gets into the mixer will be amplified and demodulated essentially as if it came in at the wanted frequency. Consider a simple example. A TV broadcast receiver is tuned to 561.25 MHz, the video carrier frequency for television channel 29. The receiver has an IF of 45 MHz, so the LO runs at 516.25 MHz. A difference frequency of 45 MHz is generated by mixing 561.25 MHz and 516.25 MHz. Suppose there is a nearby transmitter on channel 14. When the 471.25 MHz channel 14 video mixes with the 516.25 MHz LO output, the difference is also 45 MHz. The receiver is tuned to channel 29, but it will also pick up channel 14 if the channel 14 signal reaches the mixer. The preselector and image filters must pass the desired signal but reject the image. Figure 3 shows the frequency relationship among the desired signal, the image, and the LO for a single-conversion receiver. Note that the image and the wanted response are separated by twice the IF frequency. A dual-conversion superhet would have three images.

Images are the key drawback to the superheterodyne architecture. Their elimination requires filters, and image rejection is easier with high IF frequencies. The higher the IF frequency, the more difficult it is to make narrowband filters. Filters are the major impediment to fully integrated UHF receivers. They are usually separate discrete components.

Spurious Responses

The image is only one of many possible unwanted mixer outputs. The mixer is an inherently nonlinear device that generates and combines harmonics of the LO and signal frequencies. Continuing with the numbers from the previous example, the second harmonic of the 516.25 MHz LO appears at 1032.5 MHz. If a 538.75 MHz signal reaches the mixer, the mixer generates a second harmonic at 1077.5 MHz. The mixer also generates the sum and the difference of the harmonics. One of these products is at the 45 MHz IF frequency, and the receiver has a spurious response at 538.75 MHz. This response is sometimes called the half IF spur because it appears 22.5 MHz or one-half the IF frequency from the desired response. Two times the IF, in this case 90 MHz, separates the image from the wanted signal. It is much easier to design the image and the preselector filters to remove the image than the half IF spur.

Other spurious products are a serious problem in superhet receivers. Mixers generate not only the second harmonic but higher-order harmonics as well. Balanced mixers, which suppress the even-order harmonics, are widely used to eliminate some of the spurious mixing products. UHF receivers may have multiple mixers and intermediate frequencies, and pre-

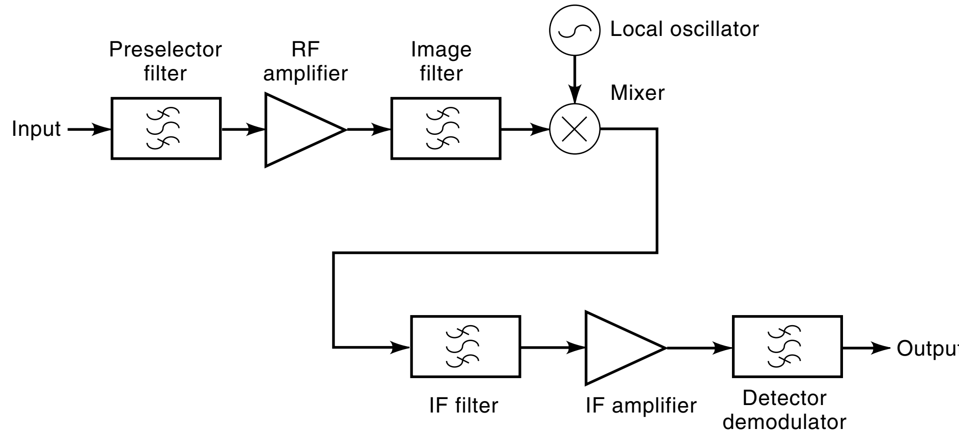

Figure 2. The architecture of a superheterodyne receiver.

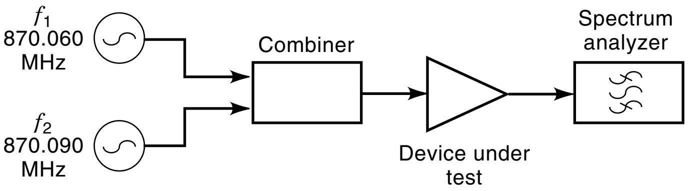

Figure 4. A test set up for measuring third-order products. The frequencies shown are for the example presented in the text.

dicting all the spurious mixing products can be difficult. Software for this purpose is commercially available to help the designer select mixers.

Strong Signal Behavior. At UHF frequencies it is difficult to build a preselector filter narrow enough to pass a single channel of information. It may not be desirable to build very narrowband filters if the receiver is to be tuned over a range of frequencies. If the range of desired signal frequencies cannot pass through the preselector filters, then these filters must be retuned when the LO is tuned to the new frequency. This process, called tracking, increases the complexity of the receiver. For these reasons the receiver's ultimate bandwidth is usually set at IF, and a number of unwanted signals can reach the mixer.

All of the unwanted signals that reach the mixer will produce sum and difference frequency products with the LO. The RF amplifier may generate some of the unwanted signals. RF amplifiers are not perfectly linear; strong signals can cause them to saturate. This nonlinearity generates harmonics, which combine either in the amplifier itself or in the mixer.

The nonlinear behavior of amplifiers and mixers is specified in terms of third-order mixing products. Figure 4 shows a test set up for measuring these products. The output for an ideal amplifier would be only at the input frequencies f_1 and f_2. Amplifier nonlinearities generate harmonics of f_1 and f_2 plus the mixing products of these harmonics. These mixing products are specified in terms of the harmonic number of the signals that generate them. Particularly important are the third-order products $2f_1 - f_2$ and $2f_2 - f_1$. Figure 5 shows the output of a nonideal amplifier. The third-order products are the most problematic since their frequencies fall close to the desired signal and are difficult to filter.

As an example, consider a handheld analog cellular telephone receiver. Channel 1 is 870.030 MHz, channel 2 is 870.060 MHz, channel 3 is 870.090 MHz, and channel 4 is

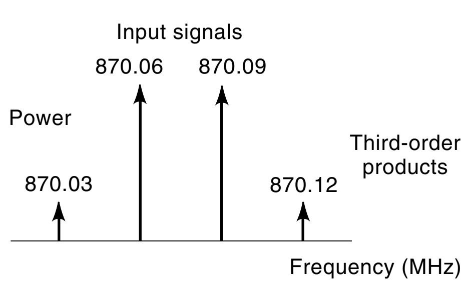

Figure 5. Sketch of a spectrum analyzer display showing the output of a nonideal amplifier with strong input signals at 870.06 and 870.09 MHz. The amplifier generates unwanted third-order products at 870.03 and 870.12 MHz.

870.120 MHz. The second harmonic of channel 2 is 1740.12 MHz. If this mixes with channel 3, the difference is 870.030 MHz, which is channel 1. Similarly, the second harmonic of channel 3 mixes with channel 2 to produce a signal at 870.12 MHz, which is channel 4. Figure 5 shows that third-order mixing of channels 2 and 3 creates signals on channels 1 and 4. If the receiver is tuned to channel 1 or 4 and strong channel 2 and 3 signals are present, then nonlinear RF amplifier or mixer products will interfere with channel 1 or 4, limiting the receiver's ability to detect a weak signal on these channels.

The nonlinear products increase with increasing signal levels. The power in the third-order products increases three times faster than the power of the desired signals. The point where the power in the third-order products would be equal to the power in the desired signal is called the third-order intercept point.

Spurious Free Dynamic Range. The weakest signal the receiver can detect is limited by the internally generated noise. The equivalent power of this noise is the noise floor. The strongest signals the receiver can tolerate without internally generated interference are those that create a third-order mixing product that equals the noise floor. The ratio of the strongest signal power to the noise floor power is the spurious free dynamic range (SFDR).

High-gain, low-noise RF amplifiers maximize sensitivity. Maximizing SFDR requires a careful tradeoff among the gain, noise performance, and third-order intercept of all the stages prior to the narrowest filter in the system. Building a sensitive receiver is relatively easy; building a sensitive receiver that can handle strong signals can be a challenge.

Other Receiver Topologies

Direct Conversion Receivers. The superhet receiver converts the incoming signal to an intermediate frequency, but it is possible to convert the radio signal directly to the original baseband of the transmitted information. This requires the LO to be tuned to the frequency of the incoming signal. If the signal and LO frequencies are equal, their difference is zero. The mixer output is the original information, which was contained in modulation sidebands, about the carrier frequency. A receiver that works this way is called a direct conversion (DC), homodyne, or zero IF receiver (see Fig. 6).

Direct conversion receivers offer a simpler design and fewer components than superhets. High-gain amplifiers are easier to build at baseband than at the signal or IF frequency, so a DC receiver can be as sensitive as a superhet. This topology minimizes the number of components at the RF and IF frequencies. On the other hand, mixer imbalance and LO leakage (LO feedthrough) into the antenna can cause large DC offsets. Local oscillator phase noise is highest close to the LO frequency, and the mixer translates this noise directly to baseband. Low frequency noise in mixers and high-gain baseband amplifiers can limit sensitivity. Depending on the choice of mixer, DC receivers have spurious responses at integer multiples of the input frequency, so a preselector filter is still required. Since all the signal processing occurs at baseband, it is possible to integrate the entire receiver, including the mixer. This is attractive for small low-power receivers like those found in pagers. DC receivers cannot be used for narrowband FM without extra signal processing.

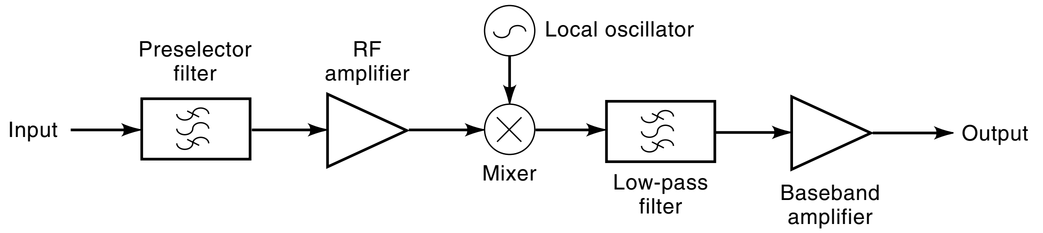

Figure 6. The homodyne or direct conversion receiver. The incoming signal is converted directly to baseband without intermediate processing at an intermediate frequency.

Tuned Radio Frequency Receivers. The tuned radio frequency (TRF) receiver of Fig. 7 is an old design that offers great simplicity. The signal passes through a preselector filter and is amplified by an RF amplifier at the signal frequency. The classic TRF receiver consists of a cascade of tuned amplifiers. The filtering and amplifying functions are combined. The amplified signal goes directly to the detector, which is typically a simple diode amplitude demodulator. TRF receivers work well with amplitude modulation or on-off keyed digital signals. They are not used for narrowband phase or frequency modulation, since these waveforms are difficult to demodulate at UHF. The simplicity of the TRF is attractive for low-current, low-cost applications. Because the TRF receiver has no oscillators, there is no oscillator radiation. TRF receivers escape the government regulations that limit RF emissions. They have none of the spurious mixing responses that are a problem in superhet receivers. Because TRF receivers contain no mixers, they have no images and can reproduce exactly the frequency or phase information in the original signal.

TRF receivers have several disadvantages. They are not frequency agile and thus are useful only for single-frequency systems. TRF receivers cannot use standard low cost filters like those available at common IFs for superhets. Narrowband filters, which match modulation bandwidths, are difficult to build at UHF, and tuning a TRF receiver to a new frequency requires retuning or replacing the filters. TRF receiver sensitivity is limited because of the difficulty of building stable high-gain amplifiers at UHF. For these reasons, the UHF applications for TRF receivers tend to be limited to very low cost short-range devices.

Regenerative and Superregenerative Receivers. Regenerative receivers come from the earliest days of radio and are capable of very high sensitivity with only a single active device. A regenerative receiver is an amplifier to which frequency selective positive feedback has been applied. If the feedback is adjusted below the point of oscillation, the receiver acts as a square law detector. It is suitable for amplitude modulated signals. The feedback can be advanced to the point where oscillation occurs. The regenerative receiver then acts as a self-oscillating direct conversion receiver. In this mode, it will demodulate single sideband (SSB) or continuous wave signals.

The superregenerative receiver is a variation on the regenerative theme. The positive feedback is advanced beyond the point where oscillations begin. This increases the gain. It takes a finite amount of time for the oscillation amplitude to build up due to energy storage in the oscillator-tuned circuit. Before the oscillation amplitude reaches a significant level, the oscillating amplifier is shut off or "quenched." The process of oscillation buildup and quenching is repeated. Injecting a signal close to the oscillation frequency speeds the buildup of oscillations. The envelope of any amplitude modulation on the injected signal can be extracted from the amplitude of the oscillations in the superregenerative detector.

Superregenerative receivers find application in short-range, low-cost devices such as radio-controlled toys and garage door openers. They work well at UHF, and their high sensitivity and extreme simplicity make them attractive for such applications.

The major drawbacks of a superregenerative receiver are poor selectivity and the potential to create interference. They can be easily overloaded by strong adjacent channel signals, and, if not properly designed, they can radiate a potent signal of their own. The use of positive feedback results in very high gain, but it accentuates any variations in amplifier gain due to temperature, voltage, aging, or other effects. Stable performance is difficult to obtain, and receiver bandwidth will vary inversely with gain. It is very difficult to meet emission specifications with regenerative and superregenerative receivers.

DESIGNING SUPERHETERODYNE RECEIVERS FOR UHF

Weak Signal Behavior

Noise Temperature and Receiver Sensitivity. Sensitivity is a measure of a receiver's weak signal performance. Depending on the particular application, sensitivity may be expressed in terms of (1) the receiver's noise floor, (2) the minimum detectable signal, or (3) the minimum input signal level necessary to achieve a useful output. However defined, sensitivity is

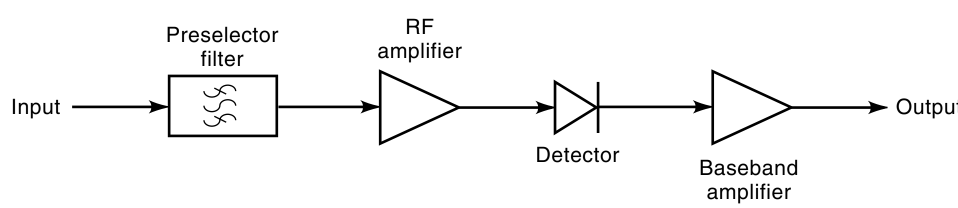

Figure 7. The tuned radio frequency receiver. The incoming signal is amplified and detected without frequency conversion.

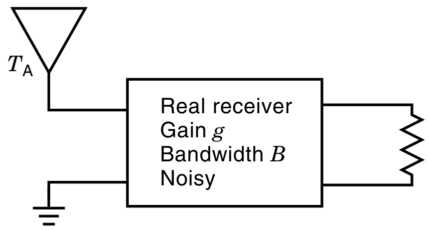

Figure 8. Representation of a real receiver. It amplifies thermal noise from the antenna and adds its own internally generated noise.

closely related to the irreducible noise level at the receiver's output.

Noise is generated within all electronic components, active or passive. The noise power that a resistor at physical temperature T would deliver to an ideal power meter whose response is frequency independent over a measurement bandwidth B is given by

$$P_N = kTB \tag{1}$$

where k is Boltzmann's constant (1.38×10^{-23} J/K).

Any other one-port noise source can be described by an equivalent noise temperature T_N such that the noise delivered to an ideal power meter with measurement bandwidth B is

$$P_N = kT_N B \tag{2}$$

Now imagine a two-port device with gain g connected between an antenna or other noise source with noise temperature T_A and a load. The noise power delivered to the load will consist of amplified input noise plus additional noise that is generated inside the two-port device:

$$p_N = gkT_A B + \Delta p \tag{3}$$

where Δp is the internally generated noise (see Fig. 8).

For analysis, it is convenient to represent the internally generated noise as if it came from a fictitious noise source at the input of a noiseless equivalent circuit of the two-port device. This noise temperature T_e of this fictitious noise source is the effective input noise temperature of the device (see Fig. 9):

$$p_N = gkT_A B + \Delta p = gkT_A B + gkT_e B = gk(T_A + T_e)B \tag{4}$$

If a receiver with effective input noise temperature T_e is connected to an antenna with equivalent noise temperature

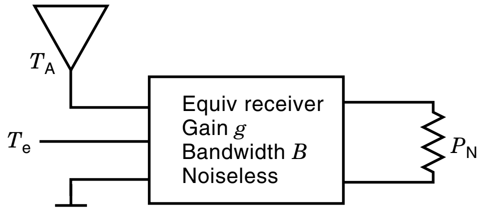

Figure 9. The noiseless equivalent receiver. Internally generated noise is represented as if it came from a fictitious input at temperature T_e.

T_A, the resulting system noise temperature T_S is given by

$$T_S = T_A + T_e \tag{5}$$

The receiver noise floor is $kT_S B$, where B is the overall receiver bandwidth (usually set by the IF filter). The minimum detectable signal (MDS) is usually specified as the noise floor. Depending on the application, the receiver sensitivity may be defined as the noise floor or as the minimum signal necessary to produce a specified output signal-to-noise ratio (SNR). The noise floor is sometimes specified with a bandwidth B of 1 Hz. At room temperature, this corresponds to -174 dBm.

Noise Figure. While noise temperature is perhaps a more immediately useful quantity, the noise figure of a UHF receiver is more commonly specified. The noise figure of a two-port device was originally defined as the ratio of the input SNR to the output SNR. This definition is quite useful for "back of the envelope" calculations for point-to-point microwave systems, but it suffers from a lack of uniqueness (since it depends on the antenna noise temperature) and universal applicability. Officially, noise figure is "the ratio of (A) the total noise power per unit bandwidth (at a corresponding output frequency) delivered by the system into an output termination to (B) the portion thereof engendered at the input frequency by the input termination, whose noise temperature is standard (290 K at all frequencies)" (1).

Mathematically, the noise figure is given as a ratio by nf and in decibels by NF:

$$\mathrm{nf} = 1 + \frac{T_e}{290} \tag{6}$$

$$\mathrm{NF} = 10\log_{10}(\mathrm{nf}) \tag{7}$$

While some authors argue rather vehemently that noise figure is not a meaningful concept, it is well established as a specification for UHF receivers and their components. Overall values of 2 dB are achievable. Most calculations ultimately require the noise temperature, conveniently obtained from the noise figure by

$$T_e = 290(\mathrm{nf} - 1) \tag{8}$$

The noise figure as defined in Eq. (6) is the standard noise figure, based on an assumed standard source noise temperature of 290 K. This is the one that manufacturers measure and quote. An actual noise figure, based on the true source temperature, is often used to calculate the minimum detectable signal or SNR degradation. See Ref. 2 for an excellent discussion of noise figure issues.

Determining Receiver Noise Temperature and Noise Figure. Most analyses of receiver performance assume that bandwidth narrows as one moves from the RF input to the IF output. The last stage has the narrowest bandwidth, and it effectively determines the overall bandwidth. Thus, if the preselector, RF amplifier, mixer, and so on, have bandwidths B_1, B_2, B_3 . . . B_N, and if B_N is much less than any of the others, then the overall bandwidth B is given by

$$B \approx \min\{B_1, B_2, B_3 \ldots B_N\} = B_N \tag{9}$$

Under these conditions, the overall noise temperature and noise figure are given by

$$T_e = T_1 + \frac{T_2}{g_1} + \frac{T_3}{g_1 g_2} + \cdots T_N \prod_{m=1}^{N-1} \frac{1}{g_m} \tag{10}$$

$$\mathrm{nf}_o = \mathrm{nf}_1 + \frac{\mathrm{nf}_2 - 1}{g_1} + \frac{\mathrm{nf}_3 - 1}{g_1 g_2} + \cdots (\mathrm{nf}_N - 1) \prod_{m=1}^{N-1} \frac{1}{g_m} \tag{11}$$

where T_i, g_i, and B_i are the noise temperature, gain, and bandwidth of the ith stage. It is important to note that the gains and noise figures in the preceding equations are ratios, not decibel values.

If one bandwidth dominates but is not the bandwidth of the last block in the chain, it is still possible to calculate T_e and NF_o. This situation occurs in some modern receiver designs that put most of their gain in a wideband amplifier at the end of the IF chain. A narrowband low-gain amplifier precedes the mixer. This architecture leads to better dynamic range performance. Under these conditions, let B_1 and g_1 be the bandwidth and gain of the low gain and narrowband part of the receiver, and let B_2 and g_2 be the bandwidth and gain of the subsequent high gain and wideband part of the receiver. The corresponding noise temperatures and noise figures are T_1 and nf_1 and T_2 and nf_2. Under these conditions, the output noise power is given by Eq. (12) and the overall noise temperature and noise figure by Eqs. (13) and (14).

$$\begin{aligned} p_o &= g_1 g_2 k T_A B_1 + g_1 g_2 k T_1 B_1 + g_2 k T_2 B_2 \\ &= g_1 g_2 k T_A B_1 + g_1 g_2 k T_e B_1 \end{aligned} \tag{12}$$

$$T_e = T_1 + T_2 \frac{B_2}{g_1 B_1} \tag{13}$$

$$\mathrm{nf}_o = 1 + \frac{T_e}{T_o} = \mathrm{nf}_1 + (\mathrm{nf}_2 - 1)\frac{B_2}{g_1 B_1} \tag{14}$$

It is possible for the wideband IF stage to dominate the receiver's noise performance in this topology. Additional filters are sometimes added just prior to the detector, or as part of the detector, effectively narrowing B_2.

Mixer Noise Performance. Like all two-port devices, mixers both process incoming noise and add to it their own internally generated noise. The situation is more complicated in mixers because the input noise is translated in frequency from two places in the spectrum. Noise coming in at the wanted signal frequency and at the unwanted image frequency appears at the IF frequency. Depending on how the total output noise power is interpreted, a mixer can be described by both a double sideband (DSB) noise figure and a single sideband (SSB) noise figure. A single sideband noise temperature corresponds to the single sideband noise figure, and a double sideband noise temperature corresponds to the double sideband noise figure. The SSB quantities are twice as large (or 3 dB larger if expressed in decibels) as the DSB quantities, which seems backward.

This confusion arises largely because SSB and DSB apply to the NF measurement technique rather than to the way in which the mixer is used. In an NF measurement, the input to the mixer is connected to a broadband noise source, and the noise power at the mixer output is compared to the noise power at the mixer input. The noise figure so measured is called the DSB NF because noise got into the mixer through both the wanted signal frequency and the unwanted image frequency. Noise at the two frequencies is analogous to the two sidebands that surround a carrier in some modulation schemes. For the given output power, there is twice as much input noise power as there would be in an SSB noise measurement. Thus, the signal-to-noise ratio is 3 dB better than it would be in an SSB noise measurement, and the DSB noise figure is 3 dB better than the SSB noise figure. See Refs. 3 and 4 for a detailed discussion of the measurement issues.

A double set of parameters with the SSB quantities larger than the DSB quantities leads to a great deal of confusion about which noise figure should be used for a particular application. See Ref. 2 for a detailed discussion of this point. The rule of thumb is if, for a particular application, the mixer input sees equal incoming noise powers at the signal and image frequencies, the mixer is described by the SSB noise temperature and noise figure. If the input noise level at the signal frequency is much greater than the input noise level at the image frequency, then the frequency-translated image noise has little effect on the output noise power, and the mixer is described by the DSB noise temperature and noise figure.

The last situation is attractive because it allows the lower noise figure to be used. The reader should note that its application does require that the mixer see insignificant input noise in the image band. If the stage immediately ahead of the mixer is an image rejection filter, its noise output in the image band should be checked. The filter could look like a noise source at the ambient temperature.

LO Phase Noise. Local oscillator noise can be a significant contributor to the overall receiver noise level. Oscillator noise takes two forms: amplitude and phase noise. In well-designed oscillators, the effect of amplitude noise can be neglected (5), but phase noise effectively phase modulates the oscillator frequency. Oscillator performance is measured in terms of the power spectral density of the resulting modulation sidebands. The spectral density can be predicted from the Q of the oscillator resonator and from the noise power generated by the active device in the oscillator (6). Figure 10 shows the phase noise in a typical oscillator output spectrum.

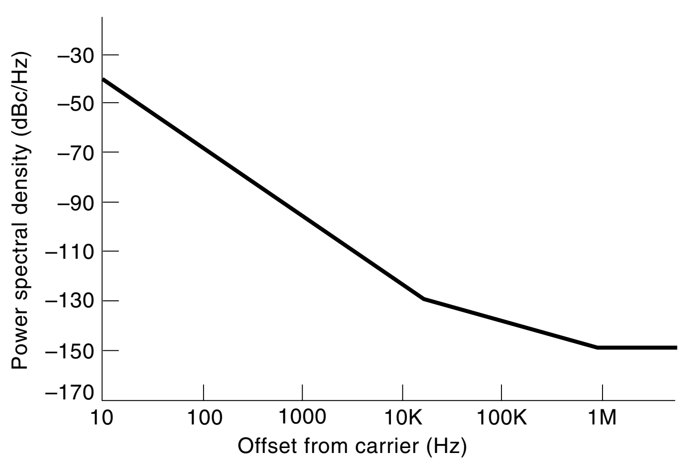

Figure 10. The phase noise spectrum of a typical local oscillator.

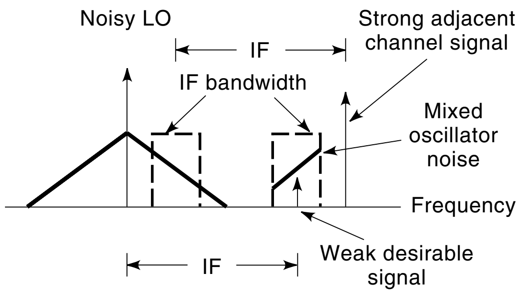

Figure 11. An illustration of reciprocal mixing, the process by which local oscillator phase noise combines with an adjacent channel signal to raise the receiver noise floor.

Phase noise degrades receiver dynamic range through what is called "reciprocal mixing." Figure 11 shows the effect of reciprocal mixing in a receiver containing a noisy LO and a strong adjacent channel signal that is outside the IF bandwidth. Without the LO noise, this signal would be rejected by the IF filter. With LO noise the strong adjacent channel signal acts as a "local oscillator" for the oscillator noise. The oscillator noise appears as signals adjacent to the LO, and those noise frequencies separated by the IF from the interfering signal will be mixed into the IF. The noise floor is increased by the oscillator phase noise, and it obscures the desired weak signal.

Phase noise produces an additional receiver impairment in systems where information is carried in signal frequency (frequency modulation, FM) or phase (phase modulation, PM). In digital phase shift keyed (PSK) systems, it is necessary to regenerate the phase of the carrier signal as a demodulation reference. Mixing transfers the phase noise of the receiver's LO to the incoming signal. This increases the phase uncertainty of the demodulation reference and leads to bit errors.

Strong Signal Behavior

Nonlinear Operation and Intermodulation Products. In ideal linear components superposition holds, and the output waveform is linearly proportional to the input waveform. No frequencies appear in the output waveform that were not present in the input waveform. Any real two-port device will, when driven hard enough, become nonlinear. Nonlinear operation in receivers creates unwanted signals called intermodulation products that interfere with the wanted signals. It also can cause a loss of sensitivity when an unwanted strong signal is close in frequency to a wanted weak signal.

To illustrate nonlinearity, consider an RF amplifier with a sinusoidal input at frequency f_1. A typical plot of input power versus the output power delivered at frequency f_1 would appear as shown in Fig. 12.

At low power levels, the relationship between output and input powers is linear. At high levels of input power, the slope decreases and the input-output relationship becomes nonlinear. This onset of nonlinearity is called gain compression (or just compression). A common measure of large-signal handling ability is the input 1 dB compression point, the input power level at which the output power falls 1 dB below the extrapolation of the linear relationship. Gain compression in a receiver results in an effect called desensitizing. If a receiver is tuned to a weak signal and a strong signal appears

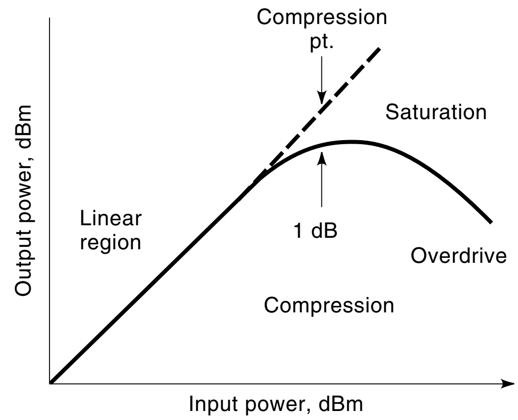

Figure 12. Nonlinear behavior of an amplifier. As the input power level increases, the gain decreases below its linear value.

in the RF amplifier's passband, the strong signal can reduce the RF amplifier gain. The gain reduction can make the weak signal disappear even though the strong signal is not translated into the IF passband and never reaches the demodulator. Desensitizing is a problem in large signal handling that is distinct from intermodulation products.

Increasing the input power beyond the 1 dB compression point causes the plot to fall farther below a linear relationship. This part of the curve is called the compression region. The output power reaches a peak and then decreases. The peak is called saturation, and the region beyond the peak is the overdrive region.

Output power falls below the linear value after compression begins because output is developed at frequencies other than the input frequency. As long as the input is a sinusoid at frequency f_1, these frequencies are harmonics of f_1 (i.e., $2f_1$, $3f_1$ . . .) and easy to filter. If the input contains two or more frequencies, then the resulting intermodulation products can interfere with and distort the wanted output signal.

Intermodulation products are usually described in terms of a two-tone test, where the input signal is two equal-amplitude sinusoids at closely spaced frequencies f_1 and f_2. These represent a wanted signal and an equal-amplitude adjacent-channel interferer. Nonlinearities cause outputs to appear at all the sums and positive differences of integer combinations of f_1 and f_2. The most important are the third-order products at frequencies $2f_1 - f_2$ and $2f_2 - f_1$, described earlier (see Fig. 13).

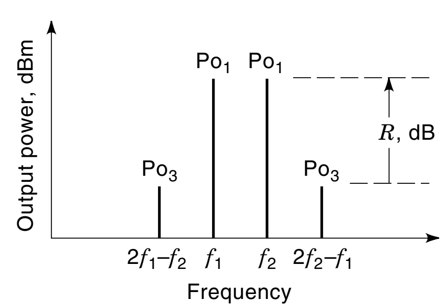

Figure 13. The spectrum of the output of a nonlinear amplifier with inputs at frequencies f_1 and f_2. The amplifier creates unwanted third-order products at frequencies $2f_1 - f_2$ and $2f_2 - f_1$. The wanted output signals are at power level Po_1 and the unwanted products are at power level Po_3.

To quantify the process, one should plot the output power Po_3 at one of the third-order frequencies ($2f_1 - f_2$ or $2f_2 - f_1$) versus the input power Po_1 at f_1 or f_2. On a dBm or dBW scale, the curve will be a straight line with a slope of 3, at least for reasonable values of input power (7). On the same graph we can also plot output power at one of the input frequencies. Below the compression region, this will be the straight line. If we extrapolate the straight line far enough, it will cross the third-order curve at the third-order intercept point. The corresponding input power is called the third-order input intercept point IIP3, and the corresponding output power is called the third-order output intercept point OIP3 (see Fig. 14). IIP3 and OIP3 measure the strong-signal handling capabilities of an amplifier, mixer, or other two-port device. Note that the third-order intercept point is a graphical construction. No real device operates at that point.

To measure the intercept points, one can drive the device at a level where the third-order products are measurable and view the output on a spectrum analyzer. Figure 13 sketches the resulting display. If Po_1 and Po_3 are the output powers in dBm at one of the wanted frequencies and one of the third-order frequencies, then the rejection R is given by

$$R = \mathrm{Po}_1 - \mathrm{Po}_3\ \mathrm{dB} \tag{15}$$

Po_1 is related to the input power P_i at one of the wanted frequencies (f_1 or f_2) by the gain, G, of the device.

$$\mathrm{Po}_1 = P_i + G\ \mathrm{dBm} \tag{16}$$

The input and output intercept points can be calculated from

$$\mathrm{IIP}_3 = \frac{R}{2} + P_i\ \mathrm{dBm} \tag{17}$$

$$\mathrm{OIP}_3 = \frac{R}{2} + Po_1\ \mathrm{dBm} \tag{18}$$

$$\mathrm{OIP}_3 = \mathrm{IIP}_3 + G\ \mathrm{dBm} \tag{19}$$

Determining Receiver Third-Order Intercept Point. Consider a receiver that consists of a cascaded system of M stages with dB gains G_i and dBm input intercept points IIP_i. The corresponding linear values are g_i and iip_i.

Following Ref. 8, we assume that (1) the interfaces between stages are all at 50 Ω, and (2) the third-order products add in-phase. Assumption (1) is realistic, and assumption (2) leads to a worst-case analysis. Under these conditions, we can project the output intercept points of the individual stages through to the output of the last stage and add the projected values reciprocally. For 1, 2, 3, and M stages, the overall output intercept point in milliwatts is given by

$$\mathrm{oip_o} = \frac{1}{\dfrac{1}{\mathrm{oip}_1}} \text{ for 1 stage} \tag{20}$$

$$\mathrm{oip_o} = \frac{1}{\dfrac{1}{\mathrm{oip}_2} + \dfrac{1}{g_2 \times \mathrm{oip}_1}} \text{ for 2 stages} \tag{21}$$

$$\mathrm{oip_o} = \frac{1}{\dfrac{1}{\mathrm{oip}_3} + \dfrac{1}{g_3 \times \mathrm{oip}_2} + \dfrac{1}{g_3 \times g_2 \times \mathrm{oip}_1}} \text{ for 3 stages} \tag{22}$$

$$\mathrm{oip_o} = \frac{1}{\dfrac{1}{\mathrm{oip}_M} + \sum_{i=1}^{M-1} \dfrac{1}{\mathrm{oip}_i \times \prod_{k=i+1}^{M} g_k}} \text{ for } M \text{ stages} \tag{23}$$

This formula can be written in a simpler form to yield $\mathrm{OIP_o}$ directly in dBm:

$$\mathrm{OIP_o} = -10\log_{10}\left[\sum_{i=1}^{M} \frac{1}{\mathrm{oip}_i\, g_{i+1} g_{i+2} \cdots g_M}\right] \tag{24}$$

The overall input intercept point is the overall output intercept point divided by the total gain.

$$\mathrm{iip_o} = \frac{\mathrm{oip_o}}{\prod_{i=1}^{M} g_i} \tag{25}$$

Expressed in dBm,

$$\mathrm{IIP_o} = \mathrm{OIP_o} - \sum_{i=1}^{M} G_i \tag{26}$$

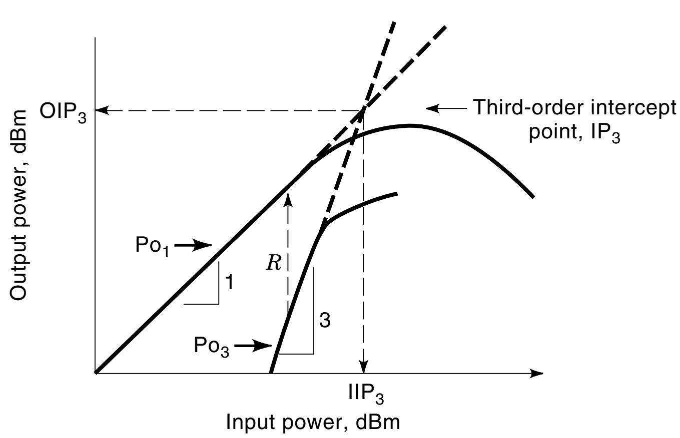

Figure 14. An illustration of how first-order (Po_1) and third-order (Po_3) output power increase with increasing input power in a nonlinear device. The straight-line extrapolations of the two curves cross at the third-order intercept point.

Dynamic Range

The dynamic range of a receiver is the decibel difference between the strongest signal and the weakest signal that the receiver can handle. There are multiple definitions of dynamic range, depending on how the strongest signal and the weakest signal are defined.

Spurious Free Dynamic Range. Spurious free dynamic range makes the weakest signal the MDS (receiver noise floor $kT_S B$), where T_S is the system noise temperature and B is the bandwidth. T_S is the sum of the antenna noise temperature T_A and the effective input noise temperature of the receiver T_e:

$$T_S = T_A + T_e \tag{27}$$

so this definition describes the receiver when it is used with an antenna having a specified noise temperature.

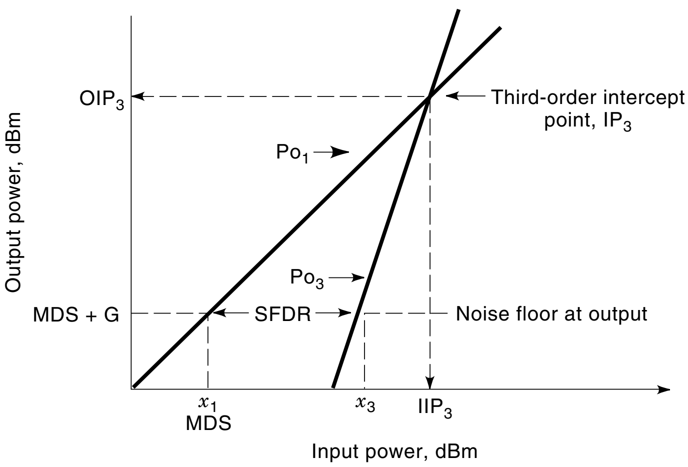

Figure 15. The spurious free dynamic range of a receiver is the decibel difference between the noise floor and the input signal level that would bring third-order products to the noise floor.

The strongest signal used in the SFDR definition is the input power that, in a two-tone intermodulation test, makes the power in either of the third-order products at the receiver output equal to the noise power (see Fig. 15). Mathematically,

$$\mathrm{SFDR} = \frac{2}{3}(\mathrm{IIP}_3 - \mathrm{MDS})\,\mathrm{dB} \tag{28}$$

Other Definitions of Dynamic Range. In practice, third-order products may be tolerated at levels somewhat higher than the noise floor. The maximum permissible signal may be the input power for which the rejection R in Eq. (17) reaches a specified level.

UHF Receiver Design

LO and IF Frequency Selection. There are several standard IF frequencies (10.7 MHz and 45 MHz are two examples commonly used in UHF radios), and the selected IF frequency should be one for which appropriately priced components are available. The higher the IF frequency, the farther images will lie from the wanted frequency and the easier it will be to filter them out. Beyond these general guidelines, the IF and LO frequencies should be selected so that no high-level intermodulation products fall within the IF passband.

To illustrate the process, consider a mixer with input signal f_S, local oscillator signal f_L, and wanted IF output signal f_I. Depending on whether the LO frequency is above (high-side injection) or below (low-side injection) the signal frequency, the mixer will produce a wanted output at either

$$f_I = f_L - f_R \tag{29}$$

or

$$f_I = f_R - f_L \tag{30}$$

The mixer will also produce unwanted outputs at all positive values of

$$f_o(m,n) = \pm(mf_L \mp nf_R) \tag{31}$$

where m and n are positive integers. If any of these spurious responses ("spurs") fall within the IF passband—that is, if

$$f_o(m,n) = f_I \pm \frac{B}{2} \tag{32}$$

where B is the IF bandwidth—they can interfere with wanted signals. The frequencies f_I, f_R, and f_L must be chosen so that this either does not occur or any spurs within the IF passband are at negligible power levels. The process, described later, is outlined in Ref. 9. The amplitudes of the spurs depend on the nature of the mixer's nonlinearity. Typical values are found in Ref. 10 and in most mixer manufacturer's catalogs.

We began by treating the frequencies as parameters and m and n as positive real variables. The relationship between m and n is

$$n = \pm\frac{f_I}{f_R} \pm m\frac{f_L}{f_R} \tag{33}$$

All solutions to Eq. (33) that yield integer values of m and n correspond to spurious responses that may fall within the IF passband of the receiver.

Plotting these equations on a set of n versus m axes (Fig. 16) yields three straight lines whose equations are

$$\begin{aligned} n &= \frac{f_I}{f_R} + m\frac{f_L}{f_R}\,(\text{curve I}) \\ n &= \frac{f_I}{f_R} - m\frac{f_L}{f_R}\,(\text{curve II}) \\ n &= -\frac{f_I}{f_R} + m\frac{f_L}{f_R}\,(\text{curve III}) \end{aligned} \tag{34}$$

We plot these for f_R and f_L corresponding to the upper and lower limits of the receiver's tuning range. The needed lines are easy to draw from the known intercepts (f_I/f_R) and (f_I/f_L) and the slope (f_L/f_R). Ideally only the line representing the wanted response should pass through a point corresponding to integer values of m and n. That should be the (1, 1) point.

If one of the plotted curves comes close to an integer-valued point, we can determine if the corresponding spur lies within the passband by plotting the appropriate line with f_I replaced by $f_I \pm B/2$.

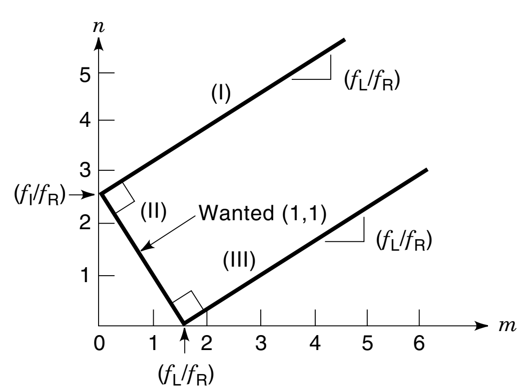

Figure 16. A graphical technique to check for mixer spurious responses in a receiver. The three straight lines are plotted from Eq. (34). In an ideal receiver design, the lines would not cross any points corresponding to integer values of both m and n except (1, 1).

With properly chosen IF and LO frequencies, no high-level spurs will fall within the IF passband. Usually, a high LO frequency gives better performance.

Mixer Selection (11). Almost any nonlinear device can serve as a mixer. Mixers can be active or passive, and they can rely on filters or cancellation or on some combination of both to provide needed isolation between their RF, IF, and LO ports. Figures of merit for mixers include conversion gain, noise figure, third-order intercept point, required LO drive, and relative levels of intermodulation products. Some mixer types are more sensitive to impedance mismatches than others.

Active mixers require dc power, less amplifier gain, and less LO drive than passive mixers. Passive mixers do not need dc, but they require more LO drive and more amplifier gain than active mixers. Which type of mixer requires less total dc power for the whole receiver depends on the overall design. Manufacturing factors (cost, ease of automated assembly, etc.) may be more important in mixer selection than small differences in RF characteristics or power consumption.

Mixers may be unbalanced, single balanced, or double balanced. An unbalanced mixer usually has a single active component (a diode or a transistor) and relies on filters to provide LO-RF and LO-IF isolation. Single-balanced mixers use cancellation to achieve LO-RF isolation and filters for LO-IF isolation. Double-balanced mixers use cancellation to achieve both LO-RF and LO-IF isolation. Usually (but not always) whether a mixer is unbalanced, single balanced, or double balanced can be determined by counting the balun transformers. An unbalanced mixer has none, a single-balanced mixer usually has one, and a double-balanced mixer usually has two.

Diode mixers operate as switches and chop the RF waveform at the LO frequency. Since proper operation depends on the LO rather than the RF signal turning the diodes on and off, the maximum RF power that a diode mixer can handle without unacceptable distortion is somewhere between 10 and 6 dB below the LO level. Switching-diode mixers usually offer a larger dynamic range but higher conversion loss and noise figure than mixers whose operation is based on device nonlinearity.

Low-cost double-balanced diode mixers are widely available. They are inherently broadband and offer conversion gains typically between −6 and −8 dB. Required RF drive levels are fairly high—+5 dBm is typical.

Passive field-effect transistor (FET) mixers apply the LO directly to the gate of an unbiased FET. The LO drive modulates the channel resistance at the LO frequency, and the RF signal applied to the drain sees this modulation. Because their operation is based on this resistance modulation, passive FET mixers are often called FET resistive mixers. Their primary advantage over diode mixers is that they offer very good intermodulation distortion performance; third-order input intercept points of +30 dBm or better are possible. FET resistive mixers can be made with single devices or in single-balanced and double-balanced configurations.

Active FET mixers can consist of single devices. In the past, dual-gate active FET mixers were common, but these have largely disappeared. Gilbert cell multipliers offer uniformly good performance.

An image-canceling mixer contains two internal mixers whose LO drives are 90° out of phase. The RF amplifier output is divided and fed to both mixers in phase. The output of one internal mixer is phase shifted by an additional 90°. The resulting waveforms may be added or subtracted to cancel the unwanted (image) response. (See Ref. 2.) Successful operation of an image-canceling mixer depends on maintaining the required power levels and phase shifts over the IF bandwidth for the expected signal amplitudes and operating temperature ranges. Typical image suppression is in the 28 to 45 dB range.

RF and IF Amplifiers. RF amplifiers for UHF receivers are selected to give the desired overall noise figure and dynamic range. IF amplifiers are selected to present a particular desired signal level at the demodulator. To keep the demodulator from being overdriven at high input signal levels, IF amplifiers may incorporate limiting or automatic gain control (AGC), depending on whether or not signal amplitude information is important. Both RF and IF amplifiers are available as separate components for all standard frequency bands, chips combining IF and mixing or RF and mixing functions are widely available. These typically incorporate Gilbert cell multipliers. One current example is the Motorola MC13156 wideband IF system that may be used as the basis for a complete radio or IF system for frequencies up to 500 MHz. Another is the RF Micro-Devices RF2411, covering 500 MHz to 1900 MHz.

RF and IF Filters. The first stage of most receivers is a bandpass filter (often called a preselector) that rejects noise and unwanted signals (particularly unwanted signals at image frequencies) outside of the desired tuning range. Bandpass filters at IF keep unwanted mixer products out of the demodulator, select the desired channel, and determine the overall noise bandwidth of the receiver. The IF filter usually determines the selectivity of a superhet receiver.

Selecting RF and IF filters is similar to selecting mixers. There are many competing types and usually no immediately obvious best choice for a given application. RF filter design and manufacturing are so specialized that receiver designers usually select filters from catalogs and data sheets instead of building their own. Selection is based on technical characteristics, price, and manufacturing considerations.

Filters for IF include crystal, ceramic, and SAW (surface acoustic wave). RF filters can be made with SAW, dielectric, helical resonator, and transmission line technologies. *LC* filters tend to be too lossy for these applications. Active filters are usually not available or not cost effective at RF and IF frequencies.

Filter specifications are based on treating the filter as a two-port device driven by a source with a specified resistance R_I and feeding a load resistance R_o. The values of R_I and R_o depend on the filter type and frequency range. For example, ceramic filters for 10.7 MHz IF applications expect to see 330 Ω, while values between 1 and 2.5 kΩ are common for 455 kHz ceramic filters.

Let V_o and V_i be the phasor output and input voltages for a filter operating at frequency f. The complex transfer function $H(f)$ of the filter is given by

$$H(f) = \frac{V_o(f)}{V_i(f)} = |H(f)|e^{-j\phi(f)} \tag{35}$$

The filter attenuation A in dB is given by

$$A(f) = -20\log_{10}|H(f)| \tag{36}$$

Insertion loss (IL) is the value of A at the filter's center frequency f_0.

$$\mathrm{IL} = A(f_0) \tag{37}$$

Manufacturers normally provide plots of A versus f. A variety of bandwidths are often specified in addition to the expected 3 dB value. The shape factor of a filter is the ratio of one of these larger bandwidths (for example, the 60 dB bandwidth) to the 3 dB bandwidth. An ideal "brick wall" filter would have a shape factor of 1.

The phase response $\phi(f)$ of a filter is also important, but it is plotted far less frequently. Ideally, $\phi(f)$ should be a linear function of frequency. In that case, the spectral components of a complex waveform would pass through the filter without changing their relative phases. Phase distortion is particularly important in analog FM and in digital applications.

Phase distortion is measured by group delay, T, which has units of time and is given by

$$T = \frac{\partial\phi}{\partial\omega} = \frac{1}{2\pi}\frac{\partial\phi}{\partial f} \tag{38}$$

Relating receiver performance to filter group delays usually requires computer simulation. No simple formulas are available.

Some mixers (diode mixers in particular) are sensitive to the impedance presented at the IF port at frequencies outside of the passband. Some crystal filters are particularly troubling in this regard. Diplexer circuits are available to isolate the mixer from the filter's impedance variations. See Ref. 2 for a further discussion of this issue.

Demodulators. The choice of demodulator for a given receiver design depends on the modulation that is to be received. For a given application, demodulators differ in fidelity, dynamic range, and input and output signal levels.

RF Integrated Circuits for UHF Receivers. The level of integration available in receivers and receiver subsystems is increasing rapidly, particularly for consumer applications. For further information, see Refs. 12–14.

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ULTRASHORT PULSE TECHNOLOGY.

See PULSE COMPRESSION.