RF and Microwave Wireless Systems

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To my parents and my family

Contents

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CHAPTER FIVE

Receiver System Parameters

5.1 TYPICAL RECEIVERS

A receiver picks up the modulated carrier signal from its antenna. The carrier signal is downconverted, and the modulating signal (information) is recovered. Figure 5.1 shows a diagram of typical radio receivers using a double-conversion scheme. The receiver consists of a monopole antenna, an RF amplifier, a synthesizer for LO signals, an audio amplifier, and various mixers, IF amplifiers, and filters. The input signal to the receiver is in the frequency range of 20–470 MHz; the output signal is an audio signal from 0 to 8 kHz. A detector and a variable attenuator are used for automatic gain control (AGC). The received signal is first downconverted to the first IF frequency of 515 MHz. After amplification, the first IF frequency is further downconverted to 10.7 MHz, which is the second IF frequency. The frequency synthesizer generates a tunable and stable LO signal in the frequency range of 535–985 MHz to the first mixer. It also provides the LO signal of 525.7 MHz to the second mixer.

Other receiver examples are shown in Fig. 5.2. Figure 5.2*a* shows a simplified transceiver block diagram for wireless communications. A T/R switch is used to separate the transmitting and receiving signals. A synthesizer is employed as the LO to the upconverter and downconverter. Figure 5.2*b* is a mobile phone transceiver (transmitter and receiver) [1]. The transceiver consists of a transmitter and a receiver separated by a filter diplexer (duplexer). The receiver has a low noise RF amplifier, a mixer, an IF amplifier after the mixer, bandpass filters before and after the mixer, and a demodulator. A frequency synthesizer is used to generate the LO signal to the mixer.

Most components shown in Figs. 5.1 and 5.2 have been described in Chapters 3 and 4. This chapter will discuss the system parameters of the receiver.

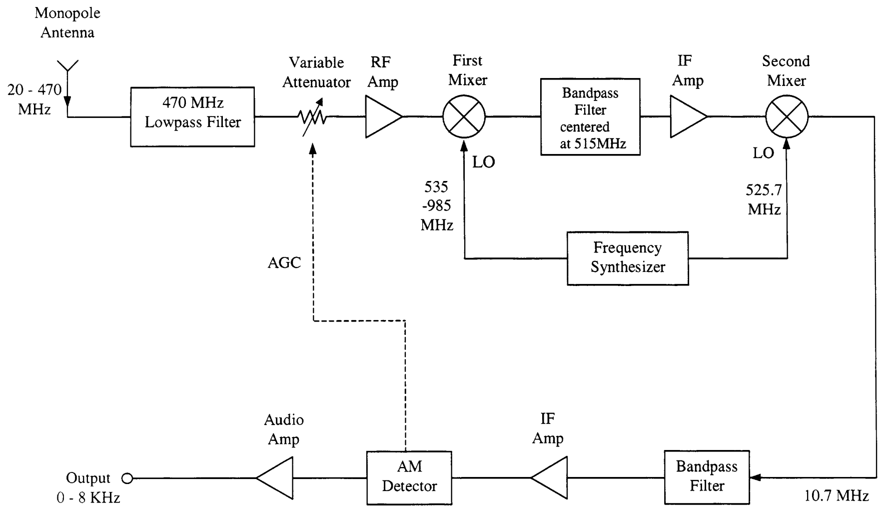

FIGURE 5.1 Typical radio receiver.

5.2 SYSTEM CONSIDERATIONS

The receiver is used to process the incoming signal into useful information, adding minimal distortion. The performance of the receiver depends on the system design, circuit design, and working environment. The acceptable level of distortion or noise varies with the application. Noise and interference, which are unwanted signals that appear at the output of a radio system, set a lower limit on the usable signal level at the output. For the output signal to be useful, the signal power must be larger than the noise power by an amount specified by the required minimum signal-to-noise ratio. The minimum signal-to-noise ratio depends on the application, for example, 30 dB for a telephone line, 40 dB for a TV system, and 60 dB for a good music system.

To facilitate the discussion, a dual-conversion system as shown in Fig. 5.3 is used. A preselector filter (Filter 1) limits the bandwidth of the input spectrum to minimize the intermodulation and spurious responses and to suppress LO energy emission. The RF amplifier will have a low noise figure, high gain, and a high intercept point, set for receiver performance. Filter 2 is used to reject harmonics generated by the RF amplifier and to reject the image signal generated by the first mixer. The first mixer generates the first IF signal, which will be amplified by an IF amplifier. The IF amplifier should have high gain and a high intercept point. The first LO source should have low phase noise and sufficient power to pump the mixer. The receiver system considerations are listed below.

1. *Sensitivity.* Receiver sensitivity quantifies the ability to respond to a weak signal. The requirement is the specified signal-noise ratio (SNR) for an analog receiver and bit error rate (BER) for a digital receiver.

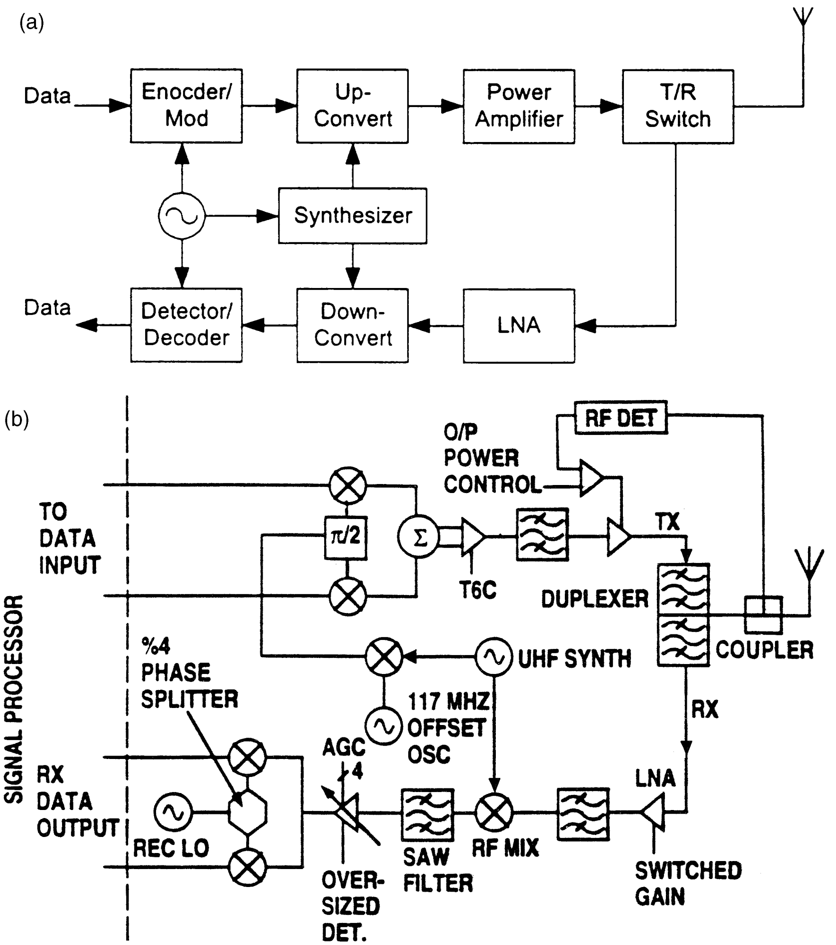

FIGURE 5.2 (a) Simplified transceiver block diagram for wireless communications. (b) Typical mobile phone transceiver system. (From reference [1], with permission from IEEE.)

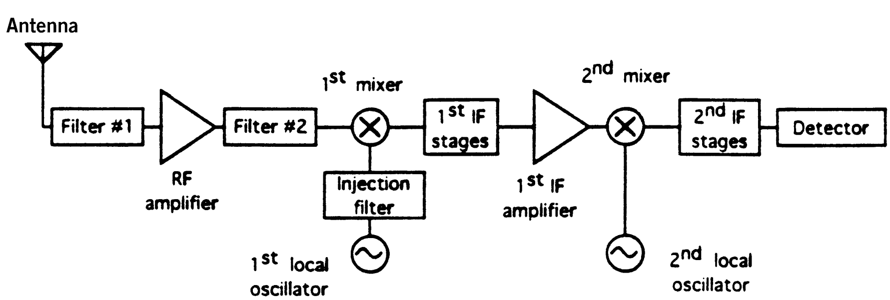

FIGURE 5.3 Typical dual-conversion receiver.

2. *Selectivity*. Receiver selectivity is the ability to reject unwanted signals on adjacent channel frequencies. This specification, ranging from 70 to 90 dB, is difficult to achieve. Most systems do not allow for simultaneously active adjacent channels in the same cable system or the same geographical area.
3. *Spurious Response Rejection*. The ability to reject undesirable channel responses is important in reducing interference. This can be accomplished by properly choosing the IF and using various filters. Rejection of 70 to 100 dB is possible.
4. *Intermodulation Rejection*. The receiver has the tendency to generate its own on-channel interference from one or more RF signals. These interference signals are called intermodulation (IM) products. Greater than 70 dB rejection is normally desirable.
5. *Frequency Stability*. The stability of the LO source is important for low FM and phase noise. Stabilized sources using dielectric resonators, phase-locked techniques, or synthesizers are commonly used.
6. *Radiation Emission*. The LO signal could leak through the mixer to the antenna and radiate into free space. This radiation causes interference and needs to be less than a certain level specified by the FCC.

5.3 NATURAL SOURCES OF RECEIVER NOISE

The receiver encounters two types of noise: the noise picked up by the antenna and the noise generated by the receiver. The noise picked up by the antenna includes sky noise, earth noise, atmospheric (or static) noise, galactic noise, and man-made noise. The sky noise has a magnitude that varies with frequency and the direction to which the antenna is pointed. Sky noise is normally expressed in terms of the noise temperature (T_A) of the antenna. For an antenna pointing to the earth or to the horizon $T_A \simeq 290$ K. For an antenna pointing to the sky, its noise temperature could be a few kelvin. The noise power is given by

$$N = kT_AB \tag{5.1}$$

where B is the bandwidth and k is Boltzmann's constant,

$$k = 1.38 \times 10^{-23} \text{ J/K}$$

Static or atmospheric noise is due to a flash of lightning somewhere in the world. The lightning generates an impulse noise that has the greatest magnitude at 10 kHz and is negligible at frequencies greater than 20 MHz.

Galactic noise is produced by radiation from distant stars. It has a maximum value at about 20 MHz and is negligible above 500 MHz.

Man-made noise includes many different sources. For example, when electric current is switched on or off, voltage spikes will be generated. These transient spikes occur in electronic or mechanical switches, vehicle ignition systems, light switches, motors, and so on. Electromagnetic radiation from communication systems, broadcast systems, radar, and power lines is everywhere, and the undesired signals can be picked up by a receiver. The interference is always present and could be severe in urban areas.

In addition to the noise picked up by the antenna, the receiver itself adds further noise to the signal from its amplifier, filter, mixer, and detector stages. The quality of the output signal from the receiver for its intended purpose is expressed in terms of its signal-to-noise ratio (SNR):

$$\text{SNR} = \frac{\text{wanted signal power}}{\text{unwanted noise power}} \tag{5.2}$$

A tangential detectable signal is defined as SNR $= 3\,\text{dB}$ (or a factor of 2). For a mobile radio-telephone system, SNR $> 15\,\text{dB}$ is required from the receiver output. In a radar system, the higher SNR corresponds to a higher probability of detection and a lower false-alarm rate. An SNR of 16 dB gives a probability detection of 99.99% and a probability of false-alarm rate of 10^{-6} [2].

The noise that occurs in a receiver acts to mask weak signals and to limit the ultimate sensitivity of the receiver. In order for a signal to be detected, it should have a strength much greater than the noise floor of the system. Noise sources in thermionic and solid-state devices may be divided into three major types.

1. *Thermal, Johnson, or Nyquist Noise*. This noise is caused by the random fluctuations produced by the thermal agitation of the bound charges. The *rms* value of the thermal resistance noise voltage of V_n over a frequency range B is given by

$$V_n^2 = 4kTBR \tag{5.3}$$

   where k = Boltzman constant $= 1.38 \times 10^{-23}$ J/K
   T = resistor absolute temperature, K
   B = bandwidth, Hz
   R = resistance, Ω

   From Eq. (5.3), the noise power can be found to exist in a given bandwidth regardless of the center frequency. The distribution of the same noise-per-unit bandwidth everywhere is called white noise.

2. *Shot Noise*. The fluctuations in the number of electrons emitted from the source constitute the shot noise. Shot noise occurs in tubes or solid-state devices.

3. *Flicker, or* $1/f$, *Noise*. A large number of physical phenomena, such as mobility fluctuations, electromagnetic radiation, and quantum noise [3], exhibit a noise power that varies inversely with frequency. The $1/f$ noise is important from 1 Hz to 1 MHz. Beyond 1 MHz, the thermal noise is more noticeable.

5.4 RECEIVER NOISE FIGURE AND EQUIVALENT NOISE TEMPERATURE

Noise figure is a figure of merit quantitatively specifying how noisy a component or system is. The noise figure of a system depends on a number of factors such as losses in the circuit, the solid-state devices, bias applied, and amplification. The noise factor of a two-port network is defined as

$$F = \frac{\text{SNR at input}}{\text{SNR at output}} = \frac{S_i/N_i}{S_o/N_o} \tag{5.4}$$

The noise figure is simply the noise factor converted in decibel notation.

Figure 5.4 shows the two-port network with a gain (or loss) G. We have

$$S_o = GS_i \tag{5.5}$$

Note that $N_o \neq GN_i$; instead, the output noise $N_o = GN_i +$ noise generated by the network. The noise added by the network is

$$N_n = N_o - GN_i \quad \text{(W)} \tag{5.6}$$

Substituting (5.5) into (5.4), we have

$$F = \frac{S_i/N_i}{GS_i/N_o} = \frac{N_o}{GN_i} \tag{5.7}$$

Therefore,

$$N_o = FGN_i \quad \text{(W)} \tag{5.8}$$

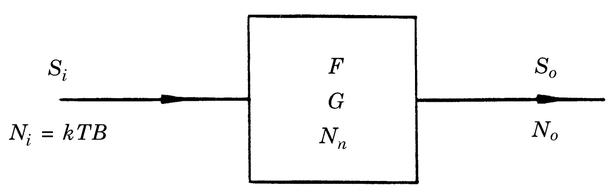

FIGURE 5.4 Two-port network with gain G and added noise power N_n.

Equation (5.8) implies that the input noise N_i (in decibels) is raised by the noise figure F (in decibels) and the gain (in decibels).

Since the noise figure of a component should be independent of the input noise, F is based on a standard input noise source N_i at room temperature in a bandwidth B, where

$$N_i = kT_0B \quad \text{(W)} \tag{5.9}$$

where k is the Boltzmann constant, $T_0 = 290$ K (room temperature), and B is the bandwidth. Then, Eq. (5.7) becomes

$$F = \frac{N_o}{GkT_0B} \tag{5.10}$$

For a cascaded circuit with n elements as shown in Fig. 5.5, the overall noise factor can be found from the noise factors and gains of the individual elements [4]:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \cdots + \frac{F_n - 1}{G_1G_2\cdots G_{n-1}} \tag{5.11}$$

Equation (5.11) allows for the calculation of the noise figure of a general cascaded system. From Eq. (5.11), it is clear that the gain and noise figure in the first stage are critical in achieving a low overall noise figure. It is very desirable to have a low noise figure and high gain in the first stage. To use Eq. (5.11), all F's and G's are in ratio. For a passive component with loss L in ratio, we will have $G = 1/L$ and $F = L$ [4].

Example 5.1 For the two-element cascaded circuit shown in Fig. 5.6, prove that the overall noise factor

$$F = F_1 + \frac{F_2 - 1}{G_1}$$

Solution From Eq. (5.10)

$$N_o = F_{12}G_{12}kT_0B \qquad N_{o1} = F_1G_1kT_0B$$

From Eqs. (5.6) and (5.8)

$$N_{n2} = (F_2 - 1)G_2kT_0B$$

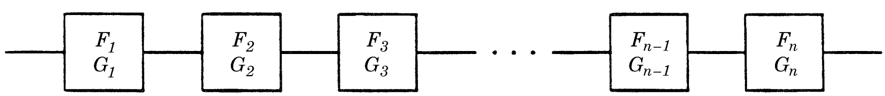

FIGURE 5.5 Cascaded circuit with n networks.

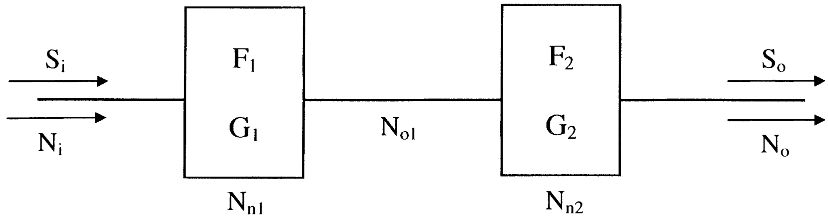

FIGURE 5.6 Two-element cascaded circuit.

From Eq. (5.6)

$$N_o = N_{o1}G_2 + N_{n2}$$

Substituting the first three equations into the last equation leads to

$$\begin{aligned} N_o &= F_1G_1G_2kT_0B + (F_2 - 1)G_2kT_0B \\ &= F_{12}G_{12}kT_0B \end{aligned}$$

Overall,

$$\begin{aligned} F = F_{12} &= \frac{F_1G_1G_2kT_0B}{G_1G_2kT_0B} + \frac{(F_2 - 1)G_2kT_0B}{G_1G_2kT_0B} \\ &= F_1 + \frac{F_2 - 1}{G_1} \end{aligned}$$

The proof can be generalized to n elements. ■

Example 5.2 Calculate the overall gain and noise figure for the system shown in Fig. 5.7.

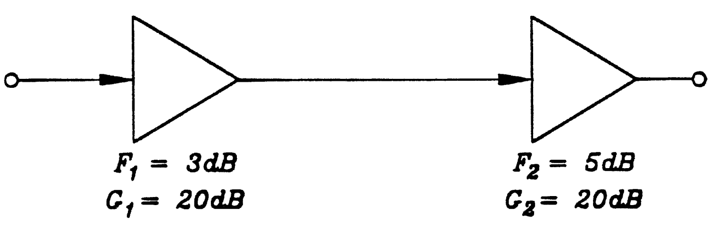

FIGURE 5.7 Cascaded amplifiers.

Solution

$$F_1 = 3 \text{ dB} = 2 \qquad F_2 = 5 \text{ dB} = 3.162$$
$$G_1 = 20 \text{ dB} = 100 \qquad G_2 = 20 \text{ dB} = 100$$
$$G = G_1 G_2 = 10{,}000 = 40 \text{ dB}$$
$$F = F_1 + \frac{F_2 - 1}{G_1} = 2 + \frac{3.162 - 1}{100}$$
$$= 2 + 0.0216 = 2.0216 = 3.06 \text{ dB}.$$

■

Note that $F \approx F_1$ due to the high gain in the first stage. The first-stage amplifier noise figure dominates the overall noise figure. One would like to select the first-stage RF amplifier with a low noise figure and a high gain to ensure the low noise figure for the overall system.

The equivalent noise temperature is defined as

$$T_e = (F - 1)T_0 \tag{5.12}$$

where $T_0 = 290$ K (room temperature) and F in ratio. Therefore,

$$F = 1 + \frac{T_e}{T_0} \tag{5.13}$$

Note that T_e is not the physical temperature. From Eq. (5.12), the corresponding T_e for each F is given as follows:

F (dB)	3	2.28	1.29	0.82	0.29
T_e (K)	290	200	100	60	20

For a cascaded circuit shown as Fig. 5.8, Eq. (5.11) can be rewritten as

$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots + \frac{T_{en}}{G_1 G_2 \cdots G_{n-1}} \tag{5.14}$$

where T_e is the overall equivalent noise temperature in kelvin.

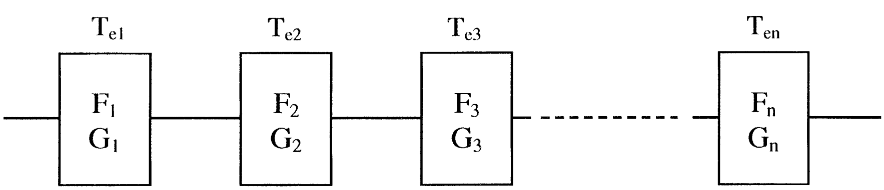

FIGURE 5.8 Noise temperature for a cascaded circuit.

The noise temperature is useful for noise factor calculations involving an antenna. For example, if an antenna noise temperature is T_A, the overall system noise temperature including the antenna is

$$T_S = T_A + T_e \tag{5.15}$$

where T_e is the overall cascaded circuit noise temperature.

As pointed out earlier in Section 5.3, the antenna noise temperature is approximately equal to 290 K for an antenna pointing to earth. The antenna noise temperature could be very low (a few kelvin) for an antenna pointing to the sky.

5.5 COMPRESSION POINTS, MINIMUM DETECTABLE SIGNAL, AND DYNAMIC RANGE

In a mixer, an amplifier, or a receiver, operation is normally in a region where the output power is linearly proportional to the input power. The proportionality constant is the conversion loss or gain. This region is called the dynamic range, as shown in Fig. 5.9. For an amplifier, the curve shown in Fig. 5.9 is for the fundamental signals. For a mixer or receiver, the curve is for the IF signals. If the input power is above this range, the output starts to saturate. If the input power is below this range, the noise dominates. The dynamic range is defined as the range between the 1-dB compression point and the minimum detectable signal (MDS). The range could be specified in terms of input power (as shown in Fig. 5.9) or output power. For a mixer, amplifier, or receiver system, we would like to have a high dynamic range so the system can operate over a wide range of input power levels.

The noise floor due to a matched resistor load is

$$N_i = kTB \tag{5.16}$$

where k is the Boltzmann constant. If we assume room temperature (290 K) and 1 MHz bandwidth, we have

$$\begin{aligned} N_i &= 10 \log kTB = 10 \log(4 \times 10^{-12}\ \text{mW}) \\ &= -114\ \text{dBm} \end{aligned} \tag{5.17}$$

The MDS is defined as 3 dB above the noise floor and is given by

$$\begin{aligned} \text{MDS} &= -114\ \text{dBm} + 3\ \text{dB} \\ &= -111\ \text{dBm} \end{aligned} \tag{5.18}$$

Therefore, MDS is -111 dBm (or 7.94×10^{-12} mW) in a megahertz bandwidth at room temperature.

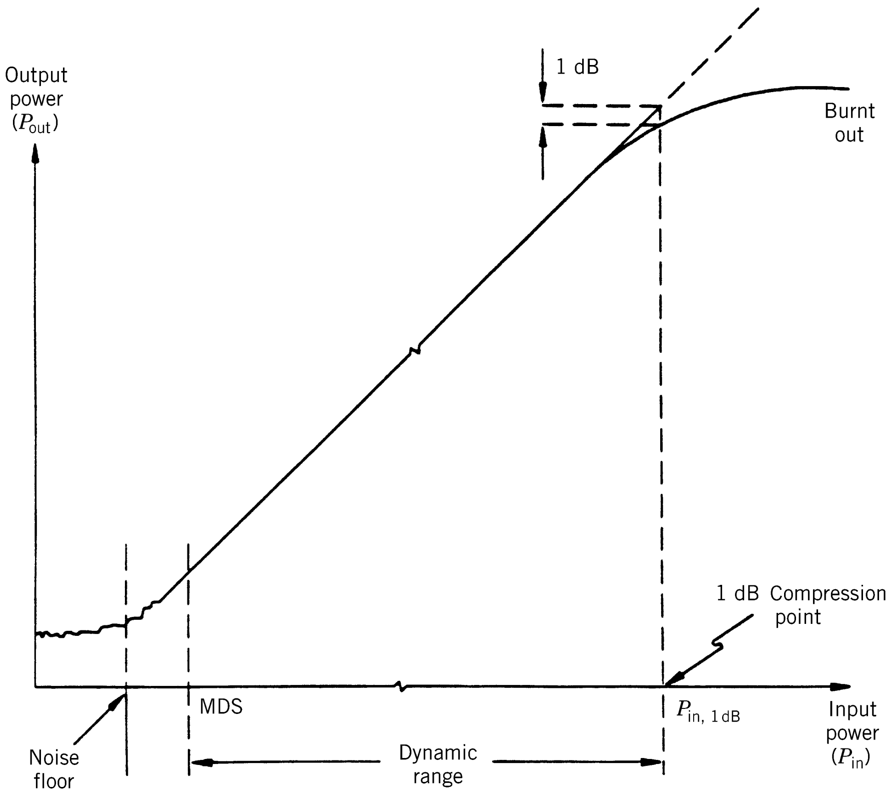

FIGURE 5.9 Realistic system response for mixers, amplifiers, or receivers.

The 1-dB compression point is shown in Fig. 5.9. Consider an example for a mixer. Beginning at the low end of the dynamic range, just enough RF power is fed into the mixer to cause the IF signal to be barely discernible above the noise. Increasing the RF input power causes the IF output power to increase decibel for decibel of input power; this continues until the RF input power reaches a level at which the IF output power begins to roll off, causing an increase in conversion loss. The input power level at which the conversion loss increases by 1 dB, called the 1-dB compression point, is generally taken to be the top limit of the dynamic range. Beyond this range, the conversion loss is higher, and the input RF power not converted into the desired IF output power is converted into heat and higher order intermodulation products.

In the linear region for an amplifier, a mixer, or a receiver,

$$P_{\text{in}} = P_{\text{out}} - G \tag{5.19}$$

where G is the gain of the receiver or amplifier, $G = -L_c$ for a lossy mixer with a conversion loss L_c (in decibels).

The input signal power in dBm that produces a 1-dB gain in compression is shown in Fig. 5.9 and given by

$$P_{\text{in},1\text{dB}} = P_{\text{out},1\text{dB}} - G + 1\text{ dB} \tag{5.20}$$

for an amplifier or a receiver with gain.

For a mixer with conversion loss,

$$P_{\text{in},1\text{dB}} = P_{\text{out},1\text{dB}} + L_c + 1\text{ dB} \tag{5.21}$$

or one can use Eq. (5.20) with a negative gain. Note that $P_{\text{in},1\text{dB}}$ and $P_{\text{out},1\text{dB}}$ are in dBm, and gain and L_c are in decibels. Here $P_{\text{out},1\text{dB}}$ is the output power at the 1-dB compression point, and $P_{\text{in},1\text{dB}}$ is the input power at the 1-dB compression point. Although the 1-dB compression points are most commonly used, 3-dB compression points and 10-dB compression points are also used in some system specifications.

From the 1-dB compression point, gain, bandwidth, and noise figure, the dynamic range (DR) of a mixer, an amplifier, or a receiver can be calculated. The DR can be defined as the difference between the input signal level that causes a 1-dB compression gain and the minimum input signal level that can be detected above the noise level:

$$\text{DR} = P_{\text{in},1\text{dB}} - \text{MDS} \tag{5.22}$$

Note that $P_{\text{in},1\text{dB}}$ and MDS are in dBm and DR in decibels.

Example 5.3 A receiver operating at room temperature has a noise figure of 5.5 dB and a bandwidth of 2 GHz. The input 1-dB compression point is +10 dBm. Calculate the minimum detectable signal and dynamic range.

Solution

$$\begin{aligned} F &= 5.5\text{ dB} = 3.6 \qquad B = 2 \times 10^9\text{ Hz} \\ \text{MDS} &= 10\log kTBF + 3\text{ dB} \\ &= 10\log(1.38 \times 10^{-23} \times 290 \times 2 \times 10^9 \times 3.6) + 3 \\ &= -102.5\text{ dBW} = -72.5\text{ dBm} \\ \text{DR} &= P_{\text{in},1\text{dB}} - \text{MDS} = 10\text{ dBm} - (-72.5\text{ dBm}) = 82.5\text{ dB} \end{aligned}$$

■

5.6 THIRD-ORDER INTERCEPT POINT AND INTERMODULATION

When two or more signals at frequencies f_1 and f_2 are applied to a nonlinear device, they generate IM products according to $mf_1 \pm nf_2$ (where $m, n = 0, 1, 2, \ldots$). These may be the second-order $f_1 \pm f_2$ products, third-order $2f_1 \pm f_2$, $2f_2 \pm f_1$ products, and so on. The two-tone third-order IM products are of primary interest since they tend to have frequencies that are within the passband of the first IF stage.

Consider a mixer or receiver as shown in Fig. 5.10, where f_{IF1} and f_{IF2} are the desired IF outputs. In addition, the third-order IM (IM3) products f_{IM1} and f_{IM2} also appear at the output port. The third-order intermodulation (IM3) products are generated from f_1 and f_2 mixing with one another and then beating with the mixer's LO according to the expressions

$$(2f_1 - f_2) - f_{\text{LO}} = f_{\text{IM1}} \tag{5.23a}$$

$$(2f_2 - f_1) - f_{\text{LO}} = f_{\text{IM2}} \tag{5.23b}$$

where f_{IM1} and f_{IM2} are shown in Fig. 5.11 with IF products for f_{IF1} and f_{IF2} generated by the mixer or receiver:

$$f_1 - f_{\text{LO}} = f_{\text{IF1}} \tag{5.24}$$

$$f_2 - f_{\text{LO}} = f_{\text{IF2}} \tag{5.25}$$

Note that the frequency separation is

$$\Delta = f_1 - f_2 = f_{\text{IM1}} - f_{\text{IF1}} = f_{\text{IF1}} - f_{\text{IF2}} = f_{\text{IF2}} - f_{\text{IM2}} \tag{5.26}$$

These intermodulation products are usually of primary interest because of their relatively large magnitude and because they are difficult to filter from the desired mixer outputs (f_{IF1} and f_{IF2}) if Δ is small.

The intercept point, measured in dBm, is a figure of merit for intermodulation product suppression. A high intercept point indicates a high suppression of undesired intermodulation products. The third-order intercept point (IP3 or TOI) is the theoretical point where the desired signal and the third-order distortion have equal magnitudes. The TOI is an important measure of the system's linearity. A

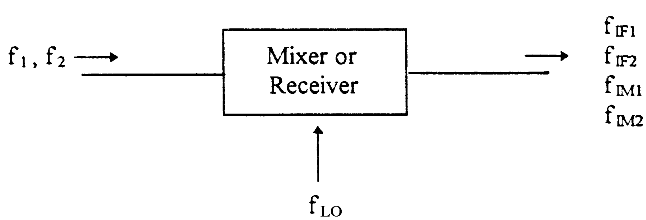

FIGURE 5.10 Signals generated from two RF signals.

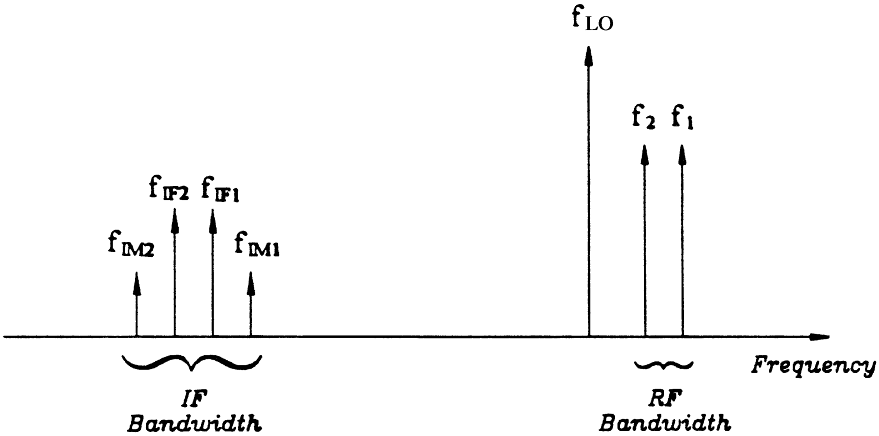

FIGURE 5.11 Intermodulation products.

convenient method for determining the two-tone third-order performance of a mixer is the TOI measurement. Typical curves for a mixer are shown in Fig. 5.12. It can be seen that the 1-dB compression point occurs at the input power of +8 dBm. The TOI point occurs at the input power of +16 dBm, and the mixer will suppress third-order products over 55 dB with both signals at −10 dBm. With both input signals at 0 dBm, the third-order products are suppressed over 35 dB, or one can say that IM3 products are 35 dB below the IF signals. The mixer operates with the LO at 57 GHz and the RF swept from 60 to 63 GHz. The conversion loss is less than 6.5 dB.

In the linear region, for the IF signals, the output power is increased by 1 dB if the input power is increased by 1 dB. The IM3 products are increased by 3 dB for a 1-dB increase in P_{in}. The slope of the curve for the IM3 products is 3 : 1.

For a cascaded circuit, the following procedure can be used to calculate the overall system intercept point [6] (see Example 5.5):

1. Transfer all input intercept points to system input, subtracting gains and adding losses decibel for decibel.
2. Convert intercept points to powers (dBm to milliwatts). We have IP_1, IP_2, ..., IP_N for N elements.
3. Assuming all input intercept points are independent and uncorrelated, add powers in "parallel":

$$\mathrm{IP3}_{\mathrm{input}} = \left(\frac{1}{\mathrm{IP}_1} + \frac{1}{\mathrm{IP}_2} + \cdots + \frac{1}{\mathrm{IP}_N}\right)^{-1} \quad (\mathrm{mW}) \tag{5.27}$$

4. Convert $\mathrm{IP3}_{\mathrm{input}}$ from power (milliwatts) to dBm.

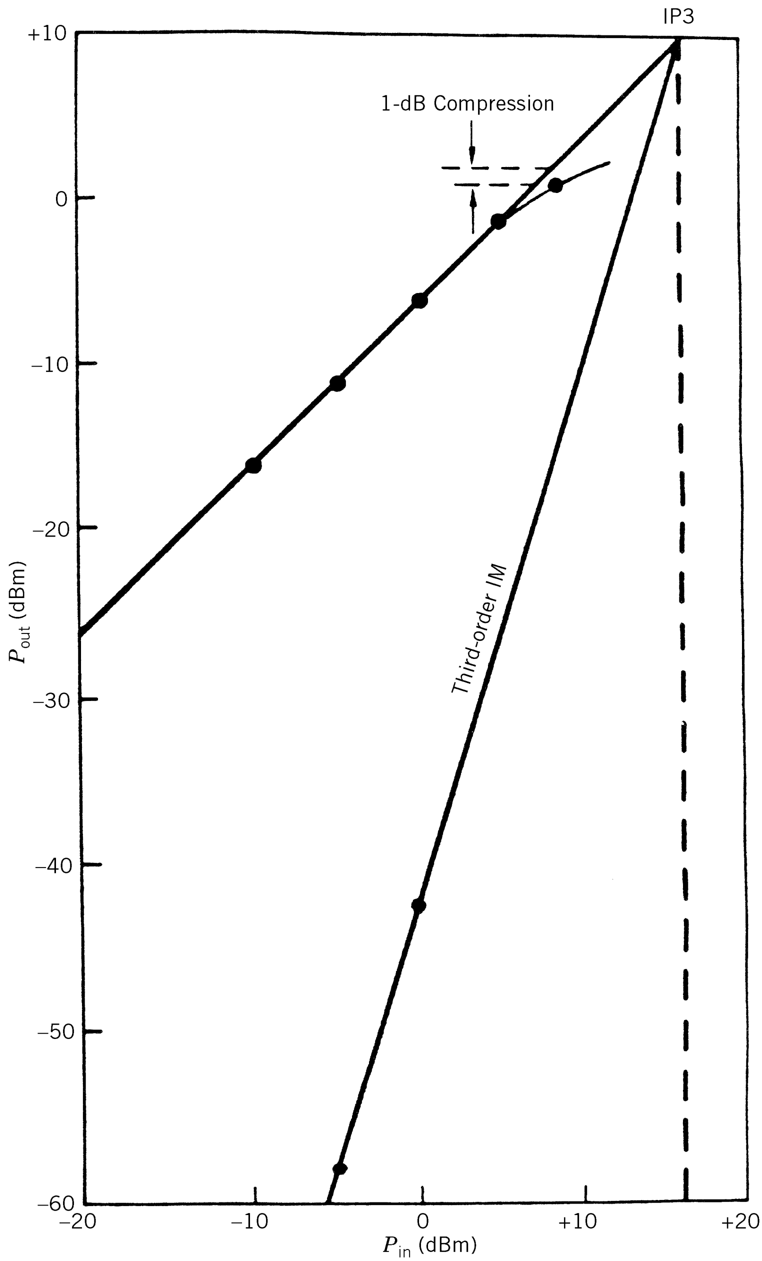

FIGURE 5.12 Intercept point and 1-dB compression point measurement of a V-band crossbar stripline mixer. (From reference [5], with permission from IEEE.)

Example 5.4 When two tones of -10 dBm power level are applied to an amplifier, the level of the IM3 is -50 dBm. The amplifier has a gain of 10 dB. Calculate the IM3 output power when the power level of the two-tone is -20 dBm. Also, indicate the IM3 power as decibels down from the wanted signal.

Solution $$P_{in} = -20\text{dBm}$$

As shown in Fig. 5.13,

$$\begin{aligned}\text{IM3 power} &= (-50\ \text{dBm}) + 3 \times [-20\ \text{dBm} - (-10\ \text{dBm})] \\ &= -50\ \text{dBm} - 30\ \text{dBm} = -80\ \text{dBm}\end{aligned}$$

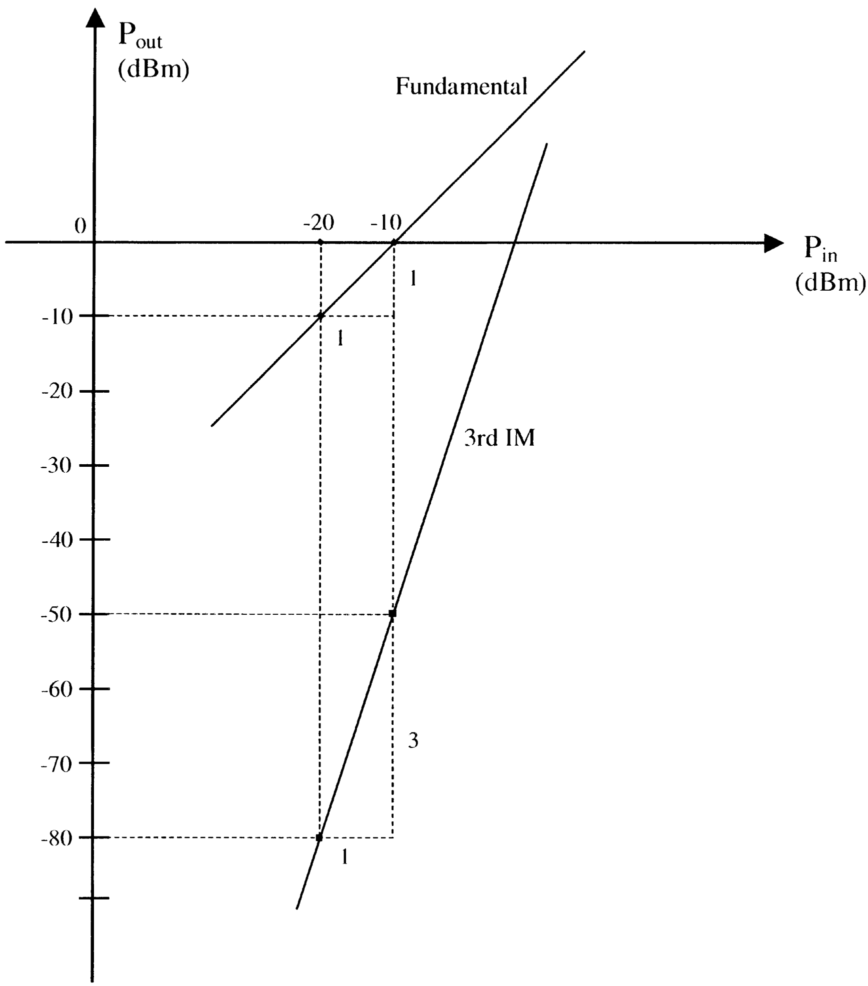

FIGURE 5.13 Third-order intermodulation.

Then

$$\text{Wanted signal at } P_{\text{in}} = -20 \text{ dBm has a power level}$$
$$= -20 \text{ dBm} + \text{gain} = -10 \text{ dBm}$$
$$\text{Difference between wanted signal and IM3}$$
$$= -10 \text{ dBm} - (-80 \text{ dBm}) = 70 \text{ dB down}$$

■

Example 5.5 A receiver is shown in Fig. 5.14. Calculate the overall input IP3 in dBm.

Solution Transfer all intercept points to system input; the results are shown in Fig. 5.14. The overall input IP3 is given by

$$\begin{aligned}
\text{IP3} &= 10 \log\left(\frac{1}{\text{IP}_1} + \frac{1}{\text{IP}_2} + \frac{1}{\text{IP}_3} + \frac{1}{\text{IP}_4} + \frac{1}{\text{IP}_5}\right)^{-1} \\
&= 10 \log\left(\frac{1}{\infty} + \frac{1}{15.85} + \frac{1}{\infty} + \frac{1}{19.95} + \frac{1}{100}\right)^{-1} \\
&= 10 \log 8.12 \text{ mW} = 9.10 \text{ dBm}
\end{aligned}$$

■

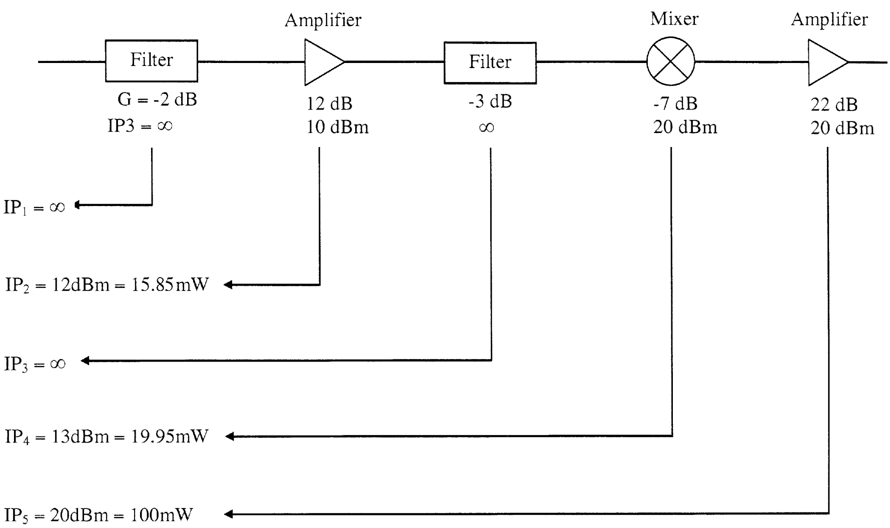

FIGURE 5.14 Receiver and its input intercept point.

5.7 SPURIOUS RESPONSES

Any undesirable signals are spurious signals. The spurious signals could produce demodulated output in the receiver if they are at a sufficiently high level. This is especially troublesome in a wide-band receiver. The spurious signals include the harmonics, intermodulation products, and interferences.

The mixer is a nonlinear device. It generates many signals according to $\pm m f_{\mathrm{RF}} \pm n f_{\mathrm{LO}}$, where $m = 0, 1, 2, \ldots$ and $n = 0, 1, 2, \ldots$, although a filter is used at the mixer output to allow only f_{IF} to pass. Other low-level signals will also appear at the output. If $m = 0$, a whole family of spurious responses of LO harmonics or $n f_{\mathrm{LO}}$ spurs are generated.

Any RF frequency that satisfies the following equation can generate spurious responses in a mixer:

$$m f_{\mathrm{RF}} - n f_{\mathrm{LO}} = \pm f_{\mathrm{IF}} \tag{5.28}$$

where f_{IF} is the desired IF frequency.

Solving (5.28) for f_{RF}, each (m, n) pair will give two possible spurious frequencies due to the two RF frequencies:

$$f_{\mathrm{RF1}} = \frac{n f_{\mathrm{LO}} - f_{\mathrm{IF}}}{m} \tag{5.29}$$

$$f_{\mathrm{RF2}} = \frac{n f_{\mathrm{LO}} + f_{\mathrm{IF}}}{m} \tag{5.30}$$

The RF frequencies of f_{RF1} and f_{RF2} will generate spurious responses.

5.8 SPURIOUS-FREE DYNAMIC RANGE

Another definition of dynamic range is the "spurious-free" region that characterizes the receiver with more than one signal applied to the input. For the case of input signals at equal levels, the spurious-free dynamic range SFDR or $\mathrm{DR}_{\mathrm{sf}}$ is given by

$$\mathrm{DR}_{\mathrm{sf}} = \tfrac{2}{3}(\mathrm{IP3} - \mathrm{MDS}) \tag{5.31}$$

where IP3 is the input power at the third-order, two-tone intercept point in dBm and MDS is the input minimum detectable signal.

Equation (5.31) can be proved in the following: From Fig. 5.15, one has

$$BD = \tfrac{1}{3} CD \qquad EB = AB$$

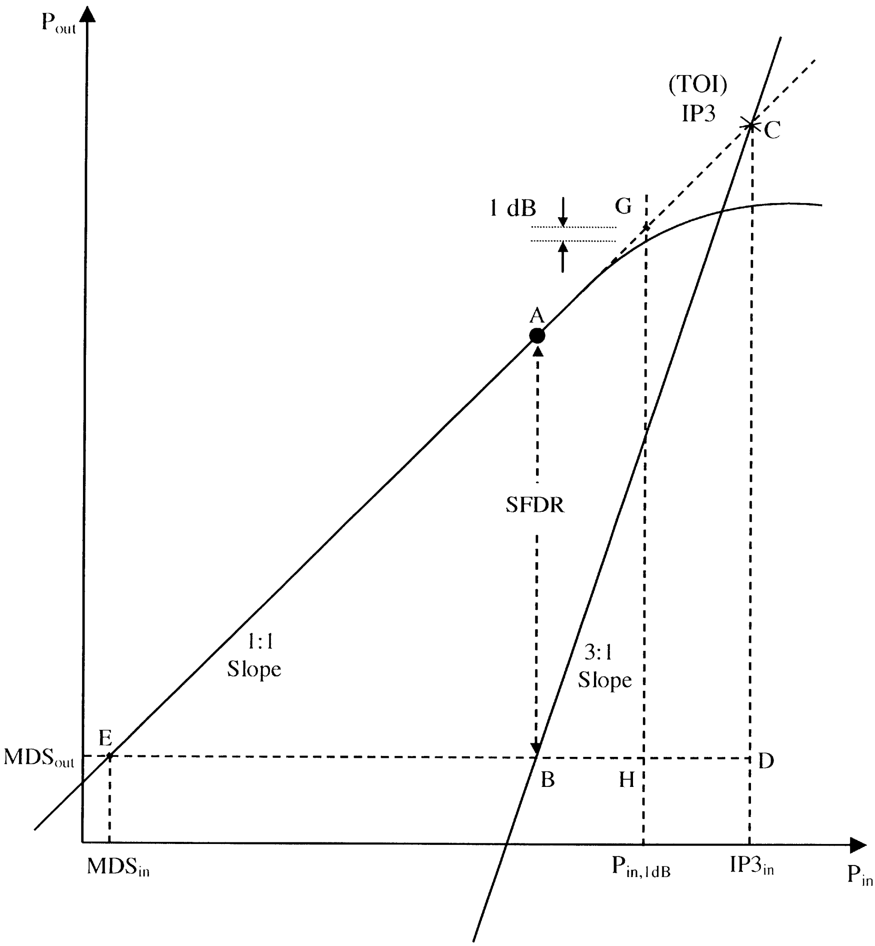

FIGURE 5.15 Spurious-free dynamic range.

From the triangle *CED*, we have

$$CD = ED = EB + BD = AB + \tfrac{1}{3}CD$$

Therefore,

$$AB = \tfrac{2}{3}CD = \tfrac{2}{3}(\mathrm{IP3_{out}} - \mathrm{MDS_{out}})$$

or since $CD = ED$,

$$\mathrm{DR_{sf}} = AB = \tfrac{2}{3}ED = \tfrac{2}{3}(\mathrm{IP3_{in}} - \mathrm{MDS_{in}})$$

and AB is the spurious-free dynamic range. Note that GH is the dynamic range, which is defined by

$$\mathrm{DR} = GH = EH = P_{\mathrm{in,1dB}} - \mathrm{MDS_{in}}$$

The $\mathrm{IP3_{in}}$ and $\mathrm{IP3_{out}}$ differ by the gain (or loss) of the system. Similarly, $\mathrm{MDS_{in}}$ differs from $\mathrm{MDS_{out}}$ by the gain (or loss) of the system.

PROBLEMS

5.1 Calculate the overall noise figure and gain in decibels for the system (at room temperature, 290 K) shown in Fig. P5.1.

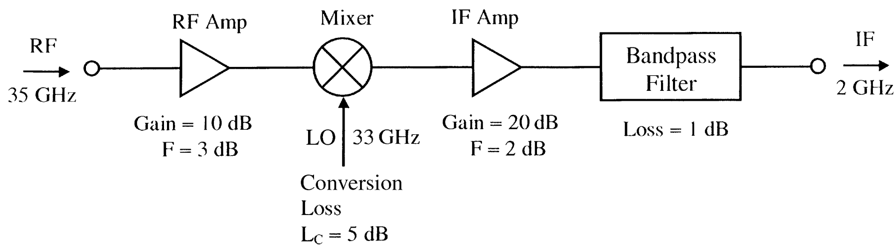

FIGURE P5.1

5.2 The receiver system shown in Fig. P5.2 is used for communication systems. The 1-dB compression point occurs at the output IF power of +20 dBm. At room temperature, calculate (a) the overall system gain or loss in decibels, (b) the overall noise figure in decibels, (c) the minimum detectable signal in milliwatts at the input RF port, and (d) the dynamic range in decibels.

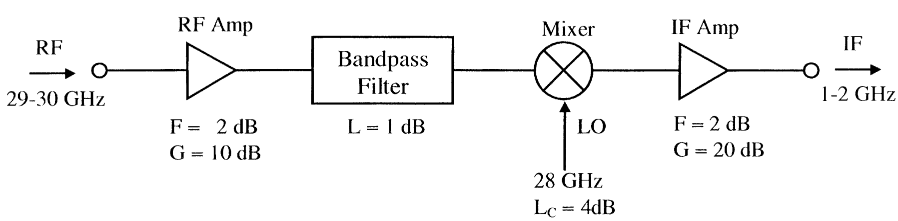

FIGURE P5.2

5.3 A receiver operating at room temperature is shown in Fig. P5.3. The receiver input 1-dB compression point is +10 dBm. Determine (a) the overall gain in decibels, (b) the overall noise figure in decibels, and (c) the dynamic range in decibels.

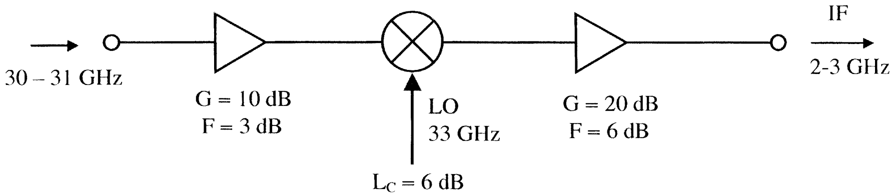

FIGURE P5.3

5.4 The receiver system shown in Fig. P5.4 has the following parameters: $P_{\text{in,1dB}} = +10$ dBm, $\text{IP3}_{\text{in}} = 20$ dBm. The receiver is operating at room temperature. Determine (a) the noise figure in decibels, (b) the dynamic range in decibels, (c) the output SNR ratio for an input SNR ratio of 10 dB, and (d) the output power level in dBm at the 1-dB compression point.

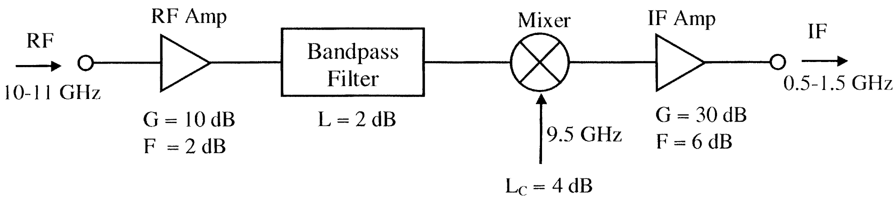

FIGURE P5.4

5.5 Calculate the overall system noise temperature and its equivalent noise figure in decibels for the system shown in Fig. P5.5.

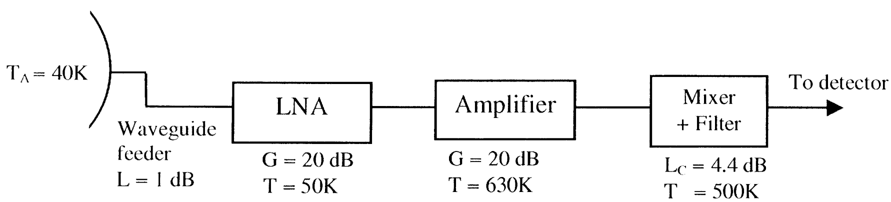

FIGURE P5.5

5.6 When two 0-dBm tones are applied to a mixer, the level of the IM3 is -60 dBm. The mixer has a conversion loss of 6 dB. Assume that the 1-dB compression point has input power generated greater than $+13$ dBm. (a) Indicate the IM3 power as how many decibels down from the wanted signal. (b) Calculate the IM3 output power when the level of the two tones is -10 dBm, and indicate the IM3 power as decibels down from the wanted signal. (c) Repeat part (b) for the two-tone level of $+10$ dBm.

5.7 At an input signal power level of -10 dBm, the output wanted signal from a receiver is 50 dB above the IM3 products (i.e., 50 dB suppression of the IM3 products). If the input signal level is increased to 0 dBm, what is the suppression level for the IM3 products?

5.8 When two tones of −20 dBm power level are incident to an amplifier, the level of the IM3 is −80 dBm. The amplifier has a gain of 10 dB. Calculate the IM3 output power when the power level of the two tones is −10 dBm. Also, indicate the IM3 power as decibels down from the wanted signal.

5.9 Calculate the overall system IP3 power level for the system shown in Fig. P5.9.

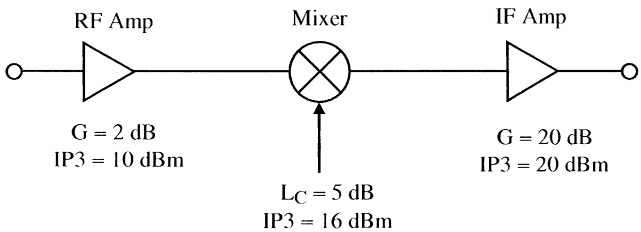

FIGURE P5.9

5.10 For the system shown in Fig. P5.10, calculate (a) the overall system gain in decibels, (b) the overall noise figure in decibels, (c) the equivalent noise temperature in kelvin, (d) the minimum detectable signal (MDS) in dBm at input port, and (e) the input IP3 power level in dBm. The individual component system parameters are given in the figure, and the system is operating at room temperature (290 K).

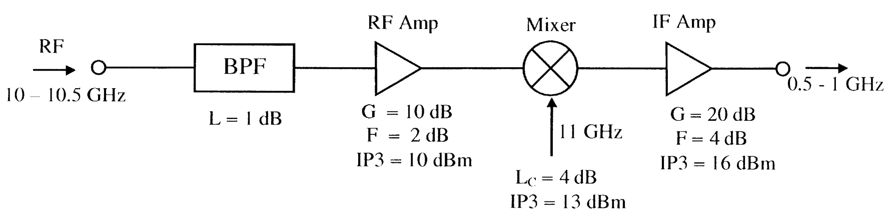

FIGURE P5.10

5.11 A radio receiver operating at room temperature has the block diagram shown in Fig. P5.11. Calculate (a) the overall gain/loss in decibels, (b) the overall noise figure in decibels, and (c) the input IP3 power level in dBm. (d) If the input signal power is 0.1 mW and the SNR is 20 dB, what are the output power level and the SNR?

5.12 In the system shown in Fig. P5.12, determine (a) the overall gain in decibels, (b) the overall noise figure in decibels, and (c) the overall intercept point power level in dBm at the input.

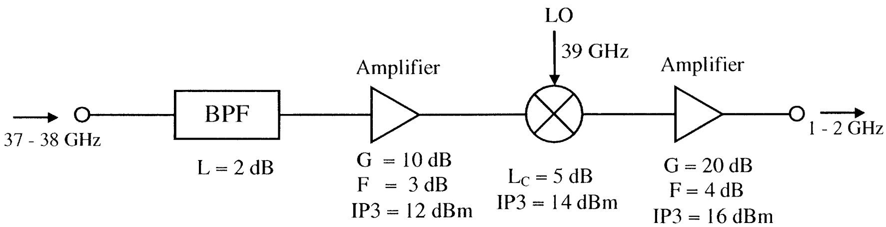

FIGURE P5.11

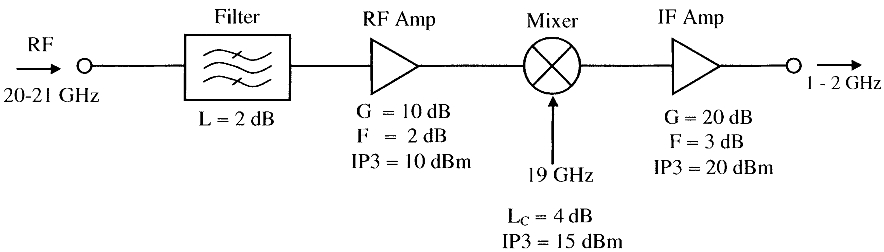

FIGURE P5.12

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