Semiconductor Photodetectors for Optical Communications

Photonic Communications Engineering Lecture

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Noise and Detection

Noise degrades signals. Without noise, it would not matter how little optical power arrived at the receiver.

Signal quality is measured in several ways.

Analog systems:

The signal-to-noise ratio (SNR) is the measure.

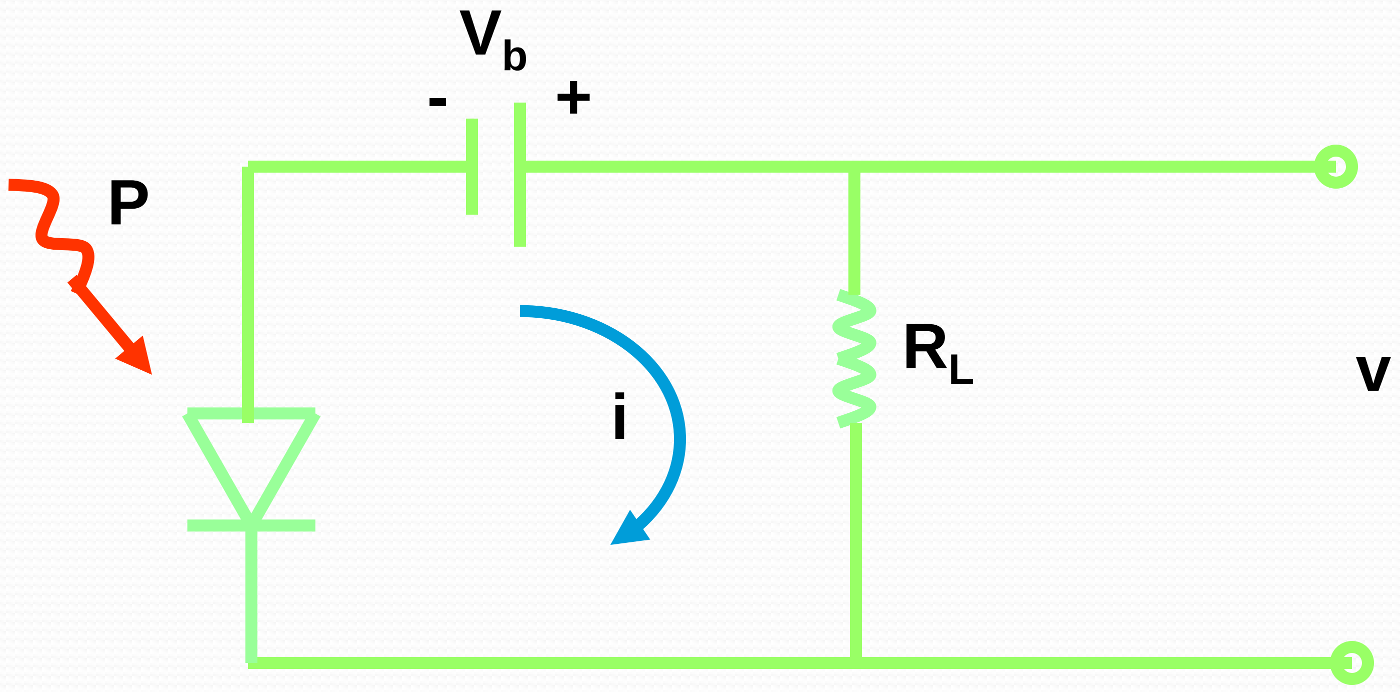
Digital systems:

The bit-error-rate (BER) is the measure.

Thermal and Shot Noise

Thermal Noise

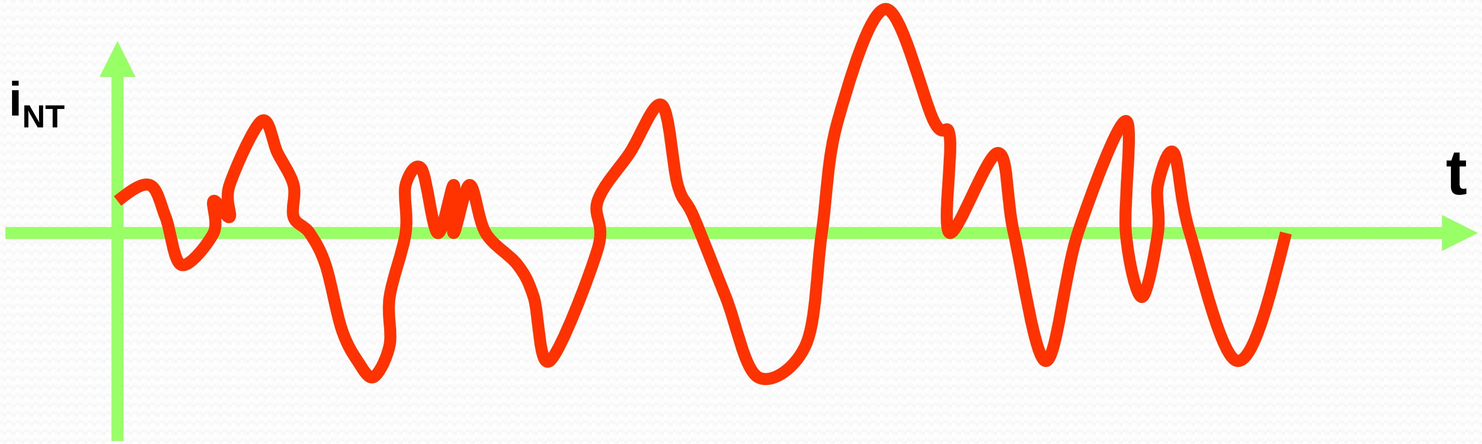
Recall the simple receiver circuit :



Even if P = 0 (and the photodiode dark current is zero), a current

$$i = i_{NT}$$

will exist in resistor R_L. It has zero average value, but it is random, like:

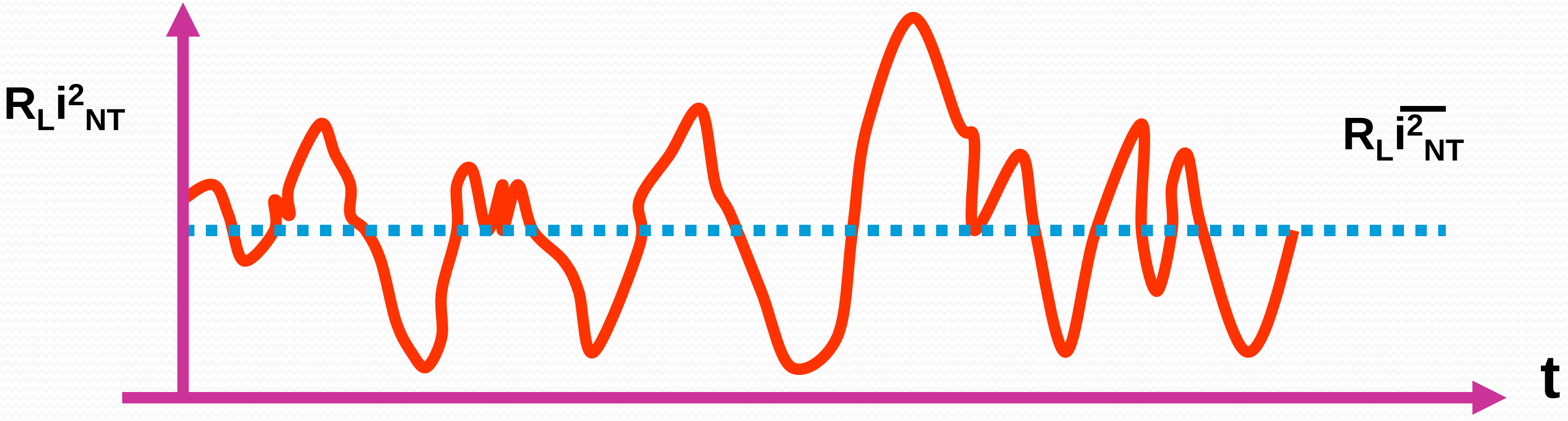


The current arises from the random thermal motion of the electrons. The instantaneous noise power is

$$R_L\, i^2_{NT}$$

The average thermal noise power is

$$R_L\, \overline{i^2}_{NT}$$



$\overline{i^2}_{NT}$ = mean square thermal noise current.

It is given by :

$\overline{i^2}_{NT} = 4kT\Delta f / R_L$

k = 1.38×10^{-23} J /K, Boltzmann constant

T = temperature, K

Δf = receiver's bandwidth.

Usually Δf is a bit larger than the information bandwidth.

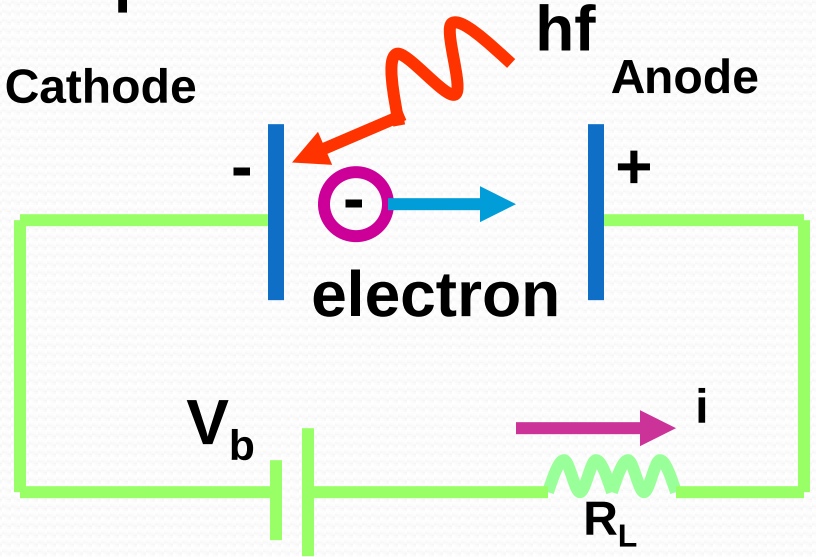
The load resistor's equivalent circuit looks like:

where R_L is an ideal (noiseless) resistor.

Shot Noise

It is caused by the discrete nature of charge carriers (electrons and holes).

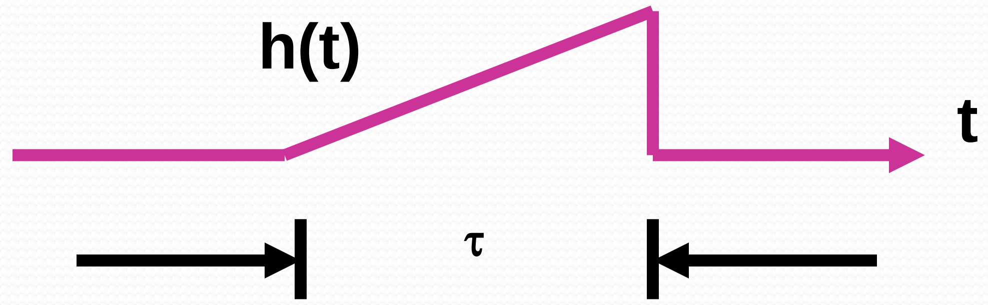
Consider the single emitted photoelectron, shown for vacuum phototube.



A current exists in the circuit during the transit time (τ) of the emitted electron.

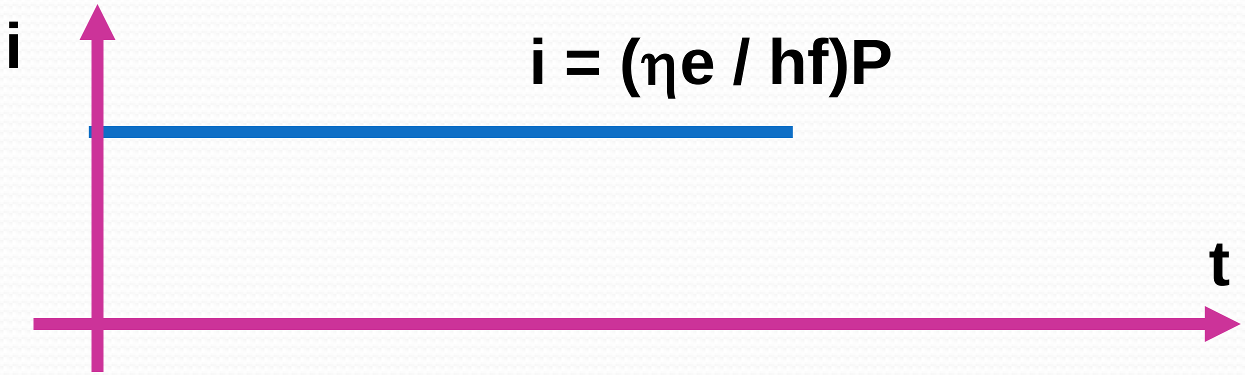
τ = time for travel from cathode to anode.

The electron recombines at the anode with a positive ion. The current caused by a single electron looks something like :



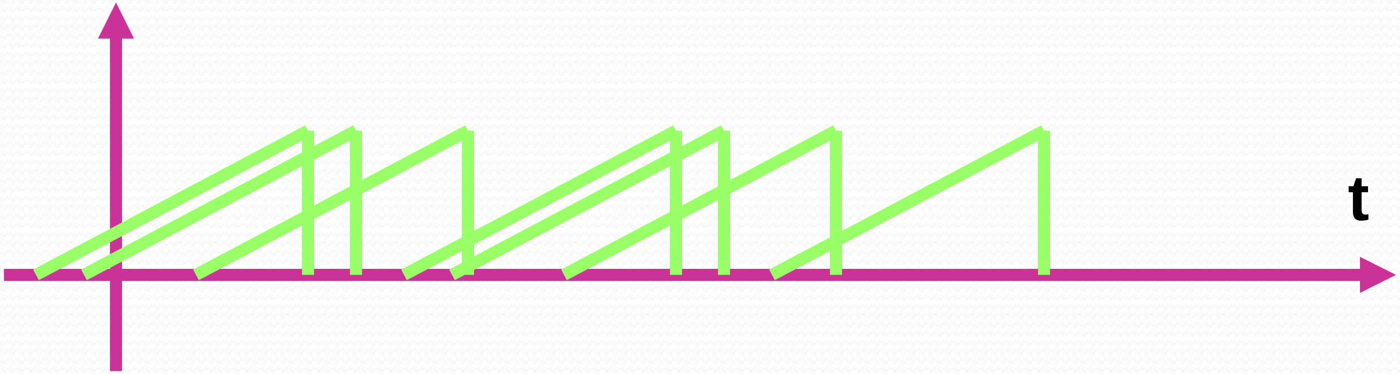
Every electron produces the same current pulse shape.

Consider constant optical power P incident on the detector. The expected current is :



This current is made up of numerous pulses of the type shown by h(t).

Example :

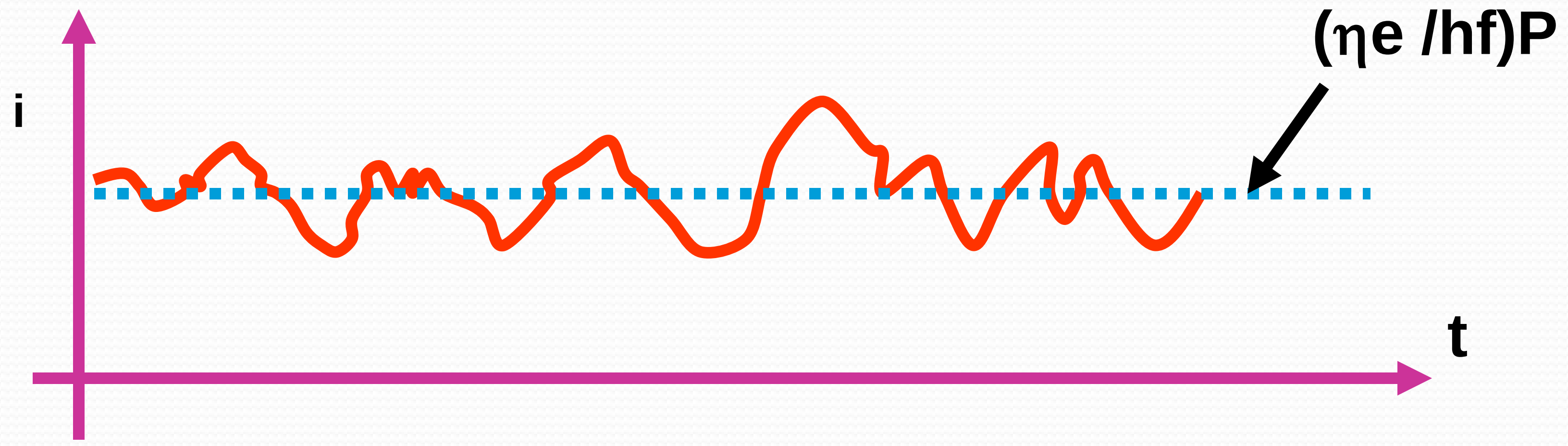


The pulses start at random times, t_N.

The total current is the sum of these pulses.

$$i = \Sigma_N h(t - t_N)$$

Total current:



The average current is still:

i = (ηe /hf)P

but noise is superimposed onto this current. This is shot noise .

The shot noise current is:

$$i_{NS} = \Sigma_N h(t - t_N) - (\eta e / hf)P$$

$$\overline{i^2}_{NS} = 2eI\Delta f$$

Δf = receiver's bandwidth

I = average current.

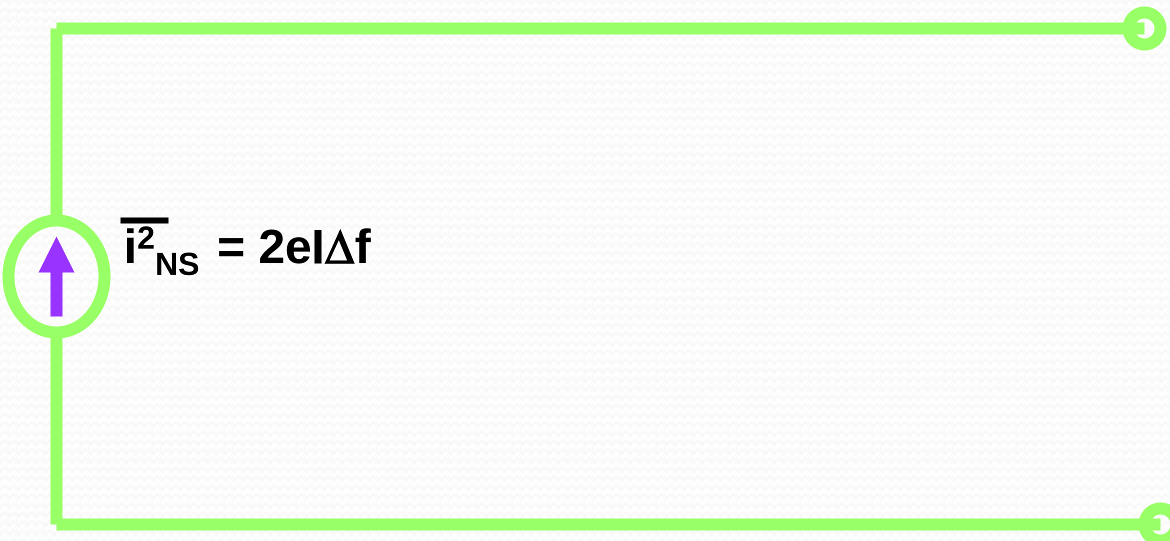
$$I = \overline{i}_S + I_D$$

where

$\overline{i}_S$ = average of the signal current

I_D = average dark current

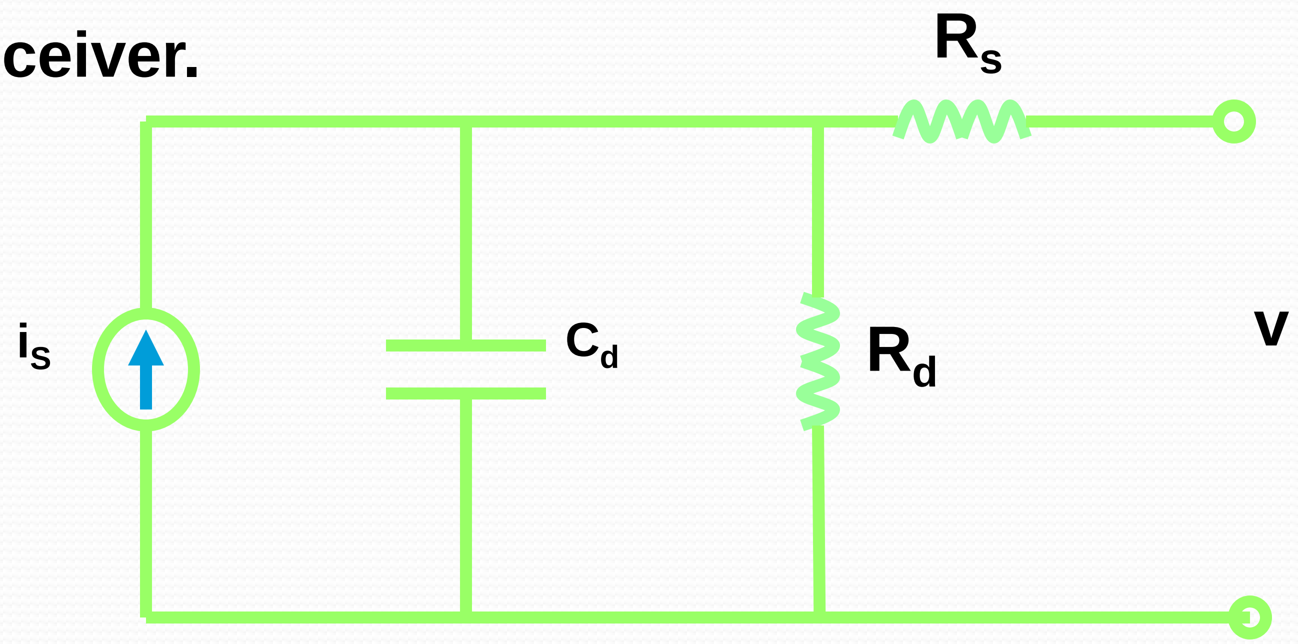
The equivalent circuit for shot noise is just a noise current generator, as shown below.



$$\overline{i^2_{NS}} = 2eI\Delta f$$

Signal-to-Noise Ratio

Consider the equivalent circuit of a photodiode receiver.



C_d = diode's junction capacitance (small)

R_d = diode's junction resistance (large)

R_s = diode's bulk series (n and p) resistance (small)

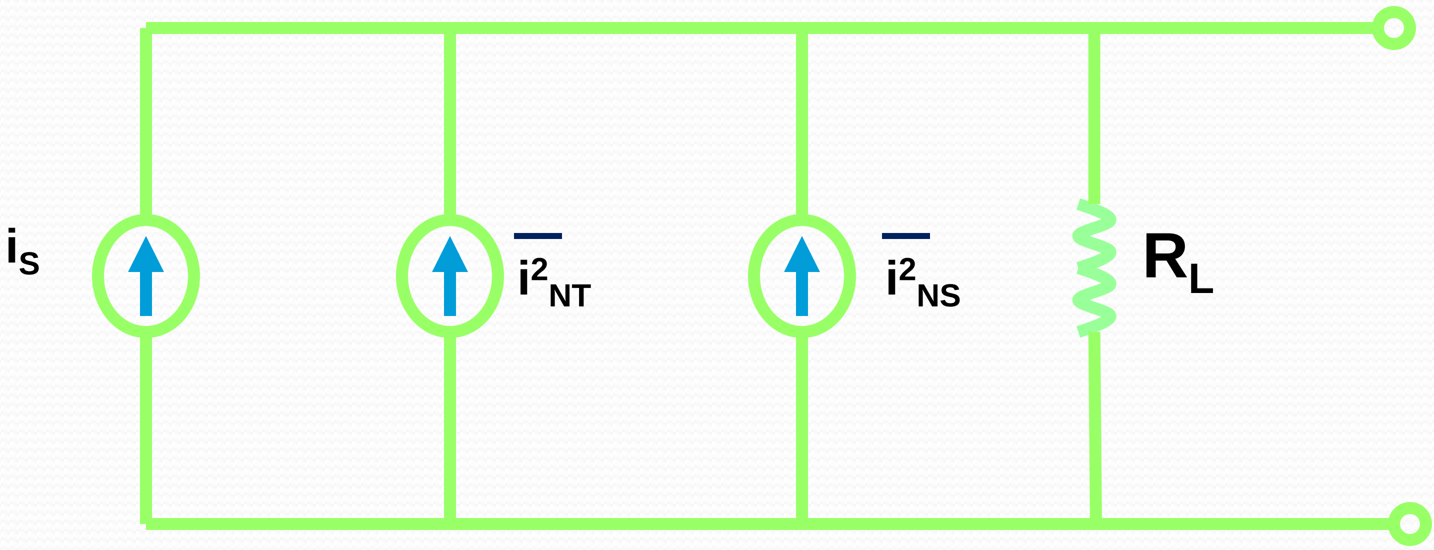
i_S is the photocurrent. As before, it is given by

$$i_s = (\eta eP/hf) = \rho P$$

For simplicity, assume $R_s = 0$ and R_d = infinite.

Also neglect C_d for purposes of noise calculations, since it does not affect the noise in the circuit.

The simplified receiving circuit, including all sources of thermal and shot noise is now:



We will use this circuit to compute SNR.

Constant Power SNR

Let the incident optical power P be a constant. This corresponds to a binary 1 in a digital system.

Compute the SNR.

SNR = average signal power / average noise power

These are the electrical powers. From the equivalent circuit, we see that

$$SNR = (R_L \overline{i^2_S}) / (R_L \overline{i^2_{NS}} + R_L \overline{i^2_{NT}})$$

$$SNR = \overline{P}_{ES} / (\overline{P}_{NS} + \overline{P}_{NT})$$

$$SNR = \overline{i^2_S} / (\overline{i^2_{NS}} + \overline{i^2_{NT}})$$

These equations are general. For the special case where P = a constant:

$$\overline{i_S} = i_S = (\eta e / hf)P = \rho P$$

$$\overline{P}_{ES} = R_L\, \overline{i^2}_S = (\eta e P/ hf)^2 R_L$$

$$\overline{P}_{NT} = R_L\, \overline{i^2}_{NT} = (4kT\Delta f / R_L)\, R_L = 4kT\Delta f$$

$$\overline{P}_{NS} = R_L\, \overline{i^2}_{NS} = 2e[\, I_D + (\eta e P/ hf)]\, \Delta f\, R_L$$

Then

$$SNR = \frac{[(\eta e P/ hf)^2 R_L\,]}{\{2e[\, I_D + (\eta e P/ hf)]\, \Delta f\, R_L\, \} + 4kT\Delta f}$$

Example:

Light source is an LED, 10 mW output power,

λ = 0.85 μm.

The system losses are:

coupling loss = 14 dB

fiber loss = 20 dB

connector losses = 10 dB

Total loss = 44 dB

Compute the received power.

$$dB = \log (P_R / P_T)$$

$$- 44 = \log (P_R / P_T)$$

$$(P_R / P_T) = 10^{-4.4}$$

$$P_R = 10 \times 10^{-4.4} = 10(3.98 \times 10^{-5})$$

$$P_R = 4 \times 10^{-4} \text{ mW}$$

Alternative calculation for the received power:

$$P_T = 10 \text{ mW} = 10 \text{ dBm}$$

$$\text{Loss} = - 44 \text{ dB}$$

$$P_R = - 34 \text{ dBm}$$

Check :

$$dBm = 10 \log P_R$$

$$-34 = 10 \log P_R$$

$$P_R = 10^{-3.4} = 4 \times 10^{-4} \text{ mW}$$

This result checks.

The receiver has the following characteristics:

ρ = 0.5 A/W (responsivity)

I_D = 2 nA (dark current)

R_L = 50 Ω (load resistance)

Δf = 10 MHz (receiver bandwidth)

T = 300 K (27 ^{0}C) receiver temperature

Find :

- Signal current and power
- Shot noise power
- Thermal noise power
- SNR

Solution :

Signal Current

$$i_S = \rho P_R = 0.5(4 \times 10^{-4}) = 2 \times 10^{-4}\ mA$$

$$i_S = 0.2\ \mu A = 200\ nA$$

$$i_S = 200\ nA \gg I_D = 2\ nA$$

Signal Power

$$\overline{P}_{ES} = R_L\, \overline{i^2}_S = 50(0.2 \times 10^{-6})^2 = 2 \times 10^{-12}\ W$$

Shot Noise Power

$$\overline{P}_{NS} = 2e\, i_S\, R_L\, \Delta f = 2(1.6 \times 10^{-19})\,(0.2 \times 10^{-6})\,(50)10^{7}$$

$$\overline{P}_{NS} = 3.2 \times 10^{-17}\ W$$

Thermal Noise Power

$$\overline{P}_{NT} = 4kT\Delta f = 4(1.38 \times 10^{-23})\ 300 \times 10^{7}$$

$$\overline{P}_{NT} = 1.66 \times 10^{-13}\ W$$

Note

$$\overline{P}_{NT} >> \overline{P}_{NS}$$

Thus, we have a thermal-noise limited system, and

$$SNR = \overline{P}_{ES} / \overline{P}_{NT} = 2 \times 10^{-12} / 1.66 \times 10^{-13} = 12$$

$$SNR_{dB} = 10 \log SNR$$

$$SNR_{dB} = 10 \log 12 = 10.8\ dB$$

If the system were shot-noise limited, then

$$\mathbf{SNR = \eta P / 2hf\Delta f = i_s / 2e\Delta f}$$

$$\mathbf{SNR = 0.2 \times 10^{-6} / 2(1.6 \times 10^{-19})\, 10^{7} = 62{,}500}$$

$$\mathbf{SNR_{dB} = 10 \log 62{,}500 = 48\ dB}$$

Note the improvement if the system were shot-noise limited. We can approach this higher SNR if we use a photodetector with internal gain, or use heterodyne detection.

References

1. Joseph Palais. Fiber Optics Communications, 5th Edition. New Jersey: Prentice Hall, 2004.
2. Frank L. Pedrotti and Leno Pedrotti. Introduction to Optics. New Jersey: Prentice Hall, 1993
3. Pallab Bhattacharya. Semiconductor Optoelectronic Devices, 2nd Edition. New Jersey: Prentice Hall, 1997.