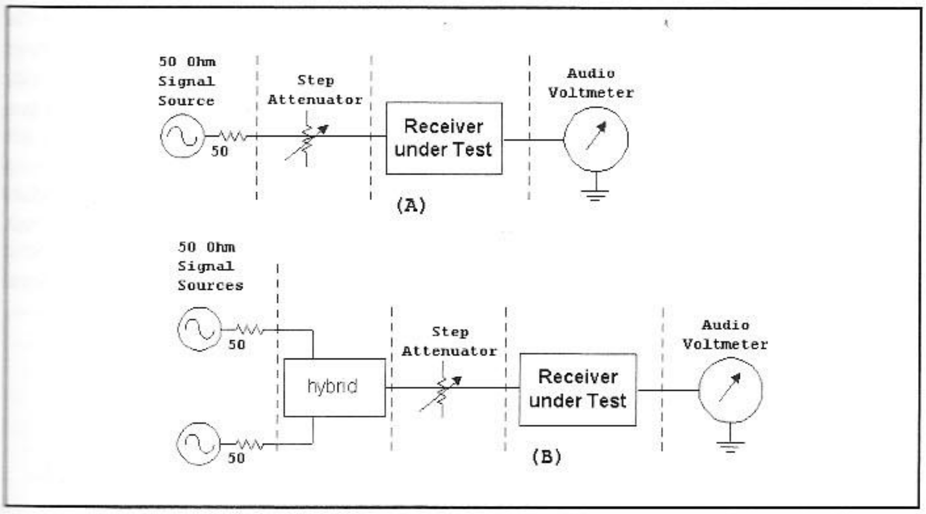

Fig 6.62—Setup for measurement of receiver dynamic range. See text for discussion.

end filtering does nothing to attenuate the original signals that cause the distortion, nor does it attenuate the products once they have been generated. First impressions suggest that this distortion would ruin all communications, but things are not that severe. The detail that saves our receivers is the characteristic that a third-order distortion product will increase or decrease in proportion to the *cube* of the input signals. So, if input signals become 1 dB weaker, the resulting distortion decreases by 3 dB. Third-order IMD in a receiver is characterized by a third-order input intercept. Although third-order IMD is an insidious problem, it is easy to measure. Generally, anything we do to a front-end design to improve IMD will also improve gain compression and second-order IMD. For these reasons, the third-order input intercept becomes a central design consideration for receivers.

Dynamic Range and Intercepts

We often hear folks talking about *dynamic range* of an amplifier or receiver, but the term is often ill defined. When asked about it, the person will say it is the difference in dB between the largest signal that a circuit can handle and the smallest. But what is the weakest signal and what defines it? How large can the largest be and how do we define that?

We use the following *receiver* definition: Two-tone dynamic range is the dB difference between two signal levels; The weakest signal that a receiver can deal with is the *minimum discernable signal*, or MDS while the strongest signal is one of two signals of equal strength that produce a third-order distortion product with a response equal to that of the MDS.

MDS was defined earlier and is the available power from a room temperature signal source that will cause the output to increase by 3 dB above the background noise. MDS is related to receiver noise figure and bandwidth by

$$\text{MDS (dBm)} = -174 \text{ dBm} + 10\log(\text{BW}) + \text{NF} \qquad \textbf{Eq 6.12}$$

where BW is the receiver *noise* bandwidth in Hz and NF is the noise figure in dB. Noise bandwidth is usually close to signal bandwidth at the –6 dB points.[13] For example, a receiver with a 2.5-kHz bandwidth and a 10-dB noise Figure has a –130-dBm MDS. The test setup used to measure MDS is shown in **Fig 6.62A**. The signal in dBm available to the receiver is the generator output less the attenuation value in dB.

After measuring MDS, a second signal source is added to the test set, as shown in Fig 6.62B. The sources are adjusted to have equal outputs. The *hybrid* in that figure is a circuit element that combines the outputs of two 50-Ω generators to form one 50-Ω source while isolating the two generators from each other. (See Chapter 7 under Return Loss Bridge.) The combined output is adjusted as needed in the step attenuator. The level available to the receiver input is adjusted until the response on the meter is exactly the same 3-dB-above-the-noise response that we saw when measuring MDS.

Consider an example. First, turn AGC off for all DR and intercept measurements. With no input signals, the audio output from our receiver is 5 mV, RMS. This is the result of receiver noise. We now inject a 14.010-MHz signal from a generator and adjust the level and receiver tuning until the audio output is 7.1 mV, 3 dB above the noise level. This happened with a generator output of –130 dBm, which becomes the MDS. Next, we set up the signal generators at 14.03 and 14.05 MHz, leaving the receiver tuned to 14.01 MHz. We increase the level of the two tones until we get the same output that we saw with the MDS measurement. This occurs with a signal at the input of –44 dBm per tone. Each tone is 86 dB above MDS, so our two-tone dynamic range is 86 dB.

We can measure the receiver input third-order intercept directly with the same equipment. (See Chapter 2, section 6, to

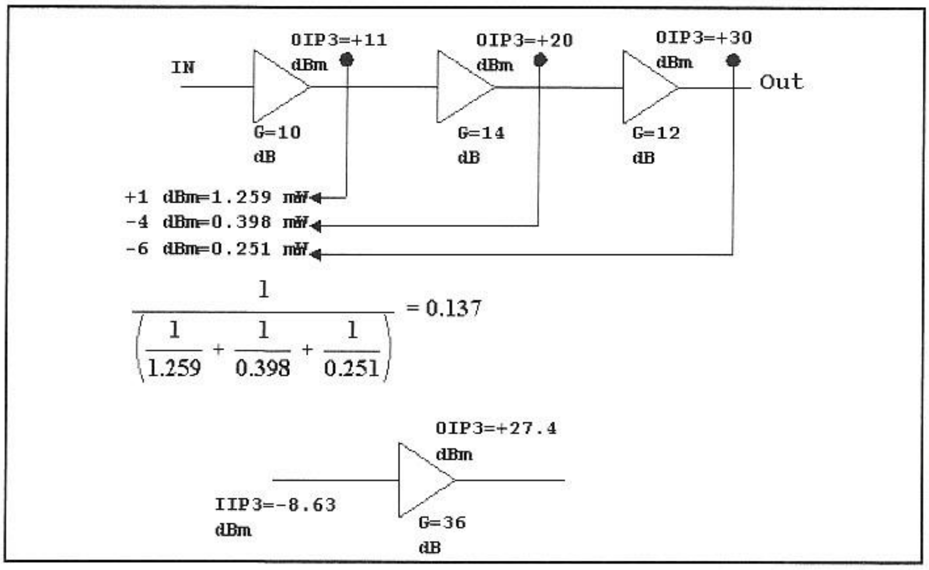

Fig 6.63—Three amplifier stages are cascaded. The intercept for the cascade is calculated by normalizing the intercepts to one plane in the system, converting values from dBm to mW, combining values in the way that resistors in parallel are combined, and then converting back to dBm. See text for details.

see how intercept is defined and measured.) Set the attenuator output for a larger output per tone than was used in the direct DR measurement. Tune the receiver to 14.01 MHz and note an output of 100 mV in the audio voltmeter. We note that the available signals at 14.03 MHz and 14.05 MHz is –31 dBm per tone or per signal. We now tune the receiver to 14.03 MHz where we encounter a very loud signal. The attenuator is increased until the output level is again at 100 mV, finding that this happened when we had added 60 dB of attenuation. Hence, the distortion products are 60 dB below the desired response. This is the IMD Ratio, or IMDR. Rewriting an equation from section 2.6

$$IP_{3in} = P_{in} + \frac{IMDR}{2} \qquad \textbf{Eq 6.13}$$

allowing us to calculate the input intercept for the receiver as –1 dBm. While doing this measurement, it is instructive to change the input from –31 to –29 dBm, or a similar small amount. With 2-dB-larger input signals, we see IMD products that are 6 dB stronger. The IMDR becomes 56 dB, still leaving an input intercept of –1 dBm. If IP_{3in} remains a constant, the front end is said to be *well behaved*.

Two formats are used to indicate intercepts. The one we have used for an input intercept is IP_{3in}. The IP_3 part indicates that it is a third-order intercept while *in* signifies an input rather than output intercept. An equally valid designation is *IIP3* where the first *I* denotes input. The second format relates to the *output* intercept, symbolized by IP_{3out} or *OIP3*. Avoid associating the term *intercept point* with a number, for it is only confusing when the plane of definition is not specified. Strictly speaking, intercept point is the intersection of two curves.

Intercepts are not mere esoteric curiosities or receiver figures-of-merit. Rather, they are tools, useful parameters available to the designer. Intercepts offer two major capabilities:

- If the input intercept of a receiver (or any system) is known, the intermodulation distortion is well defined for all input levels.
- If the intercepts and gains for all stages in a system are known, they can be combined to calculate the intercept for the complete system. Input and output intercepts for a single stage differ by the small-signal stage gain.

Equation 6.13 lets us calculate distortion for any input level.

The intercept of a cascade was treated earlier and is illustrated here with an example: a three-stage amplifier shown in **Fig 6.63**. This cascade might be part of a wideband amplifier to be used in an SSB transmitter. The output intercepts of the three stages are known: +11, +20, and +30 dBm. The respective gains are 10, 14 and 12 dB. Recall that the input intercept of an amplifier is related to the output intercept through the stage gain. This difference is not restricted to a single stage. The output intercepts for each stage can be normalized, or "moved" to the input of the overall system, becoming +1, –4, and –6 dBm. The individual intercepts are merely adjusted by the gains in the movement process. The normalized values are converted from dBm to power in milliwatts. The values are then combined in the same way that *resistors-in-parallel* are combined, producing a net input intercept of 0.137 mW, or –8.6 dBm. The parallel resistor analogy has no significance other than being an easily remembered formula.

This can also be presented in a generalized equation

$$IP_3 = -10 \log\left(\sum_{i=1}^{N} 10^{-\frac{IP_i}{10}}\right) \quad \textbf{(General case)}$$

$$= -10 \log\left(10^{-\frac{IP_1}{10}} + 10^{-\frac{IP_2}{10}} + 10^{-\frac{IP_3}{10}}\right) \quad \textbf{(N-3, 3-stage example)}$$

Eq 6.14

where IP_3 now represents the intercept of the cascade and IP_i is the intercept of the i-th stage with all intercepts being normalized to a single plane in the amplifier. In our example, we normalized all intercepts to the system input. However, we could have picked the output, or any interface between stages. (The equation is derived in *Introduction to Radio Frequency Design*.) This method is a worst-case analysis where the intermodulation *voltages* from each stage add in phase. Our measurements indicate that this analysis works well in practical systems, so long as the individual stages are well-behaved, as defined earlier.

Receiver dynamic range is related to intercept and MDS by a simple equation. MDS is further related to bandwidth and noise figure, offering a more general equation.

$$DR(dB) = \left(\frac{2}{3}\right)(IIP3 - MDS)$$

$$= \left(\frac{2}{3}\right)(IIP3 + 174 - NF - 10\log(BW))$$

Eq 6.15

where IIP3 is the input third order intercept, NF is system noise Figure, BW is the system bandwidth. Recall that kT = –174 dBm at 290 K, explaining that term in the equation.

Some Front-End Design Examples

We are now in a position to evaluate some receiver front-end designs. A few examples will be presented using data obtained from measurements we have performed.

The first example is a popular one among the QRP clan, a receiver front end based upon the Phillips NE602 or NE612. Our evaluation data was presented in Chapter 5. A front-end block diagram, **Fig 6.64**, includes gains, intercepts, and noise figures for the stages. The result of applying the dynamic range analysis is also included. This is a simple design with only one active block, the mixer. The dynamic range is modest at 83 dB, although sensitivity is quite good. The noise figure

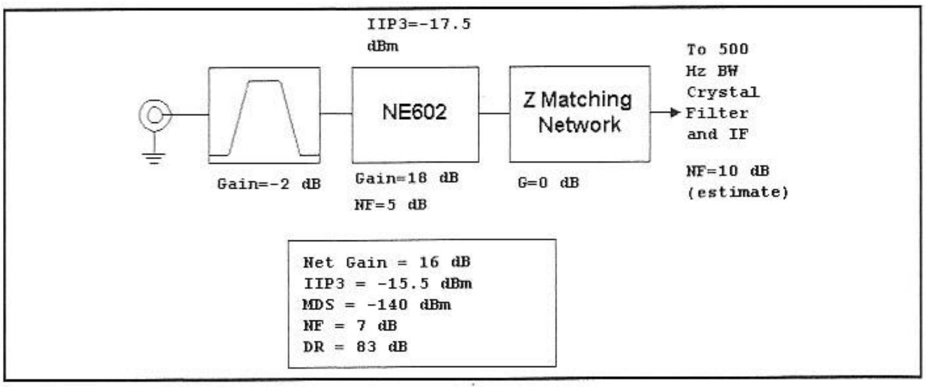

Fig 6.64—A simple receiver front end using the NE602. The IF system is estimated to have a noise figure of 10 dB.