

NOISE IN RADIO/OPTICAL COMMUNICATIONS

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Abstract

Noise is a random signal that affects the performance of all electronic and/or optical devices. Although the sources of different kinds of noise have their backgrounds in physics, engineers dealing with noise use different methods and units to specify noise. The intention of this tutorial is to describe the main effects of noise in electronics up to optical frequencies while providing links between the physics and engineering worlds. In particular, noise is considered harmful while degrading the signal-to-noise ratio or broadening the spectrum of signal sources. On the other hand, noise can be itself a useful signal. Finally, artificially generated signals that exhibit many properties of random natural noise are sometimes required.

NATURAL NOISE

Noise is a broadband signal. Therefore it makes sense to describe its intensity by the noise spectral density N_0 or amount of noise power per unit bandwidth. In electronics the most important type of noise is thermal noise. Thermal noise adds to any signal. In optics the most important type of noise is shot noise. Shot noise is a property of any signal made from a discrete number of photons.

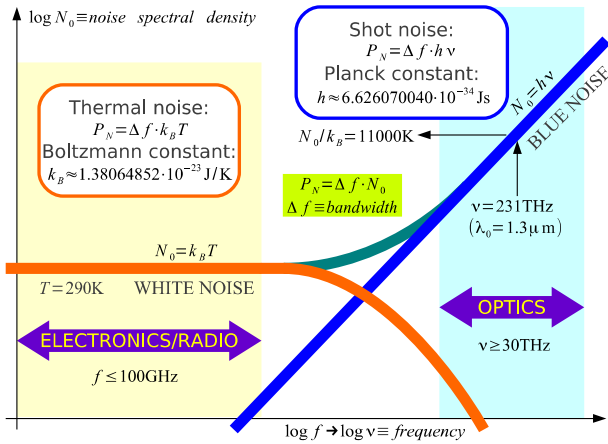


Figure 1: Noise spectral density.

Since the photon energy increases proportional with frequency, the higher the frequency the larger the shot noise spectral density. Such a noise is also called blue noise. Shot noise is unimportant in the radio-frequency range at room temperatures. Shot noise can only be observed at the highest end of the radio-frequency range at cryogenic temperatures.

Thermal noise is caused by thermal radiation. The Planck law describes the spectral brightness B_f or radiated power per unit bandwidth, unit area and unit solid angle

of a black body. A black body with zero reflectivity $\Gamma=0$ is the most efficient thermal radiator while a perfect mirror $|\Gamma|=1$ does not radiate at all.

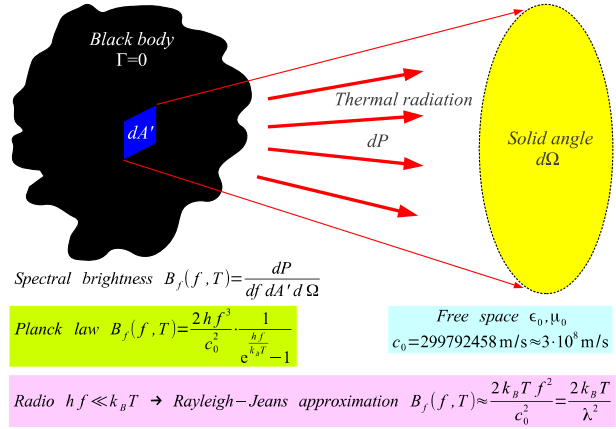


Figure 2: Black-body thermal radiation.

In the radio-frequency range it makes sense to use the Rayleigh-Jeans approximation of the Planck law to calculate the noise power collected by a lossless antenna. An antenna with a single electrical connector only collects half of the incident noise power on its effective area A_{eff} , the remaining half being orthogonally polarized.

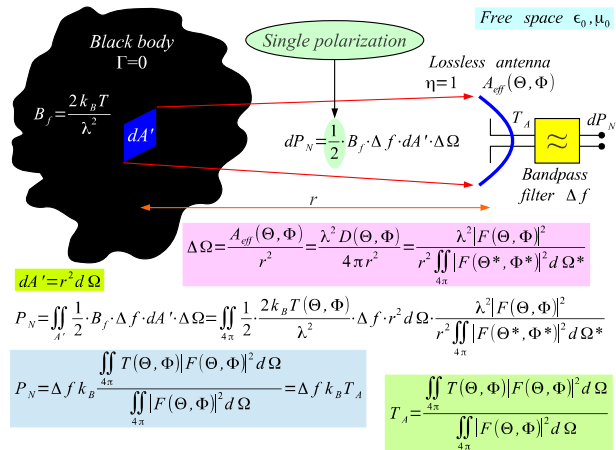


Figure 3: Received thermal-noise power.

In the radio-frequency range the noise spectral density is frequency independent. Thermal noise therefore behaves as white noise. Thermal noise spectral density is simply described by the black-body temperature T_A as observed by the radiation pattern of a lossless antenna.

Above a certain frequency the thermal noise power begins decreasing when the complete Planck law applies. However, the sum of both noise spectral densities, thermal noise and shot noise, remains a monotonic

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function of frequency. The white-noise behaviour is smoothly replaced by the blue-noise behaviour.

Expressing the noise spectral density with the noise temperature is so popular that the noise temperature is also used in cases when the noise is not of thermal origin.

SIGNAL-TO-NOISE RATIO

Any receiver (amplifier) adds its own noise therefore further degrading the signal-to-noise ratio. The additional receiver noise is usually specified as an equivalent noise temperature T_{RX} at the receiver input even if it is not of thermal origin. In the case of thermal noise, T_{RX} is usually of the same order of magnitude as the physical temperature of the amplifying device.

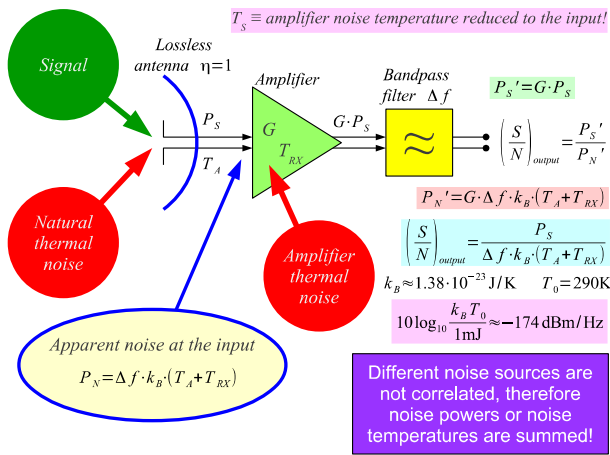


Figure 4: Receiver signal-to-noise ratio.

Alternatively the noise figure of a receiver can be specified. The noise figure has to be used carefully due to its unfortunate definition. In the case of thermal noise, selecting a reference temperature $T_0=290 \text{ K}$ allows a sensible definition of the noise figure F (in linear units) or F_{dB} (in logarithmic units) and a simple conversion from/to the receiver noise temperature T_{RX} .

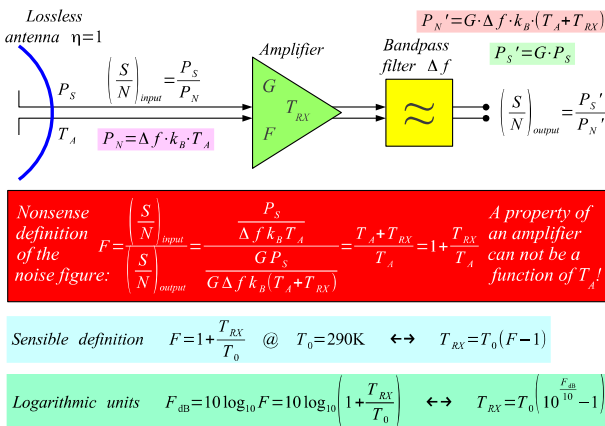


Figure 5: Amplifier noise figure.

A frequent case is an attenuator $0 < a < 1$ between the antenna and receiver. Besides attenuating both the signal P_S and the antenna noise T_A , the attenuator adds its own

thermal noise $T_R(1-1/a)$. The noise figure F or F_{dB} may simplify calculations when the attenuator temperature $T_R \approx T_0$ is close to the reference temperature.

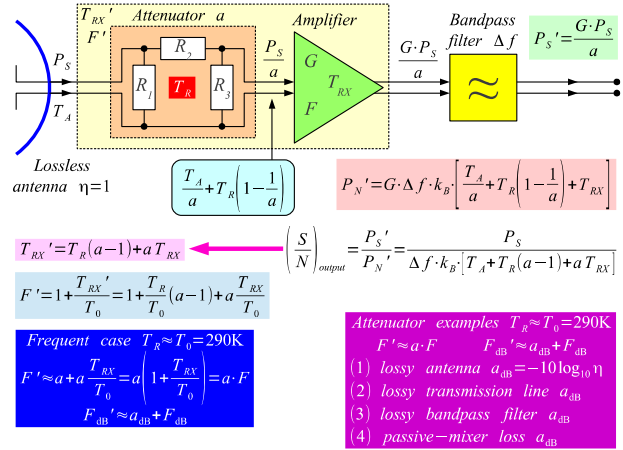


Figure 6: Attenuator noise.

OSCILLATOR PHASE NOISE

A sine-wave oscillator includes a resonator to define its frequency and an amplifier to compensate the resonator loss. Initially the amplifier provides excess gain and the oscillation starts out of noise exponentially. In the steady state, saturation reduces the gain of the amplifier and the oscillation amplitude stabilizes.

Unfortunately in the steady-state oscillation, the noise sources T_R (resonator loss) and T_G (amplifier noise) are still present, corrupting the spectrum of the generated signal, broadening the generated-signal line width by adding noise side-bands.

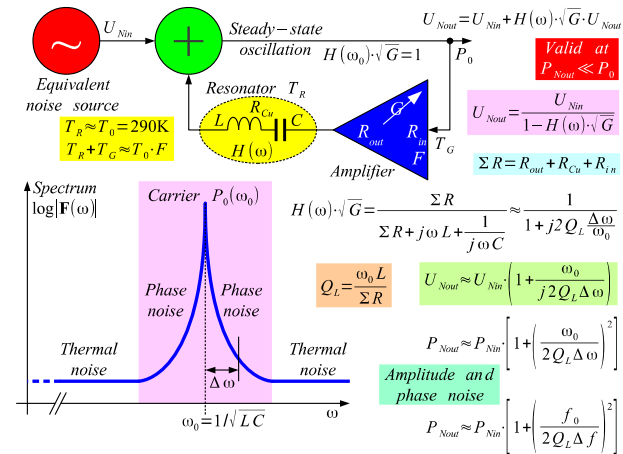


Figure 7: Oscillator phase noise.

The derivation can be simplified assuming that the noise power $P_{Nout} \ll P_0$ is much smaller than the desired carrier power at ω_0 . The saturation of the amplifier removes most amplitude noise. Noise side-bands therefore include mainly phase noise. The final result is known as Leeson's equation although today it is usually written in a slightly different way from [1].

Unfortunately, the devices used in the oscillator generate additional flicker noise ($1/f$ noise or pink noise)

at small frequency offsets $|\Delta f| < f_c$. The flicker-noise corner frequency may be as high as $f_c \approx 1$ MHz for surface devices like MOSFETs or HEMTs or as low as $f_c \approx 1$ kHz for bulk devices like bipolar transistors or junction FETs.

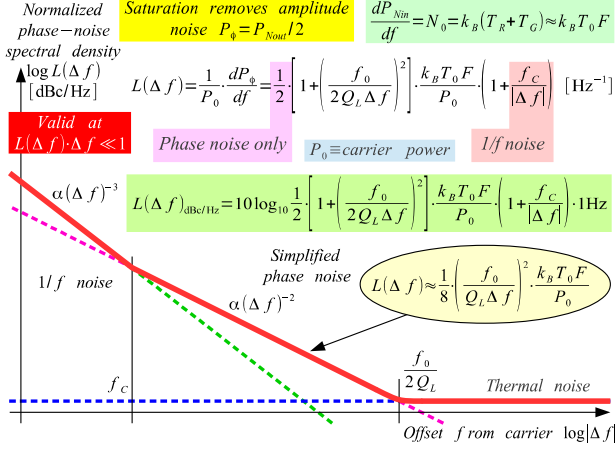


Figure 8: Leeson's equation.

The most important parameter of a good oscillator is the loaded quality Q_L of the resonator. A LC oscillator may achieve a $Q_L \approx 100$. A crystal oscillator may achieve a $Q_L \approx 10^4$. A HeNe laser may achieve a $Q_L \approx 10^8$ but its signal usually can not be used directly. Additional requirements are low-noise devices (low F and low f_c) operated at a high carrier power P_0 .

The oscillator phase noise has many detrimental effects: it increases the bit-error rate due to modulation constellation rotation, it adds residual FM in analog communications, it causes adjacent-channel interference and it causes clock jitter.

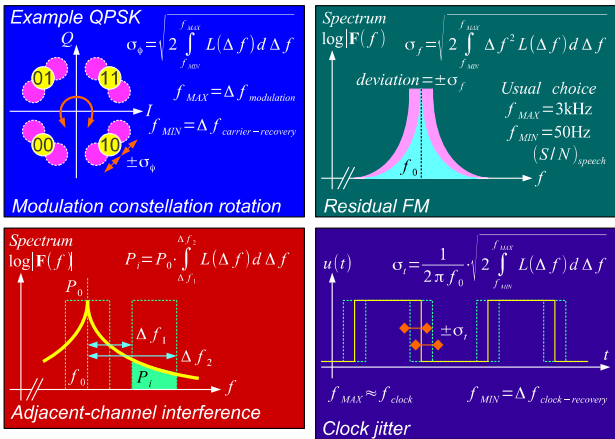


Figure 9: Effects of phase noise.

In all above case, the phase noise is integrated over a finite interval $f_{MIN} < \Delta f < f_{MAX}$ where the Leeson's equation is accurate enough in almost all real-world engineering problems having a finite bandwidth $f_{MAX} = \Delta f_{bandwidth}$ and fast-enough control loops $f_{MIN} = \Delta f_{recovery}$.

All of the above integrals give an infinite result both for $f_{MIN} \rightarrow 0$ and/or for $f_{MAX} \rightarrow \infty$. Such an infinite result has no physical background and comes from the approximations used in the derivation of the Leeson's equation. The phase

noise without approximations should include additional effects. The complete Planck law limits the bandwidth, the device f_{MAX} limits the bandwidth even more.

At the other end, at very small frequency offsets $f_{MIN} \rightarrow 0$ the noise power is no longer small compared to the carrier power. The spectrum of any real oscillator is a finite and continuous function with a rounded top at the central frequency f_0 .

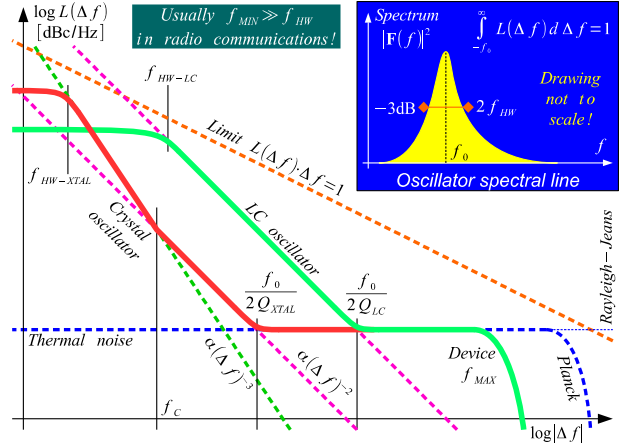


Figure 10: Phase noise without approximations.

When the flicker ($1/f$) noise can be neglected, the simplified Leeson's equation is simply extended into a Lorentzian spectral line. The -3 dB spectral-line width of a rather poor ($Q_L=10$) electrical ($f_0=3$ GHz) LC oscillator is just $f_{FWHM}=28$ Hz $\approx 10^{-8}f_0$.

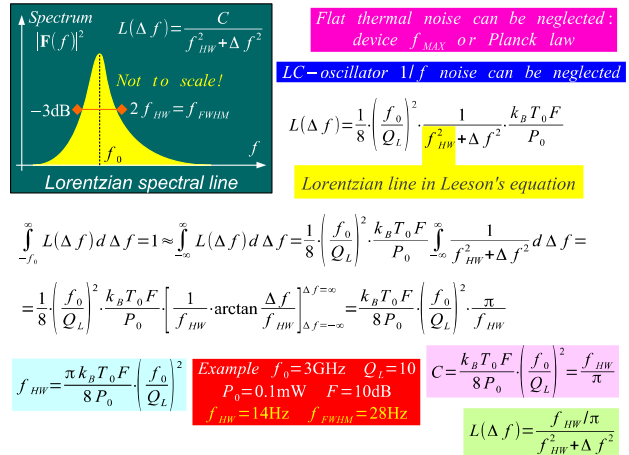


Figure 11: Lorentzian spectral-line width.

While both physicists and engineers observe the same effects, they look at different details. Physicists talk about line widths f_{FWHM} . Engineers talk about phase-noise spectral density $L(\Delta f)$ at much larger frequency offsets.

FIBER-OPTICS NOISE

Any receiver (amplifier) adds its own noise therefor

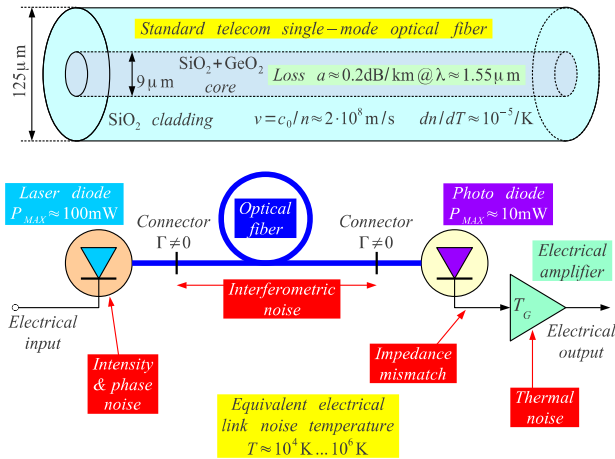


Figure 12: Optical-fiber link.

REFERENCES

- [1] JACoW, <http://www.jacow.org>
- [2] *IEEE Editorial Style Manual*, IEEE Periodicals, Piscataway, NJ, USA, Oct. 2014, pp. 34-52.