high frequency circuit design

by james k. hardy

with illustrations

by patricia hardy

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dedicated to

patricia, shawna, and sandra.

preface

High-frequency circuit design is written for those interested in a practical approach to the design of high-frequency amplifiers, oscillators, and filters. It will be valuable to technology and engineering students, practicing designers in the communications industry, and to experimenters and radio amateurs. The material complements a number of first-level communications circuit texts that are available and so concentrates on topics not normally covered by them in sufficient depth for design work.

This book is the outgrowth of a sixth semester course taught to technology students at Humber College. For maximum benefit, the reader should therefore have the equivalent of a course in ac circuit theory and the associate vector algebra and should also have completed a first-level course in communication circuits and modulation and demodulation. The mathematics within this book stays at the algebra level and involves no calculus.

Chapter 1 describes the circuitry problems that must be considered during the design process. These include internally generated noise and non-linear amplitude and phase characteristics, all of which can distort a signal as it passes through a communication system.

Chapter 2 discusses the practical nature of passive components and how their characteristics change with frequency, temperature, and in some cases, with the signal amplitude. The proper selection of components is necessary to make the final product operate as well as the initial paper work design.

The circuitry design begins with Chapter 3 where procedures for designing narrow passband filters to meet given bandwidth and skirt requirements are explained. A description of crystal and ceramic filters is included, not so much because the reader is likely to be designing them, but more for an explanation of the principles involved that may be useful in other filter designs.

Modern filter design, in Chapter 4 is a topic normally found only in high-level texts buried in a lot of mathematics. The general properties of filters are presented first, and then a specific description of input impedance, attenuation and delay characteristics are given for a group of standard designs. With the graphs, tables, and formulas provided the reader can design a filter to custom fit his exact requirements and with very good predictability.

For the student interested in a bit of the mathematical background to modern filters, Appendix 4A describes the s-plane and its relation to filter characteristics and also demonstrates how filter component values can be extracted from polynomial equations that describe the desired response.

To preserve precious signal levels, both large and small, communication circuits often require impedance-matching networks that will transfer maximum power from a source to a load. Often these are required to have bandwidths of varying amounts and provide specific attenuation outside of the passband. Designs to meet all requirements are given and are handled both mathematically and graphically—on the Smith chart.

As operating frequencies climb, the characteristics of transistors, be they bipolar or field effect, change. Their gains drop, input and output impedances decrease and become reactive, and stability decreases. Chapter 6 then serves as background information for the remaining chapters—all dealing with active circuits. The first of the active circuits are the small linear amplifiers commonly used in receivers. Chapter 7 concentrates on the design of such amplifiers and shows how to control internal noise, provide automatic gain adjustment, improve stability, and use alternate configurations to best ability.

Chapter 8 discusses oscillator circuits; what should be considered and how to design and measure the results. The traditional Colpitts and Hartley designs are presented and then the more modern technique of frequency synthesis is described. To fully appreciate this section the student may wish to brush up on the operation of logic gates first.

Chapter 9 is a collection of circuits common to transmitters and begins with a description of the specialized RF power transistor, often as complex as any integrated circuit. The chapter continues with the design of power amplifiers and how to amplitude modulate them.

Chapter 10 is a collection of receiver circuits, in particular the more critical areas which include the mixer and the detector sections. AM and FM IF amplifiers are also described.

It is a rare author who works completely by himself without outside help. In this case the author is very thankful for all the help received both from business associates and personal friends; without them there would be no book.

In particular I wish to heartily thank Linda Vince and Christine Adam for their expert typing of the manuscript, Lou Hale of Garrett Manufacturing for his assistance in providing information on components, and Bob Vince for his photographic advice. I also wish to thank my wife Patricia for her typing, drawing, and moral support throughout the project. A special thanks also to that special group of friends who provided both technical and moral support.

I hope that the readers enjoy the use of this material as much as the author did in writing it.

Jim Hardy
Georgetown, Ontario
July, 1978

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chapter 1

signal distortion

The purpose of any communication system is to carry information from one place to another. However, for various reasons, the received signal will always be of poorer quality than the transmitted signal. Some of the frequency components may be of the wrong amplitude or missing altogether, new frequencies may appear, the relative time relation of the signals may be altered, and random noise may contaminate everything. Careful control of these problems during the circuit design will result in a more useful product.

1-1 THERMAL (JOHNSON) NOISE

Whenever resistance appears in a circuit, whether actual resistors for biasing or just losses in components, noise will be generated. *Thermal noise* is caused by the random movements of free electrons in any conductor. If the conductor has any resistance, a noise voltage will be generated. Since the electron movement increases with temperature, the noise voltage will, too. The average amplitude of this noise will be constant at all frequencies, and so the noise is *white*. (*Pink* noise has an amplitude that decreases with frequency.) The appearance of white noise on an oscilloscope is shown in Figure 1-1.

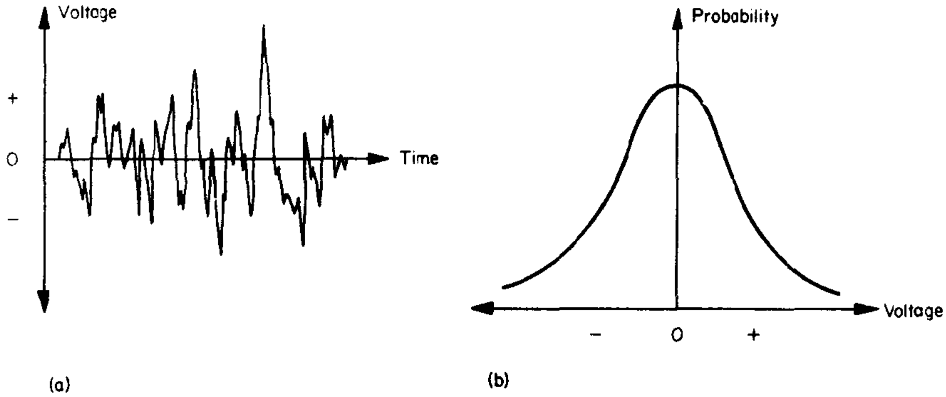

Figure 1-1 Typical white-noise voltage (a) and the probability of any voltage occurring (b).

At any instant, the amplitude of the noise voltage could be anything from very small to very large values. As shown by the probability curve, it is most likely that the amplitudes will be small; but, theoretically, spikes of infinite amplitude could occur. Noise cannot, therefore, be measured as peak voltages, and so the rms value must always be used. The open-circuit noise voltage across the terminals of a resistor is given by,

$$e_n = \sqrt{4KTBR} \qquad \text{volts (rms)} \qquad (1\text{-}1)$$

where: K = Boltzmann's constant
$= 1.38 \times 10^{-23}$ J/°K
T = absolute temperature (°C + 273)
R = resistance (Ω)
B = bandwidth (Hz)

EXAMPLE 1-1

What noise voltage is generated in a 50-Ω resistor at room temperature if the measuring instrument has a 1.0-MHz effective bandwidth?

Solution

Room temperature will be taken as +20°C or 293 °K.

$$e_n = \sqrt{4KTBR}$$
$$= \sqrt{4 \times 1.38 \times 10^{-23} \times 293 \times 1.0 \times 10^6 \times 50}$$
$$= 0.899\ \mu\text{V rms}$$

If the 50-Ω resistor used in this example was actually the source resistance of a signal generator, the normal output signal would be contaminated with noise as shown in Figure 1-2. Therefore, when any signal generator is used for testing, this noise must be taken into account.

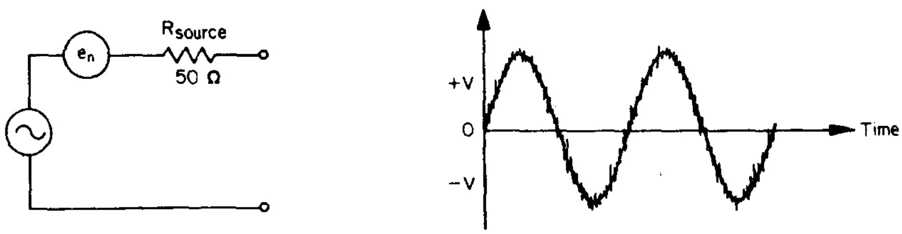

Figure 1-2 Output of a signal generator will contain some thermal noise produced in its source resistance.

The ratio of signal voltage to noise voltage from the generator is

$$\frac{S}{N}\text{ ratio} = \frac{\text{signal voltage (rms)}}{\text{noise voltage (rms)}} \qquad (1\text{-}2)$$

or

$$\frac{S}{N}\text{ ratio (dB)} = 20\log_{10}\left(\frac{\text{signal voltage}}{\text{noise voltage}}\right) \qquad (1\text{-}3)$$

It is normally assumed that all the generator noise is thermally produced in the source resistance and that the source resistance is room temperature (290°K). However, it would be easy to make a poor-quality oscillator that has a noise level far above the thermal level; fortunately, it would not sell very well.

1-2 SHOT (SCHOTTKY) NOISE

The second major source of noise in communication circuits is produced when current flows in any active device, be it bipolar or field-effect transistor, diode or vacuum tube. This noise is also white and has exactly the same appearance and probability distribution, as shown in Figure 1-1. Again, rms values must be used for its measurement, but in this case, it is usually expressed as a current. For a semiconductor diode,

$$I_n = \sqrt{2qIB} \qquad \text{amperes (rms)} \qquad (1\text{-}4)$$

where: q = charge on an electron
$= 1.60 \times 10^{-19}$ C
I = bias current (A)
B = bandwidth (Hz)

For bipolar transistors, the equation differs somewhat, since two currents and two junctions are involved. The noise produced in a transistor will be discussed in Chapter 6.

1-3 AMPLIFIER NOISE FIGURE

Because of thermal and shot noise produced in an amplifier, the signal at the output will have a higher percentage of noise than the input signal did. The amount of noise added will then determine how small a signal the amplifier can detect. A useful measure of this performance is the noise factor and corresponding noise figure:

$$\text{noise factor} = \frac{S_i/N_i}{S_o/N_o} \tag{1-5}$$

$$\text{noise figure} = 20\log_{10}\left(\frac{S_i/N_i}{S_o/N_o}\right)\ \text{dB} \tag{1-6}$$

where: S_i = input signal voltage
N_i = thermal input noise voltage from the source resistance
S_o = output signal voltage equal to $S_i \times$ amplifier gain
N_o = total output noise made up of the amplified input plus any added noise

Typical noise figure for several types of low-noise amplifiers are shown in Figure 1-3. The problem of obtaining low-noise figures at the higher frequencies is mainly due to the difficulty of obtaining reasonable power gains at those frequencies.

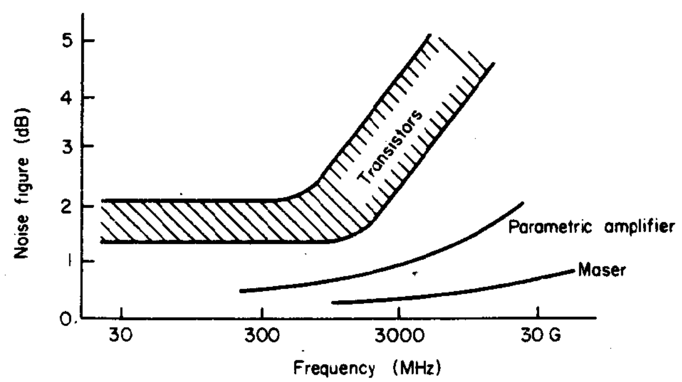

Figure 1-3 Noise figures that can be obtained with various types of low-noise amplifiers.

1-4 MEASUREMENT OF NOISE FIGURE

The *noise figure* (or *factor*) can be measured in one of two ways, depending on the type of generator used. The easiest measurement requires a calibrated noise source. This usually consists of a vacuum-tube diode whose dc plate current is controlled by changing the filament temperature (saturated operation). The shot noise from the tube is then added to the thermal noise of a 50-Ω resistor that acts as the source resistance of the noise generator. The excess shot noise can then be calibrated on a meter in terms of plate current.

To measure noise figure, the noise source is connected to the input of the receiver to be tested, and a true rms voltmeter is connected to the receiver output. (Since linearity is important, any automatic gain control must be defeated, so the voltmeter may have to be connected ahead of the receiver's detector.) With the noise source turned off, the voltmeter will read some level corresponding to the internally generated receiver noise plus the thermal noise from the generator's source resistance. The noise source is then turned on and adjusted so that the output noise level increases by 3 dB; the more excess noise that must be generated, the more noise the receiver is adding itself. The noise figure is then simply read off the meter of the noise generator. Figure 1-4 shows the general form of the noise generator and test setup. The big advantage of this measurement technique is that the receiver's gain and bandwidth characteristics do not have to be known, since the noise generator's output voltage is

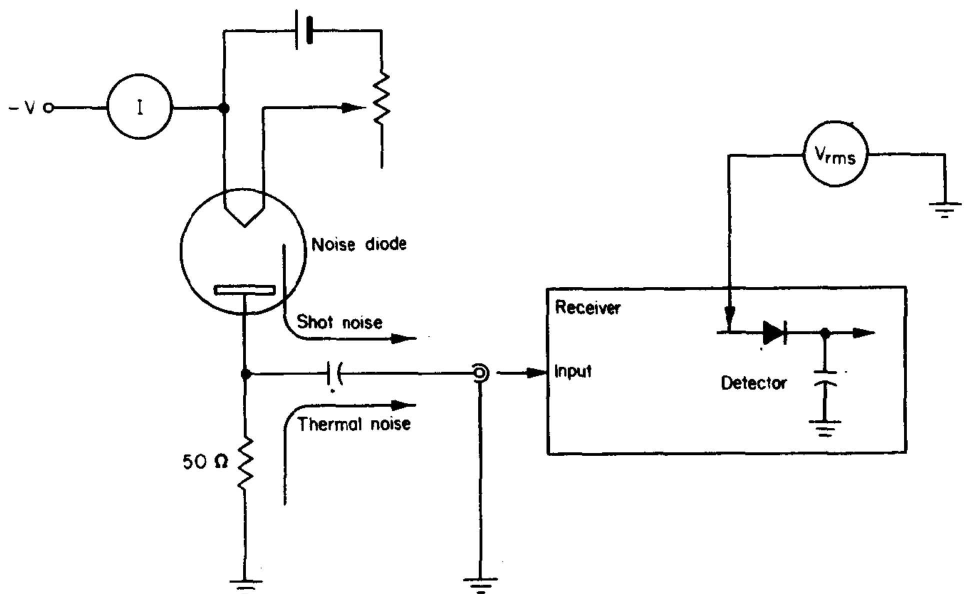

Figure 1-4 White-noise generator connected to a receiver for a noise-figure test. The rms voltmeter must be connected to a linear point in the receiver, which usually means ahead of the final detector.