Thermal & Shot Noise in Communication Systems

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1. Introduction

To some degree, all modern communication systems suffer from the adverse effects of electrical noise. There are many sources of unwanted electric signals, usually categorized as either human interference or naturally occurring noise. Noise from 60-cycle hum, ignition and commutator sparking, radars, microwave ovens, and other communication systems are examples of human interference (Davies 130). Natural noise can be produced by phenomena such as atmospheric disturbances like lightning, space born radiated signals, and circuit noise (Carlson 171).

Noise in electronic circuits can degrade signals to a point where they no longer carry relevant data. Noise can cause errors in data transmission, decrease the bandwidth of the signal, and reduce the range of transmission, all of which are important in communication systems.

Design engineers can reduce or eliminate the effects of some unwanted signals through careful planning and design, but other types of noise cannot be removed. When dealing with small signals in telecommunications systems, thermally generated noise, also known as "Johnson" noise, can interfere with the original signal and in some cases seriously degrade the performance of the entire system (Ziemer 286).

In addition to thermal noise, shot noise is another type of noise that can interfere with signals in a circuit. Shot noise has to do with the discrete nature of charge carriers, where any charge transfer for a current involves a discrete number of charge carriers resulting in a random current (de Jong 22).

2. Thermal Noise

Thermally generated noise is due to the random thermal motions of charge carriers that are present in any electronic circuit. Whenever the temperature of a conductor is above absolute zero, the random Brownian motion of charged particles (usually electrons) results in what is called thermal noise. In most cases thermal noise can be neglected because of its low level nature. However, thermal noise becomes an issue in systems where the signal levels are low or the distance between the transmitter and receiver is great (Ziemer 285). An example of this can be found in the predetection portions of an AM/FM receiver that is tuned to a distant transmitter or in a radar system where the receiver is processing a return pulse from a distant target (Ziemer 286).

Thermal noise is created in lossy elements, resistors being a major contributor. However, any component in an electronic circuit that has a resistance can generate thermal noise. Kirchoff once commented on Blackbody radiation: good emitters make good absorbers (Minkoff 31).

2.1 Power Spectral Density of Thermal Noise

In 1927, Johnson and Nyquist derived the power spectral density (PSD) for thermal noise. The PSD was derived by studying this noise in metallic resistors while treating a conductor between two resistors as a one-dimensional black body in thermal equilibrium with its surroundings (Minkoff 32).

Kinetic theory states that the average energy of a particle at an absolute temperature T is proportional to kT, where k is the Boltzmann constant. When a metallic resistance R is at temperature T, a noise voltage v(t) at the open circuited terminals is produced by random electron motion. The Gaussian distribution of v(t) has a zero mean and variance:

$$\overline{v^2} = s_v^2 = \frac{2(pkT)^2}{3h} R \qquad \text{volts squared}$$

with T measured in Kelvins (Carlson 171).

h = Planck constant = 6.62 x 10^{-34} joule second

k=Boltzmann constant = 1.37 x 10^{-23} joules per degree

Quantum mechanics states that the spectral density of thermal noise is

$$G_v(f) = \frac{2Rh|f|}{e^{h|f|/kT} - 1} \quad \text{volts squared per hertz}$$

When |f| << kT/h, the equation simplifies to:

$$G_v(f) \approx 2RkT\left(1 - \frac{h|f|}{2kT}\right)$$

using series approximations (Carlson 172).

For practical purposes, the power spectral density can be reduced even further by assuming that T is room temperature, approximately 300 K. $G_v(f)$ is nearly constant for frequencies below the infrared range, which is far above the frequency at which electrical components fail to respond (Minkoff 34). Thus, the spectral density of thermal noise is:

$$G_v(f) = 2RkT$$

which is a constant (Carlson 172). Furthermore, the conclusion can be drawn that thermal noise is white noise, as the spectral density is independent of frequency (de Jong 22).

The random motions of charge carriers that generate thermal noise is an unavoidable obstacle in communication systems. By using the power spectral density tool to estimate noise, one can use this information to better design electronic circuits to minimize the effects of thermal noise.

3. Shot Noise

First observed in vacuum tubes, shot noise is another important source of noise that communication systems may have to deal with. Shot noise is generated by a random summation of noise currents due to fluctuations in the number of charge carriers passing a given point (Minkoff 38). Schottky explained that this effect leads to a distribution of random fluctuations about a mean current value, given by the mean square current:

$$\overline{i_n^2} = 2eIB$$

where e is the electronic charge and B is the bandwidth (Davies 132). The variance of the shot noise current is:

$$2BeI = \left\langle i^2(t) \right\rangle - I^2$$

and thus the two-sided shot noise power spectral density is

$$qI$$

which is white noise, similar to thermal noise(Minkoff 38).

Shot noise is normally associated with devices not in thermal equilibrium. Some examples include a diode or transistor where minority carriers have climbed a potential barrier or a thermionic valve in which electrons that have been emitted by the cathode are accelerated towards the anode. Transistors or other parts of a circuit can amplify shot noise once it has been generated, and it may also be smoothed by a space-charge limited thermionic valve (Davies 133).

4. Conclusion

There are various types of noise that can arise in communication systems or electric circuits. Johnson noise is thermal in origin and comes from resistances in circuits. Shot noise arises due to the discrete nature of charge that carries electric currents through an electronic system.

Both thermal and shot noise are fundamental and unavoidable, even in ideal devices (Davies 151). Thus the best way to approach thermal and short noise is to minimize their effects by careful design and analysis of the devices and the circuits that use them.

References

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