Noise and interference

Radio reception is essentially a matter of signal to noise ratio (SNR). A signal must be some amplitude above the noise floor of the system in order to be detected properly.

Noise

- In the previous we have studied how radio signals (carriers) is amplified (antenna gain) and attenuated (path loss). Often a very weak signal reaches the receiver. However, since we may apply an arbitrarily high amplification in our receiver, this is not a problem.
- What cause the real problem is the interference, noise and other disturbances which we cannot control.
- What decides the quality of a communication link is the signal to noise ratio (SNR), that relates the received signal power to the ambient noise power.

Thermal noise

- All electronic systems (receivers, conductors and antennas included) have inherent thermal noise.
- The thermal noise is produced by the random motion of electrons inside a resistor.
- At all temperature above absolute zero (-273.16º Kelvin) the electrons inside a material are in random motion, i.e., a random current is generated.
- As long as there is any resistance present, the random current will generate a random voltage, $U=RI$, and hence some noise power, $P=U^2/R$.
- The reason why there is no discernible current flow in one direction is that the motions cancel out each other even over a short time period.
- Thermal noise is uniformly distributed across the frequency spectrum (white noise).
- The power density of thermal noise, N_0, is expressed as W/Hz.

Atmospheric noise

- This type of noise is caused by different electrical phenomena in the atmosphere, such as lightning bolts, etc.
- This noise does not usually exhibit the continuous characteristics that thermal noise do.
- Instead it will have a much more impulsive character.
- In particular at low frequencies(<20MHz) this type of noise dominates the noise characteristics.

Cosmic Noise

- A lot of radiation from outer space falls into the radio spectra.
- Parts of this radiation penetrate the ionosphere and reach the ground.
- The cosmic radiation may be caused by distinct bodies in space such as the sun. The sun actually cause the most trouble, for example, sunrise behind a radio link station may cause a severe increase in noise level.
- Or from more diffuse sources, so called galactic background noise.
- During world war II, the Milky Way was noted to generate noise, by British radar operators. The operators discovered that the distance that they could detect German aircrafts was dependent upon whether or not the Milky Way above the horizon.

Manmade Noise (Interference)

- This type of noise is caused by electrical equipment in the vicinity to the receiver.
- Sparks in electrical motors, engine spark plugs, and switches often generates impulse noise with high bandwidth(>100 MHz).
- Poorly shielded digital electronic equipment using high clock frequencies.
- Interfering signals from other transmitters.

Thermal noise

The thermal noise is often used as a reference, to measure the relative noise power. The spectral density of thermal noise is calculated according to:

$$N_0 = kT \qquad \text{[W/Hz]}$$

Where T is the absolute temperature in Kelvin and k is Boltzmann's constant= 1.3803×10^{-23}.

The noise power N, measured over a bandwidth, B, is then equal to:

$$N = N_0 B \qquad \text{[W]}$$

Expressed in decibel-watts:

N =10log k + 10log T + 10log B => -228.6 [dBW] + 10log T +10log B [dBW]

Noise factor I

The ***Noise temperature***, T_{source}, [Kelvin] for a noise source gives the noise density:

$N_{source} = kT_{source}$ [W/Hz]

The temperature, T, can be used to describe the strength of the noise. A component is said to have a noise temperature, T.

Another popular way to measure the noise energy is the ***noise factor***, F_{source}, for a noise source, is the ratio between the noise produced by the source and thermal noise produced by an ideal resistor.

$$F_{source} = \frac{N_{source}}{N_0} = \frac{kT_{source}}{kT_0} = \frac{T_{source}}{T_0}$$

Here we compare the noise power of our source with a reference thermal noise source with a temperature $T_0=290^o$ K.

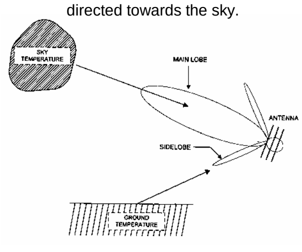
Antenna as noise source

The antenna is a significant source of noise, both internal noise and noise picked up from the surrounding.

The noise in an antenna system can be divided into three types:

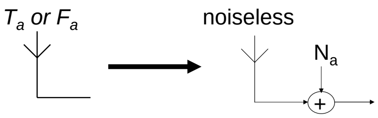
- Noise due to the loss resistance, T_r
- The sky noise, T_{sky} .
- Ground noise T_{ground}.
- Assume that M is the fraction of the total energy that enters the main lobe.
- Further assume that ⌘ is the fraction of the side lobes that are viewing the ground.

A parabolic dish antenna directed towards the sky.



$$T_a = (MT_{sky}) + \zeta(1-M)T_{GND} + T_r$$

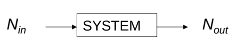
Antenna noise



$N_a = kT_a = kT_0F_a$ [W/Hz]

Noise factor II

The noise factor, F_{sys}, for a system is defined as the ratio between the noise at the output, N_{out}, and the noise at the input, N_{in}.

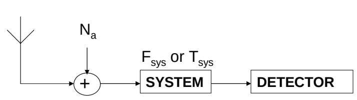


$$F_{sys} = \frac{N_{out}}{N_{in}} = \frac{N_{sys} + N_{in}}{N_{in}} = \frac{T_{sys} + T_0}{T_0}$$

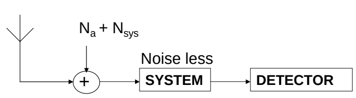
The noise density for added system noise, N_{sys}, is given by the noise temperature, T_{sys}.

$N_{sys} = kT_{sys} = kT_0(F_{sys} - 1)$ [W/Hz]

System noise



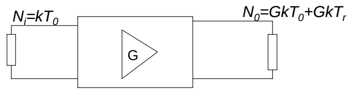
The noise density from the system is added.



$N_{sys} = kT_{sys} = kT_0(F_{sys} - 1)$ [W/Hz]

Amplification example

A receiver is characterized by its system noise figure, F_{sys}, describing the total noise of the receiver, if connected to a noise source of temperature, T_0.



The receiver is modeled as a amplifier with a power gain, *G*. The noise spectral density at the receiver output is then found as:

$N_0 = GkT_0 + GkT_r$

Where T_r is the noise temperature of the receiver itself. (This is the same output noise level we would have obtained if we had added just another noise source of temperature T_r, but with a noiseless amplifier).

The system noise figure for the receiver thus becomes:

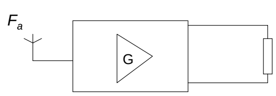
$$F_r = \frac{T_0 + T_r}{T_0} = 1 + F'$$

Where *F'* is the noise contribution of the receiver itself.

Amplification example cont.

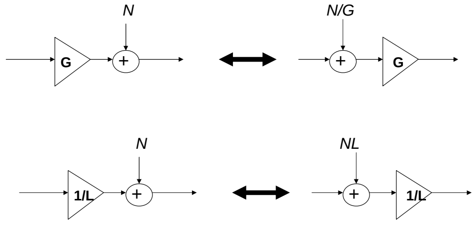
If we connect an antenna with noise figure, F_a, (caused by thermal noise in the antenna and external noise) we get the following total system noise figure:

$$F_{sys} = F' + F_a = (F_r - 1) + F_a$$



Moving noise sources

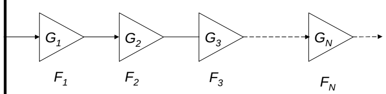
A receiver often contains amplifiers, *G*, or an attenuation element, 1/L, how do we move a noise source through such an element.



Noise in cascaded amplifiers

• Each stage in the cascade chain amplifies both signal and noise from previous stages, and also contributes with some additional noise of its own.

• Thus, in a cascaded amplifier, the final stage sees an input signal that consists of the original **signal and noise amplified by each successive stage plus the noise contributed by earlier stages**.



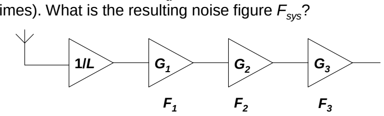
F_{sys}= total noise factor of *N* stages in cascade.
F_1= noise factor stage 1
F_2= noise factor stage 2
F_n= noise factor stage n
G_1 = gain of stage 1
G_2 = gain of stage 2
G_{N-1} = gain of stage *N*

The overall noise factor for cascaded amplifiers can be calculated from **Friis' noise equation**:

$$F_{sys} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + ... + \frac{F_N - 1}{G_1 G_2 ... G_{N-1}}$$

Noise example

A receiver is assumed to consist of 3 amplifiers with power gains G_1, G_2 and G_3 and corresponding noise figures F_1, F_2, F_3. To this we connect an antenna with temperature T_a by means of an antenna cable with attenuation A (times). What is the resulting noise figure F_{sys}?



The resulting spectral density, N_0, at the output can be written as:

$$N_0 = \frac{G_1 G_2 G_3 k T_A}{A} + G_1 G_2 G_3 \left(F_1 - 1\right) k T_0 + G_2 G_3 \left(F_2 - 1\right) k T_0 + G_3 \left(F_3 - 1\right) k T_0$$

Noise example cont.

We would like to determine $T_{sys}=F_{sys}T_0$ of the equivalent noise source at the antenna that causes this spectral density:

$$N_0 = GkT_{sys} = GF_{sys}kT_0$$

Where G is the total gain. We extract this total gain to get:

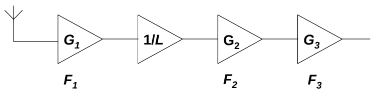
$$N_0 = \frac{G_1 G_2 G_3}{A}\left(\frac{T_A}{T_0} + A\left(F_1 - 1\right) + \frac{A\left(F_2 - 1\right)}{G_1} + \frac{A\left(F_3 - 1\right)}{G_1 G_2}\right) kT_0 = GF_{sys}T_0$$

The system noise figure can now be identified as:

$$F_{sys} = \frac{T_A}{T_0} + A\left(F_1 - 1\right) + \frac{A\left(F_2 - 1\right)}{G_1} + \frac{A\left(F_3 - 1\right)}{G_1 G_2} \approx \frac{T_A}{T_0} + A\left(F_1 - 1\right)$$

Noise example cont.

If we instead had inserted the first amplifier directly at the antenna and let the cable connect amplifiers 1 and 2, what is now the system noise figure.



The resulting spectral density at the output becomes:

$$N_0 = \frac{G_1G_2G_3}{A}kT_A + \frac{G_1G_2G_3(F_1-1)}{A}kT_0 + G_2G_3(F_2-1)kT_0 + G_3(F_3-1)kT_0$$

Noise example cont.

Which can be written as:

$$N_0 = \frac{G_1G_2G_3}{A}\left(\frac{T_A}{T_0} + (F_1-1) + \frac{A(F_2-1)}{G_1} + \frac{A(F_3-1)}{G_1G_2}\right)kT_0 = \frac{G_1G_2G_3}{A}F_{sys}T_0$$

The noise figure of the system will in this case become:

$$F_{sys} = \frac{T_A}{T_0} + (F_1-1) + \frac{A(F_2-1)}{G_1} + \frac{A(F_3-1)}{G_1G_2} \approx \frac{T_A}{T_0} + (F_1-1)$$

Noise example cont.

- As you can see from Friis' equation and the previous example, the noise factor of the entire cascaded chain is dominated by the **noise contribution of the first stage or two**.
- If the antenna noise is small the system noise figure, F_{sys}, can be reduced by a factor A if the first amplifier is placed close to the antenna.
- High gain, low noise RF amplifiers, called low noise amplifiers (LNA) is typically used for the first stage or two in a cascade chain.
- Thus, you will find an LNA at the feed point of a satellite receiver's dish antenna, and possibly one at the input of the receiver unit itself, but other amplifiers in the chain might be more modest.

Performance

Performance measure

- The two levels of performance for a radio receiver are **sensitivity** and **selectivity**.
- The **sensitivity** refers to the level of input signal required to produce a usable output signal.
- The **selectivity** refers to the ability of the receiver to reject adjacent channel signals.

Sensitivity

Signal to noise ratio

- Radio reception is essentially a matter of signal, *S*, to noise, *N*, ratio (SNR).
- A signal, *S*, must be some amplitude above the **noise floor,** *N* ,of the system in order to be detected properly.
- At the moment we assume the signal, *S* ,equal to the received power, P_r.

$$SNR = \frac{S}{N}$$

Signal to noise ratio

- The matter of signal to noise ratio (S/N, SNR) is sometimes treated in different ways, where each way try to crank some reality into the measure.
- The signal plus noise to noise ratio (S+N/N) is found quite often. As the ratio get higher the S/N and S+N/N converge (only about 0.5 dB difference at 10 dB).
- Another variant is signal plus noise plus distortion to noise (SINAD). The SINAD take into account most factors that can deteriorate reception (often used as performance measure in analog mobile phone systems or land radio systems).

Signal to noise ratio

- The sensitivity is a measure of the receiver’s ability to pick up (detect) signals.
- A typical specification might be a 0.5 ❍V sensitivity.
- The sensitivity number in microvolt is meaningless unless the test conditions are specified.
- The usual test condition is to give the sensitivity number required to produce a signal to noise ratio.
- E.g. a sensitivity of 0.5 ❍V produces a SNR of 20 dB.

Example Sensitivity - SNR

Assume that we whish to receive satellite TV channels from a geostationary satellite at 11 GHz. The bandwidth of the signal is 5 MHz and we need an SNR of 20 dB to be satisfied with the picture quality.

What is the necessary sensitivity of the receiver?

The lowest possible received power, P_{min}, is: $(P_{\min})_{dB} = (N)_{dB} + \left(\frac{S}{N}\right)_{dB}$

With given values we get:

$(P_{min})_{dB}$ = -204 + 67 + 20 = -117dBW => $2 * 10^{-12}$ W

By using ohms law (assuming Z =50 ohm) we get the lowest possible input voltage (sensitivity) to the receiver:

$$U_{\min} = \sqrt{P_{\min} Z} = 10\ \mu\text{V}$$

SNR – E_b/N_0

- In digital modulated system, the bit energy E_b, is compared to the noise spectral density, N_0.
- This E_b/N_0 measure is more convenient for determining digital data rates and error rates for digital communication system performance.
- The binary digital data is transmitted at a certain rate, R.
- One watt is 1 J/s, which means that the energy per bit in a signal is given by $E_b=ST_b$, where S is the signal power and T_b is the time required to send one bit.
- The data rate, R, is $R=1/T_b$.
- Thus:

$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{kTR}$$

SNR – E_b/N_0

•The parameter N_0 is the noise power density in watts/Hertz.

•The noise, N, in a signal with a bandwidth B is obviously $N=N_0B$ which gives:

$$\frac{E_b}{N_0} = \frac{S}{N}\frac{B}{R}$$

•E_b/N_0 also relates to the spectral efficiency.

•Shannon's law tells us that the maximum channel capacity (bits/second), C, is according to:

$$C = B\log_2(1 + S/N)$$

Where B is the bandwidth of the channel in Hertz. Shannon's law can be rewritten as:

$$\frac{S}{N} = 2^{C/B} - 1$$

SNR – E_b/N_0

Using the previous result and exchanging the notion used by Shannon with our notion of bandwidth B and rate R we get:

$$\frac{E_b}{N_0} = \frac{B}{C}(2^{C/B} - 1)$$

This formula relates the achievable spectral efficiency C/B to E_b/N_0.

Example (page 117) Suppose that we want to find the minimum E_b/N_0 to achieve a spectral efficiency of 6 bps/Hz.

Then:

$E_b/N_0=(1/6)(2^6-1)$ =10.5 => 10.21 dB

Sensitivity in a digital receiver

- The sensitivity in digital receivers cannot be defined as a voltage at a certain SNR, because a digital system does not process continuous waves.
- The measure is however very similar to the analog methods, in a digital system we consider the bit error rate (BER) as sensitivity.
- As in the analog system we have to specify the condition for the given value, the sensitivity is given as *BER* at a certain E_b/N_0.

Some words about noise floor

- Noise floor is the amount of noise produced by internal circuitry.
- It directly affects the sensitivity of the receiver.
- The noise floor is typically expressed in dBm.
- The more negative value the better.
- A typical good receiver (analog modulation) have a noise floor of -115 dBm to -130 dBm.
- The noise floor is directly dependent on the bandwidth used to make the measurement.
- The radio specification usually specifies the bandwidth, but be careful to note whether or not the bandwidth is true for the transmission mode you will use.

Selectivity