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Introduction

Preliminary Remarks

The spontaneous fluctuations of voltages or currents that we deal with are summarized under the term electronic noise. This is a historical term from the early days of radio technology. In those days, listeners were delighted when they had a more or less interference-free reception. In the background, or when the receiver was slightly detuned, a disturbing noise could be heard. In the age of digital data transmission, this everyday acoustic noise has largely disappeared from radio and telephony. Noise need not always be of electronic origin. We can hear it, for example, from a mountain stream, when rain falls on a roof or when an air conditioning system is in operation. A clearly perceptible acoustic impression results from the summation of a plurality of randomly occurring individual processes.

Since the publication of the fundamental work “Noise” by A. van der Ziel in 1954 [1], a number of publications on the theory and practice of electronic noise have been published. In the books [2–8] the physical, mathematical aspect is in the foreground. For the practitioner of circuit design and measurement technology, the books [9–14] are more suitable.

The RF-engineer we are addressing here knows noise as a visual impression at the screen of a spectrum analyzer or broadband oscilloscope. Even without an external signal, the display shows a statistical fluctuation, the “noise floor.” With an oscilloscope, this fluctuation can be seen in the time domain. When sweeping across the screen, the spot dithers irregularly around the baseline. In the spectrum analyzer it fluctuates around an average value. At first glance, the visual impression is the same. It is clear that such an irregularity, whose time dependence is obviously unrepeatable and unpredictable, can only be treated by means of the theory of fluctuation processes. It is indispensable to work with mean values, signal statistics, probability distributions, and correlation. In most cases, time averaging is used for analyses in the time domain, while in the

frequency domain the ensemble average is used. Since the noise is ergodic, there is no difference between the two.

Before turning to the noise of amplifiers, receivers, and oscillators and its measurement, it is useful to understand what laws are hidden in this apparently completely chaotic process.

The reason for this is the atomistic structure of electricity. The electric current is not a continuous flow. It consists of the contributions of the individual elementary charges. Small irregular fluctuations are superimposed on the average value. This is also the case when the mean value is zero, i.e. no current flows. As a result of the thermal motion of the free electrons in the conductor, they generate a current pulse of the duration τ when flying over the distance of a free path. This current pulse corresponds to a voltage pulse at the ends of the structure. These are very short voltage pulses in short succession. In a doped semiconductor we have, e.g. $n = 10^{17}$ electrons/cm³. The free time of flight is about $\tau = 10^{-12}$ seconds.

For a material die with a volume V of 10 μm edge length this results in z voltage impulses per second

$$z = \frac{nV}{\tau} = \frac{10^{17} 10^{-9}}{10^{-12}} = 10^{20} \quad (1.1)$$

The voltage pulses generated by the individual processes are superimposed to thermal noise at the terminals of the structure. The observation of the fluctuation of the voltage at an ohmic resistance in the time domain due to the thermal motion of the electrons is therefore an obvious entry into the physics of noise processes. However, this fluctuating voltage cannot be observed without special measurement technology. Although the oscilloscope is the appropriate instrument for the time domain, it is usually not sensitive enough. The spot on the screen of an older, analog oscilloscope with, e.g. 100 MHz bandwidth, shows, even in the most sensitive range (5 mV/div), a completely smooth curve. No matter which resistor we connect to the input. A voltage fluctuating in time can only be seen on a high performance oscilloscope with extreme bandwidth. However, this noise voltage visible there is also not generated by the thermal noise of a resistor at the input, but by the amplifier chain in the device itself. Nevertheless one has a direct picture of a typical noise process in the time domain. An example is shown in Figure 1.1. Figure 1.1a is the noise voltage on the screen of a LeCroy Wave Expert SE 70 in the y-deviation 1 mV/div [15]. Figure 1.1b is the histogram of the voltage values together with the appropriate Gaussian distribution. This “elementary image” of the noise shows us some essential properties.

The mean value is zero. The amplitude distribution, the probability density function (PDF) follows the Gaussian curve. Thus one can define a standard deviation and thus an effective value of the noise voltage.

Before we deal with the origin of these $v_{RMS} = 2.8$ mV and with the statistical quantities in detail, let us look at the screen of a spectrum analyzer. Unlike the

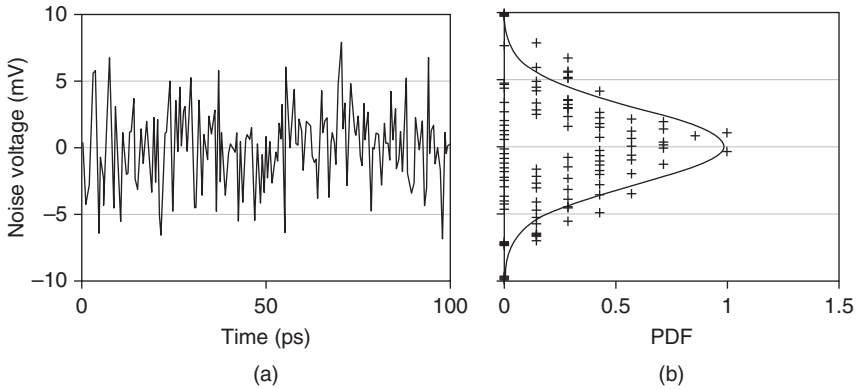


Figure 1.1 Screenshot of the noise level of a LeCroy 70 GHz oscilloscope. (a) Amplitude in the time domain. (b) Statistics of the voltage values. Gaussian distribution with $v_{RMS} = 2.8$ mV.

oscilloscope, even the simplest model shows a noise floor. What at first glance looks the same on an oscilloscope and a spectrum analyzer turns out to be quite different on closer inspection. This is generally the case with noise observations. At the output of a communication system one has a disturbing noise floor. The contributions to this come from different sources and over a wide range of channels. If one wants to minimize them, one has to understand all the elementary processes and their interaction.

Here we have a representation of the noise in the frequency domain. From the broadband noise spectrum we see a small section at the center frequency with the selected resolution bandwidth (RBW). This is not the “elementary picture” of noise as in Figure 1.1. The noise voltage in Figure 1.2 is characterized by two important networks. The IF filter with its RBW selects a narrow frequency range around the center frequency. The display is generated by a detector which displays the average value of the rectified noise voltage. The display is thus the result of data processing through a linear and a non-linear network. This also results in a change in the distribution of the amplitudes. Instead of the Gaussian distribution, we see a Rayleigh distribution on a logarithmic scale in the histogram Figure 1.2b. There is another important difference to Figure 1.1: On the spectrum analyzer [16] we see the noise from the noise. The actual noise level is the average value corresponding to the Rayleigh distribution. What we see is the remaining fluctuation that can be averaged out by reducing the video bandwidth (VBW). By reducing the VBW in relation to the RBW, the standard deviation is reduced (Figure 1.3).

Thus, by a longer averaging we can get a noise-free display of the noise. The most important use of the spectrum analyzer is to observe signals in the frequency domain. Very weak signals become visible when the noise is averaged

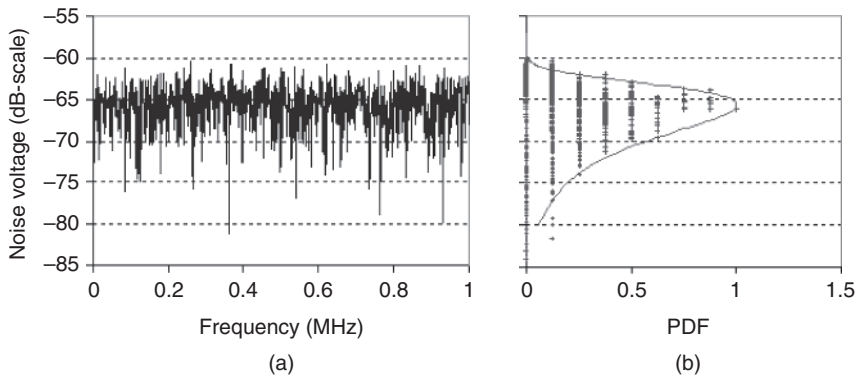


Figure 1.2 Screenshot of a spectrum analyzer (a) and histogram (b).

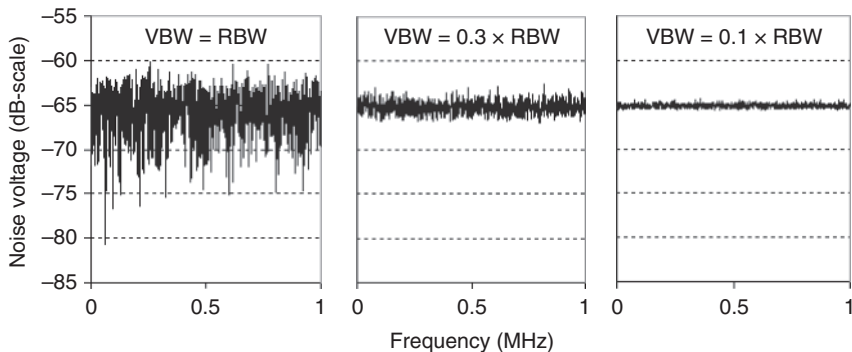


Figure 1.3 Effect of reducing “noise from noise” by reducing video bandwidth.

out. Statistical considerations make it possible to optimize bandwidth and sweep time. The level we now measure is generated by the input attenuator, the mixer, and the IF amplifier. It is easy to observe that it is directly proportional to the RBW. The larger the RBW selected, the higher the noise level.

Electronic noise is present in every component of a transmitter–receiver system, i.e. a system for transmitting information. It physically limits the transmission possibilities, since a signal that is too weak “disappears” in the noise. Even in measuring instruments, e.g. spectrum analyzers or power meters, the detection limit is given by the inherent noise. Even the mirror galvanometers previously used as sensitive current meters showed thermally induced display jitter.

A measure of the level difference between signal P_S and noise N is the signal-to-noise ratio SNR, which is usually given in dB.

$$SNR(\text{dB}) = 10 \log \frac{P_S}{N} \quad (1.2)$$

Table 1.1 Values of SINR (signal to interference and noise ratio) for various applications.

Application	Radar	Mobile phone	Entertainment, video games
SNR (dB)	+15	+18	+30

Table 1.1 shows typical values for an electronic system limited only by the noise of the receiver.

A signal beyond recognition can also be caused by interfering signals that scatter into the receiving band. This can be explained using the example of mobile radio technology (Cellular Telephone Systems).

At present the most common digital technologies are UMTS (3G) in the 1.9–2.2 GHz frequency band, bandwidth $B = 5$ MHz with QPSK modulation and LTE (4G) in the 0.7–2.7 GHz frequency band. The bandwidth is divided into sections of 200 kHz. So in the case of $B = 5$ MHz in 25 so-called resource blocks. Interference signals can, for example, come from neighboring transmitting aerials, be caused by reflection or by other techniques. Formula (1.2) is expanded by the signal level of the interference P_{INT}

$$SINR(\text{dB}) = 10 \log \frac{P_S}{N + P_{INT}} \quad (1.3)$$

$SINR$ is a measure of the ratio of useful signal to noise and interference. The following approximate specifications apply to the magnitude (Table 1.2).

We have already mentioned almost all the important phenomena of electronic noise. In Chapter 2, we will start from these empirical impressions and discuss the background of the description, the origin of the noise and its measurement in a form that is understandable for the practitioner. This is not possible without signal and circuit theory and the application of correlation matrices with their auto and cross spectral densities. Each derivation and calculation starts with elementary, easily understandable principles and formulas and is guided step by step to the result. In this way, an attempt is made to present this matter in a way that

Table 1.2 Values of SINR for mobile communication.

SINR (dB)	Reception quality	Comment
+40 ... +20	Very good	No interference
+19 ... +10	Good	Stable reception
+9 ... +5	Satisfactory	Still works
+4 ... 0	Poor	Detection limit

is understandable to the technician, although a high content of mathematics is necessarily inherent in it.

History

Electronic noise is a subfield of the physics of fluctuation phenomena. Fluctuations first became known with the discovery of Brownian molecular motion in 1827, when the botanist Robert Brown observed under the microscope that tiny dust particles in water are constantly dithering. Later it was discovered that the cause is the thermal motion of water molecules. It was possible to determine the average speed from the change of location Δx over a period of time Δt to $\bar{v} = \Delta x / \Delta t$, but it could not be explained by the expectation from the translational energy $3/2 kT$ of the water molecules.

A. Einstein showed 1906 [17] that instead of Δx the mean square of displacement $\overline{\Delta x^2}$ must be considered. He also recognized that there must be comparable electrical phenomena. In 1906 he calculated the fluctuation around the equilibrium state of an electrical capacitor from the thermal energy.

$$\overline{\Delta E} = \frac{kT}{2} = \frac{C}{2} \overline{v^2} \quad (1.4)$$

and thus established the interrelation between thermodynamics and electrical fluctuations. However, at that time these small voltages ($v = 2 \mu\text{V}$ at $C = 1 \text{ nF}$) could not be measured. At the end of the nineteenth century, mirror galvanometers were the most sensitive electrical measuring instruments. The current to be measured flows through a small coil, on which a torque acts in a magnetic field. The coil hangs on a torsion thread, to which a small mirror is attached, which deflects a light beam. The sensitivity is limited by the dithering of the mirror. The analogy to Brownian motion did not lead to success. Then cooling or evacuation of the system should have brought an improvement. The fluctuation is obviously electrical in nature.

The connection was first established by G. Ising in 1926 [18]. He related the minimum measurable voltage of a critically damped galvanometer to the thermal energy.

$$\overline{v_{MIN}^2} = 16 \overline{\Delta E} \omega_0 R \quad (1.5)$$

Here R is the internal resistance of the galvanometer coil and ω_0 is the natural frequency of the system consisting of coil mass and mirror as well as the torsion filament. The equivalent bandwidth of the critically damped galvanometer is $\Delta f \cong \omega_0/8$. If the thermal energy (1.4) is applied, the following results

$$\overline{v_{MIN}^2} = 16 \frac{kT}{2} R \times 8 \Delta f = 64 kTR \Delta f \quad (1.6)$$

Except for the factor 64 instead of 4, this is already the Nyquist formula of the thermal noise of the resistor R .

The effect of thermal noise was finally clarified by the quantitative description of H. Nyquist 1928 [19] with the derivation of the well-known Nyquist formula. This was experimentally confirmed by J.B. Johnson 1928 [20] by measurements. Shortly afterwards E.B. Moullin [21] was able to verify the value of the Boltzmann constant k to within 1% by noise measurements. Thus the correlation between thermal energy and electronic noise was secured as an inherent effect.

W. Schottky had already dealt with the limit sensitivity of radio receivers in 1918 [22]. He was primarily interested in the noise of the electron stream in the tube amplifiers used at that time, as this was by far the strongest source of interference. Today the quantized current of the charge carriers is one of the main sources of noise in modern transistors. This shot noise is described by the Schottky formula (Chapter 3).

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