Understanding Noise Figure

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One of the most frequently discussed forms of noise is known as **Thermal Noise**. Thermal noise is a random fluctuation in voltage caused by the random motion of charge carriers in any conducting medium at a temperature above absolute zero (K=273 + °Celsius). This cannot exist at absolute zero because charge carriers cannot move at absolute zero. As the name implies, the amount of the thermal noise is to imagine a simple resistor at a temperature above absolute zero. If we use a very sensitive oscilloscope probe across the resistor, we can see a very small AC noise being generated by the resistor.

- The RMS voltage is proportional to the temperature of the resistor and how resistive it is.

  Larger resistances and higher temperatures generate more noise.

The **thermal noise** phenomenon was discovered (or anticipated) by **Schottky** in 1928 and first measured and evaluated by **Johnson** in the same year.

Shortly after its discovery, **Nyquist** used a thermodynamic argument to show that the open-circuit **rms thermal noise voltage Vn** across a resistor is given by:

$$V_n = \sqrt{4kTRB}$$

where:
 k = Boltzmann constant (1.38 x 10^{-23} Joules/Kelvin)
 T = Temperature in Kelvin (K= 273+°Celsius) (Kelvin is not referred to or typeset as a degree)
 R = Resistance in Ohms
 B = Bandwidth in Hz in which the noise is observed (RMS voltage measured across the resistor is also function of the bandwidth in which the measurement is made).

Example: At 27°C, a 100 kΩ resistor in 1MHz bandwidth will add noise to the circuit as follows:

$$V_n = [4*1.38*10^{-23}*(273+27)*100*10^3*1*10^6]^{\frac{1}{2}} = 40.7 \text{ μV RMS}$$

- Low impedances are desirable in low noise circuits.
- The thermal noise voltage is dependent only on the resistive component and is independent of any reactance in the circuit. Reactances (capacitive or inductive) are due to magnetic and electric fields where electron fluctuations are non-existent.
- In a **series resonant circuit**, the noise source is the **series loss resistance**.
- The noise voltage across a **parallel resonant circuit** is Q times the noise emf (Q is the tuned-circuit quality factor or figure of merit).
- In order to compare the noise of different sources we may convert the measurement bandwidth (1MHz in our case) to 1Hz bandwidth (the lowest bandwidth denominator).
- Thermal noise is present in all circuit elements containing resistance.
- A carbon composition resistor generates the same amount of thermal noise as a metal film resistor of the same value. The noise is independent of the composition of the resistance.

- For a fixed temperature, the thermal noise voltage in a circuit can be reduced by minimizing the resistance and the bandwidth.
  Further reduction can only be obtained by operating the circuit at lower temperatures.

Noise Bandwidth, **B**, is defined as the equivalent rectangular pass-band that passes the same amount of noise power as is passed in the usable receiver bandwidth and that has the same peak in-band gain as the actual device has. It is the same as the integral of the gain of the device over the usable frequency bandwidth.
- Typically, bandwidth **B** is approximately equal to the 3dB bandwidth.
- In a receiver, for best sensitivity, **B** should be no greater than required bandwidth.

In RF applications, we usually deal with circuits having matched input and output impedances, and therefore we are more concerned with the power available from a device than the voltage. In this case, it is common to express the noise of a device in terms of the available noise power.

The maximum power transfer theorem predicts that the maximum noise power is transferred from a thermal noise source when the load impedance presents a conjugate match to the source impedance.

Available noise power P_N which can theoretically be transferred under such conditions is given:

$$P_N = kTB$$

The factor of **4R** has cancelled out so the **available noise power** does not depend upon the value of the **Resistance**. This is significant because it means that the available noise power of any resistor (or any noise source), if measured over the same bandwidth **B**, can be represented by a resistor at temperature **T**.
- Thus, **every noise source has an Equivalent Noise Temperature**.

Thermal noise power (in dBW) is defined as:

$$P_{N(dBW)} = 10 \log(kTB)$$

Where P_N in dBW is the **Noise Power** at the output of the thermal noise source, **k** is Boltzmann's constant 1.38×10^{-23} (J/K), **T** is temperature (Kelvin), and **B** is the bandwidth (Hz). At room temperature (17°C/290K), in a 1 Hz Bandwidth we can calculate the noise power P_N:

$$P_{N(dBW)} = 10 \log(1.38 \times 10^{-23} \times 290 \times 1) = -204 \text{ (dBW)}$$
$$P_{(dBW)} = 10 \log(P_{(W)} / 1W)$$

Power in dBm takes its reference as 1mW, and results the relation:

$$0 \text{ dBW} = 1 \text{ W} = 30 \text{ dBm}$$

Therefore, we can calculate the thermal noise power in dBm at (17°C/290K) in a 1 Hz BW:

$$\text{Thermal Noise Power} = -204 + 30 = -174 \text{ dBm/Hz}$$

- Noise Power of **-174 dBm/Hz** is the reference for any noise power calculation when designing RF systems working at room temperature.

- Relative to the bandwidth, we can use the reference level of -174 dBm/Hz and simply multiply it by the actual bandwidth of the radio channel.

Ex. 1: Let's calculate the thermal noise floor of the 200 kHz channel bandwidth used by GSM. We just calculate the thermal noise in 200 kHz bandwidth:

$$kTB \text{ for GSM (200 kHz)} = -174 \text{ dBm/Hz} + 10 \log (200.000 \text{ Hz}) = -121 \text{dBm}$$

The -121dBm is therefore the absolute lowest noise power we get in a 200 kHz GSM channel.

Ex. 2: An SSB receiver has a bandwidth of 2.4 kHz, which makes the thermal noise floor to be:

$$kTB \text{ for SSB (2.4 kHz)} = -174 + 10 \log (2400) = -140 \text{dBm}$$

- It does not matter if the RF system operates on 100 MHz or at 2450 MHz, the noise power / Hz will be the same, if the radio channel bandwidth is the same.
- With constant bandwidth, the thermal noise power vs temperature has linear characteristic with **Slope = kB**.
  This is an important characteristic that is used for accurate noise measurements.
- Temperatures correspond to power levels.
  When the temperature of a resistor is doubled, the output power from it is doubled (the voltage is proportional to the square root of the temperature).
- Powers from uncorrelated sources are additive, so noise temperatures are additive.
- In addition to thermal noise, amplifiers (or other devices with semiconductors) also contribute to the total system noise.

Noise Figure and Noise Factor

In 1942 Dwight O. North introduced the term **Noise Factor (F)**, which referred to absolute receiver sensitivity, which is a numeric referred to field strength. That field strength, in a plane-polarized wave passing an antenna, necessary to produce a signal power at the detector of a receiver, equal to the total noise power (from all sources) at the same point.

To characterize the receiver alone, Harald T. Friis introduced in 1944 the **Noise Figure (NF)** concept which characterized the degradation in Signal to Noise Ratio (SNR) by the receiver. The concept of Noise Figure allows the sensitivity of any amplifier to be compared to an ideal (lossless and noiseless) amplifier which has the same bandwidth and input termination.

- **Noise Figure (NF)** is a measure of how much a device (such an amplifier) degrades the Signal to Noise ratio (SNR).

$$\text{SNR\_input}_{[linear]} = \text{Input\_Signal}_{[Watt]} / \text{Input\_Noise}_{[Watt]}$$
$$\text{SNR\_input}_{[dB]} = \text{Input\_Signal}_{[dB]} - \text{Input\_Noise}_{[dB]}$$

$$\text{SNR\_output}_{[linear]} = \text{Output\_Signal}_{[Watt]} / \text{Output\_Noise}_{[Watt]}$$
$$\text{SNR\_output}_{[dB]} = \text{Output\_Signal}_{[dB]} - \text{Output\_Noise}_{[dB]}$$

- **Noise Factor (linear not dB)** of a receiver is the ratio of the SNR at its input to the ratio of the SNR at its output.

$$\text{NoiseFactor\_F}_{(linear)} = \text{SNR\_input}_{[linear]} / \text{SNR\_output}_{[linear]}$$
$$\text{NoiseFactor\_F}_{[dB]} = \text{SNR\_input}_{[dB]} - \text{SNR\_output}_{[dB]}$$
$$\text{NoiseFigure\_NF}_{[dB]} = 10 * \text{LOG} (\text{NoiseFactor\_F}_{(linear)})$$

- Note that **SNR at the output will always be smaller than the SNR at the input**, due to the fact that circuits always add to the noise in a system.
- The **Noise Factor**, at a specified input frequency, is defined as the ratio of the total Noise Power per unit bandwidth available at the output port when noise temperature of the input termination is standard (290K) to that portion of engendered at the input frequency by the input termination.

$$NoiseFactor\_F = \left(\frac{Available\_Output\_Noise\_Power}{Available\_Output\_Noise\_due\_to\_Source} \right)$$

- Noise Factor varies with the bias conditions, with frequency, with temperature, and with source resistance. All of these should be defined when specifying Noise Factor.

The concept of Noise Factor has three major limitations:
1. Increasing the source resistance may decrease the Noise Factor while increasing the total noise in the circuit.
2. If purely reactive source is used, Noise Factor is meaningless since the source noise is zero, making the noise factor infinite.
3. When the device noise is only a small percentage of the source thermal noise (as with some very low noise transistors), the Noise Factor requires taking the ratio of two almost equal numbers. This can produce inaccurate results.

- A direct comparison of two Noise Factors is only meaningful if both are measured at the same source resistance.
- Knowing the Noise Factor for one value of source resistance does not allow the calculation of the noise factor at other values of resistance. This is because both the source noise and device noise vary as the source resistance is changed.

The maximum **Noise Figure** of the receiver system, when is given the required **Receiver Sensitivity** and the required **Receiver Bandwidth,** is:

Receiver_Noise_Figure$_{[dB]}$ = 174 + Receiver_Sensitivity$_{[dBm]}$ – 10*LOG(BW$_{[Hz]}$) – SNR$_{[dB]}$

As can be seen from the equation above, **narrow Bandwidth** and **smaller SNR** will relax the required receiver Noise Figure requirements.

- When designing circuits for use with extremely weak signals, noise is an important consideration. The noise contribution of each device in the signal path must be low enough that it will not significantly degrade the Signal to Noise Ratio.
- Noise in an RF system can be generated from external sources, or the system itself.
- The Noise level of a system sets the lower limit on the magnitude of a signal that can be detected in the presence of the noise. So, to achieve the best performance you need to have a minimum residual noise level.
- Noise Figure is used to describe the noise contribution of a device. An ideal amplifier would have no noise of its own, but would simply amplify what went in to it.

- For example, a 10dB amplifier would amplify the Signal (and the Noise) at its input by 10dB. Therefore, although the noise floor at the output of the amplifier would be 10dB higher than at the input.

- An "ideal noiseless" amplifier would not change the Signal to Noise ratio (SNR).
- A "real life" amplifier will amplify not only the noise at its input, but will contribute its own noise to signal. This reduces the Signal to Noise ratio at the output of the amplifier.
- So, the "real life" amplifier has two major internal components: an "ideal noiseless" amplifier and a noise source. The noise source adds noise to any signal what enters to the amplifier and then the ideal amplifier amplifies the whole thing by an amount equal to its gain, with no noise contribution of its own.

- o For example, a 10dB attenuator placed at the input of an amplifier will increase the total Noise Figure of the system with 10dB.
- An attenuator placed at the input of a system will increase the total Noise Figure with the same amount of its attenuation.
- An attenuator placed at the input of a receiver would not affect the SNR if the level at its output is inside of the input dynamic range of the receiver.

- o As an example, let's assume that we have an amplifier at room temperature with 10dB of gain which has only a matched resistor at its input and one matched resistor at its output.
  - The noise at the input of the amplifier must be -174dBm/Hz.
  - If the amplifier is known to have a 3dB NF, the internal noise source adds an equal noise to the input noise before amplification.
  - Then 10dB of gain increases the noise by 10dB.
  - Therefore, the noise at the output of the amplifier is 13dB higher than at the input, or (-174dBm/Hz + 10dB gain +3dB NF) = -161dBm/Hz.
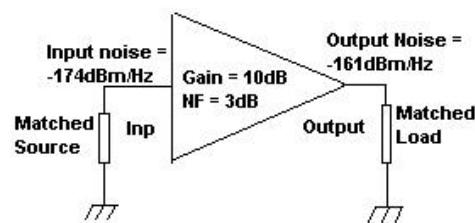
- Another way to visualize the process is to think in terms of kTB instead of dBm.
  - If the amplifier has a matched input resistance and its noise power is -174dBm/Hz, then the input resistor is supplying 1kTB of noise to the amplifier.
  - If the amplifier is known to have a noise figure of 3dB, that tells us that the internal noise source will double the noise before amplification.
  - Therefore, the internal noise source must supply an additional 1kTB of noise, to yield 2kTB, or twice the noise power the noise source is contributing.
- The noise contribution of the amplifier's noise source is fixed and does not change with input signal.
- Therefore, when more noise is present at the amplifier input, the contribution of the internal noise source is less significant in comparison.
- When the noise into an amplifier is higher than kTB (-174dBm/Hz), the amplifier 's Noise Figure plays a smaller role in the amplifier's noise contribution.
- The Noise Figure (NF) of a device is only calculated with the input noise level at kTB.
- The Noise Temperature at the output of an amplifier T_{out} (in Kelvin) is the sum of the Noise Temperature of the source T_{source} and the Noise Temperature of the amplifier itself T_{ampl} multiplied by the Power Gain of the amplifier.

$$T_{out\,(K)} = G_{(linear)} * (T_{ampl\,(K)} + T_{source\,(K)})$$

T_{out} = Noise Temperature at amplifier output in Kelvin.
G = Power Gain in linear scale not in dB.
T_{ampl} = Noise Temperature of amplifier.
T_{source} = Noise Temperature of source.

The same formula is valid for attenuators:

$$T_{out} = G_{att} * (T_{att} + T_{source})$$

- The Noise Figure of an attenuator is the same as the attenuation in dB.
- The Noise Figure of an attenuator preceding an amplifier is the Noise Figure of the amplifier plus the attenuation of the attenuator in dB.

If we use cascaded amplifiers:
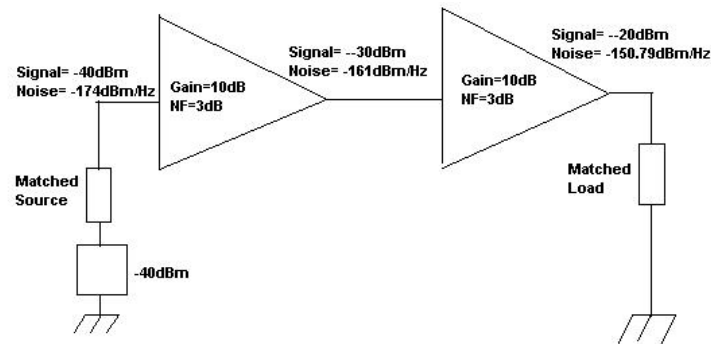
- For above example both amplifiers have 10dB gain and NF=3dB.
- The signal goes in at -40dBm with a noise floor at kTB (-174dBm/Hz).
- We can calculate that the signal at the output of the first amplifier is -30dBm and the noise is: (-174dBm/Hz input noise) + (10dB of gain) + (3dB NF) = -161dBm/Hz.
- Let see how many kTBs are entering in the second amplifier:
(-161dBm/Hz) is 13dB greater than kTB (-174dBm).
- 13dB is a power ratio of 20x. So, the noise floor at the second amplifier is 20 times kTB or 20kTB.
- Next calculate how many kTBs are added by the noise source of the second amplifier (in this case, 1kTB because the NF=3dB).
- Finally calculate increase in noise floor at the 2nd amplifier as a ratio and convert to dB.
- Ratio of (input noise floor) + (added noise) to (input noise floor) is:
(20kTB+1kTB) / (20kTB) = 21/20
- In dB = 10LOG (21/20) = 0.21dB
- Therefore, the 2nd amplifier only increases the noise floor by 0.21dB even though it has a noise figure of 3dB, because the noise floor at its input is significantly higher than kTB.
- The first amplifier degrades the signal to noise ratio by 3dB, while the second amplifier degrades it only by 0.21dB. The total Noise Figure of the two amplifiers is 3.21dB.

- When amplifiers are cascaded together in order to amplify very weak signals, it is generally the first amplifier in the chain which will have the greatest influence upon the signal to noise ratio because the noise floor is lowest at that point in the chain.
- The first amplifier in a chain should have low noise figure (noise factor) and high gain.
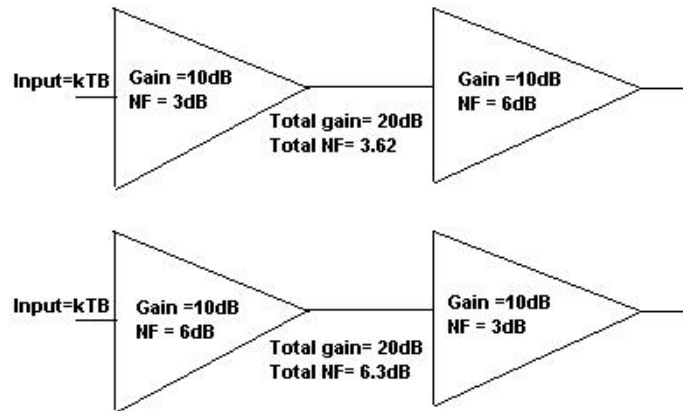
Determining the total Noise Figure of a chain of amplifiers (or other devices):

NFactor_total = NFact1 + (NFact2-1)/G1 + (NFact3-1)/(G1*G2) + (NFact3-1)/(G1*G2*....Gn-1)

where: NFactor = Noise factor of each stage (Linear not in dB).
   Noise Figure[dB] = 10*LOG (NFactor)
          G = Gain of each stage as a ratio, not dB (for example 4x, not 6dB)

- The first amplifier in a chain has the most significant effect on the total noise figure than any other amplifier in the chain.
- The lower noise figure amplifier should go first in a line of amplifiers (assuming all else is equal).
- For example, we have two amplifiers with equal gain, but with different noise figures. Assume 10dB gain in each amplifier. One amp is NF = 3dB and the other 6dB. When the 3dB NF amplifier is first in cascade, the total NF is 3.62dB. When the 6dB amplifier is first, the total NF is 6.3dB.
- This also applies to gain. If two amplifiers have the same Noise Figure but different gains, the higher gain amplifier should precede the lower gain amplifier to achieve the best overall Noise Figure.

- The overall Noise Factor of an infinite number of identical cascaded amplifiers is:
  NFactor_total = 1 + M
  with: M = (F-1) / [1 - (1/G)]
  where: **F** is Noise_Factor(linear) of each stage, and **G** is Gain(linear) of each stage.

  NoiseFigure_total[dB] = 10*LOG (NFactor_total(linear))

- At the input of the amplifier the thermal noise power vs temperature has a Slope = kB.
- At the output of the amplifier the thermal noise power vs temperature has a Slope = kBG.
- The output noise power for absolute temperature of zero is the **added noise power, Na,** generated within the amplifier.
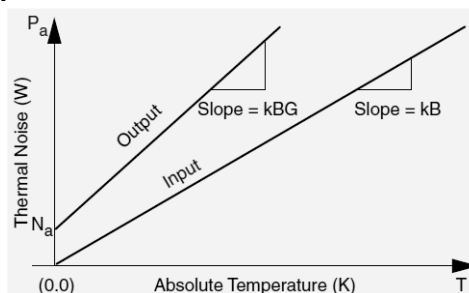
Thermal Noise Power [Watt] vs Temperature [Kelvin]

Noise Figure of a Device

- The Noise Figure of a device is the degradation in the Signal to Noise Ratio (SNR) as a signal pass through the device.

The equation of the Noise Figure of a device adopted by the IEEE (Institute of Electrical and Electronics Engineers) is:

$$\text{Device } NF_{[dB]} = 10*LOG\ [(N_a + k*T_o*B*G)\ /\ (k*T_o*B*G)]$$

N_a=Added Noise Power $_{[W]}$, T_o =290K, B=Bandwidth$_{[Hz]}$, G=Gain$_{[Linear\ not\ dB]}$, k=Boltzmann ct.

Therefore, the Noise Figure of a device is the ratio of the total Noise Power at the output, to that portion of the Noise Power at the output due to noise at the input when the input source temperature is 290 Kelvin.

- The Noise Figure of a device is independent of the signal level as long as the device is linear (output power vs. input power).

Equivalent Input Noise Temperature

- Every noise source has an **equivalent noise temperature**.

Initially used in Satellite Receivers, the **Equivalent Input Noise Temperature (T_e)**, is used to describe the noise performance of a device rather than the Noise Figure.

- T_e is the **Equivalent Input Noise Temperature** of source impedance into a perfect (noiseless) device that would produce the same **Added Noise Power (N_a).**
- T_e is mostly used as a system parameter, and is defined as:

$$T_{e(K)} = N_{a(dBW)}\ /\ (k*G_{(linear)}*B_{(Hz)})$$

the relation of T_e with the **Noise Factor (F)** is:

$$T_{e(K)} = T_{o(K)} * (F-1)$$
$$F = 1 + (T_{e(K)}\ /\ T_{o(K)})$$

For example, a device with Noise Figure NF=0.5dB (Noise Factor, F=1.122), at T_o = 290K, would have an Equivalent Input Noise Temperature, T_e = 35.4K

- The use of **Equivalent Input Noise Temperature** concept is more meaningful and convenient, even **Noise Figure** and **Noise Temperature** are related, since them both measure the same thing.
- The concept is based to the fact that the Noise Power is directly proportional to temperature, and at 0K (absolute zero) there is no noise.

For example, if heating the resistor to 400K and this produce the same noise as that generated by the receiver; we could say that the receiver Equivalent Input Noise Temperature is 400K.

- This number is independent of the receiver bandwidth, and we can use it to compare receivers of different bandwidths.
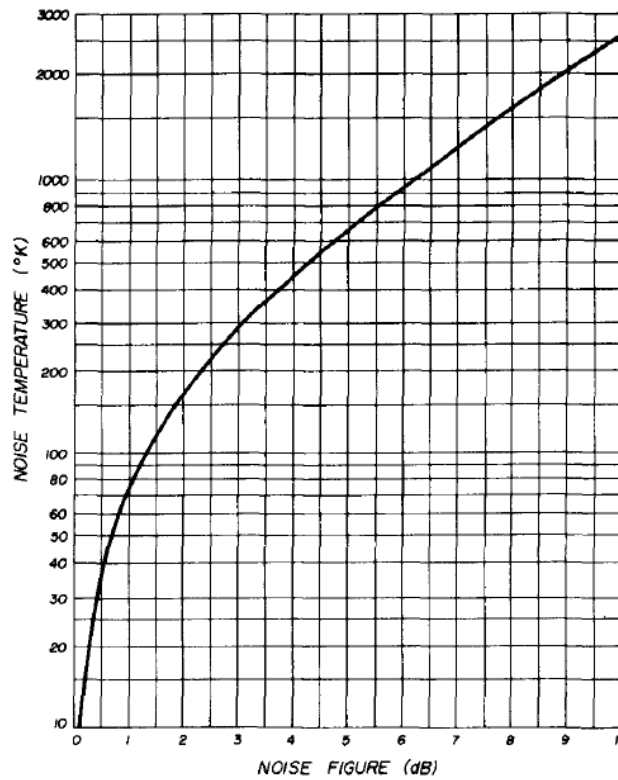
Noise Temperature [Kelvin] vs Noise Figure [dB]

Resulting **Noise Temperature referred to the input (T_{eq})** of cascaded stages is given by:

$$T_{eq} = T_1 + (T_2/G_1) + [T_3/ (G_1*G_2)] + \ldots..$$

Noise Temperature (in Kelvin) of each component in the cascade is: $T_{(1,2,3\ldots)} = T_o (F_{(1,2,3\ldots)} - 1)$
Power gain (Linear not dB) of each component in the cascade is: $G_{1,2,3\ldots}$
The Noise Figure of the cascade is: $NF_{[dB]} = 10*LOG [1+ (T_{eq} / T_o)]$

Example: Consider the case of a three-stage amplifier, each stage with 13dB gain and 60K noise temperature.
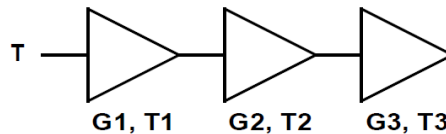
The numerical gain (linear not dB) of each stage is $G = 10^{(13/10)} = 20$
The noise temperature of the combined stages is:
$$T_{eq} = 60 + (60/20) + 60/(20*20) = 60 + 3 + 0.15 = 63.15K$$
The Noise Figure of the three-stage cascade amplifier at room temperature is:
$$NF_{[dB]} = 10*LOG [1+(63.15 / 290)] = 0.85 \text{ dB}$$

Antenna Noise Temperature

The performance of a telecommunication system depends on the Signal to Noise ratio (SNR) at the receiver's input. The electronic circuitry of the RF front-end (transmission lines, amplifiers, mixers, etc.) has a significant contribution to the system noise. However, the antenna itself is sometimes a significant source of noise, too.

- In Satellite and Space Receiving Systems, the noise level coming from the antenna can be very low, limited by the ground noise (due to the side-lobe radiation of the antenna), and by the background sky temperature (with values often below 100K).
  In these situations, small changes in the Noise Figure of the receiving system may result in much more change of the Signal to Noise Ratio (SNR).

A **receiving antenna** exhibits noise at its terminals from two sources:
1. The thermal noise generated in its ohmic resistance (usually negligible).
2. The noise received from external sources.
   Any object with temperature greater than 0K (-273°C) radiates noise energy.
   The received noise is represented as though it were thermal noise generated in a **fictitious resistance equal to the radiation resistance of the antenna**, at a temperature T_a that would account for the noise actually measured.
   Antenna temperature T_a is a parameter that describes how much noise an antenna produces in a given environment. Antenna noise temperature is not the physical temperature of the antenna but rather an expression of the available noise power at the antenna terminals. However, an antenna does not have an intrinsic "antenna temperature" associated with it; rather the antenna temperature depends on its gain pattern and the thermal environment that it is placed in.
   Antenna temperature is sometimes referred to as **noise temperature of the antenna**.

   Example: Suppose that an antenna with 200-ohm impedance exhibits an **rms** noise voltage $V_n = 0.1uV$ at its terminals, when measured in a bandwidth $B = 10^4 Hz$.
   $$V_n^2 = 4kT_aRB$$
   $$T_a = V_n^2 / 4kRB = (10^{-14}) / (4*1.38*10^{-23}*200*10^4) = 90.6K$$
   Thus, the noise at the antenna terminals is equivalent to that of a 200-ohm resistor at temperature of 90.6K.

In a satellite receive system the **noise temperature of the antenna T_a** referred to the receiver input may be defined by the **antenna feedline loss L** and the **sky temperature T_{sky}**:

$$T_a = [290*(L-1)+T_{sky}] / L$$

where T_a and T_{sky} are in Kelvin and the **feedline loss L** is linear, as a power ratio (not dB).

   Example:
   In a satellite communication system, if the feedline of the receive antenna has a loss **L** of 0.4dB (1.10 linear) and the sky (in the direction where the antenna is pointed) have a noise of 15K, then the noise temperature of the antenna T_a referred to the receiver input is 39K.

- Antenna noise temperature vs antenna pointed direction:
  - When an antenna is pointed to the night-sky, its noise temperature is very low, with temperatures between 3K to 5K at frequencies 1GHz to 10GHz.
  - The higher the elevation angle, the lower the night-sky temperature because of the lower physical temperature of the atmosphere toward zenith.
  - The sky noise depends on the frequency and also depends by the time of the day.

- Noise when antenna is pointed closer to the horizon, it is mostly due to the thermal radiation from the Earth's surface and the atmosphere.
- An antenna may also be pointed toward the ground, e.g., when it is mounted on an airplane or a satellite. The noise temperature of the ground is much higher than that of the night sky because of its much higher physical temperature.

The ground noise temperature is about 300K and it varies during the day.

The noise temperature at approximately zero elevation angle (horizon) is about 100K to 150K.

The Radiation Resistance of an antenna does not convert power to heat, and so is not a source of thermal noise.

- A **receiving antenna** is the source of thermal noise associated with its **Loss Resistance**, added to the noise arising from the reception of radiation from outer space (galactic noise or sky-noise), noise from the atmosphere, and noise from the Earth.
- The load impedance of the input of the receiver does not contribute directly to receive noise.

Noise Figure of Other Devices

- All the devices which process a signal contribute noise and thus have noise figure.
- Amplifiers, Mixers, transistors, diodes, etc., all have noise figures.
- For example, RF attenuators have a Noise Figure floor equal to their attenuation value.

A 10dB pad has a 10dB NF. If a signal enters in a pad and the noise floor is at -174 dBm/Hz the signal is attenuated by 10dB while the noise floor remains constantly (it cannot get any lower than -174 dBm/Hz at room temperature). Therefore, the signal to noise ratio through the pad is degraded by 10dB. Like amplifiers, if the noise floor is above kTB, the signal to noise ratio degradation of the pad will be less than its noise figure.

- The sources of internal noise in **Bipolar Transistors (BJT)** are the thermal agitation of charge carriers in the base, emitter and collector, fluctuations of emitter and collector current (**shot noise**), and random fluctuations as the emitter current divides between the electrodes (**partition noise**).

  The noise properties of a BJT depend on DC bias conditions, temperature and frequency. Thermal resistance is tens of ohms, and the relative noise temperature of the input conductance is seldom greater than unity.

- The forms of noise associated with **Field Effect Transistors (FET)** are the **thermal noise** in the channel, **shot noise** in the gate, and thermal noise of the output conductance.

  Thermal noise in the channel can be described in terms of **noise resistance**, **Rn**:

  $$Rn = (0.6 \text{ to } 0.75) / S$$

  where **S** is the slope of the characteristic curve of the FET, called **transconductance**.

  Shot noise in the gate is markedly smaller than the **thermal noise** of the input conductance, and is usually ignored.

- The noise behavior of **Complementary Metal Oxide Semiconductor (CMOS)** devices is dominated primarily by two noise sources: **thermal noise** and **flicker noise (1/f).**
  Other sources that are sometimes present in the noise spectrum are: the **shot noise**, the **generation-recombination noise** (G-R noise), and the "popcorn" noise (**burst noise**).
  Of these sources, **thermal noise** and **shot noise** are physically fundamental to the operation of the CMOS device and are always present.
  The quality of the manufactured CMOS device (the number of defects in the bulk silicon, in the gate oxide, and in the various interfaces) determines the level of **generation-recombination noise** (G-R) and **popcorn noise**.
  It is probable that **flicker noise** (1/f noise) appears through both quality-dependent and fundamental noise processes.

- The principal noise sources in a bipolar transistor (BJT) are thermal noise in the base spreading resistance, shot noise and flicker noise in the base bias current, and shot noise in the collector bias current.
- The principal noise sources in the FET are thermal noise and flicker noise generated in the channel. For the **Junction-Field Effect Transistor (JFET),** this assumes that the gate current is zero. Otherwise, shot noise in the gate current must be included.
- Flicker noise in a MOSFET is usually larger than in a JFET because the MOSFET is a surface device in which the fluctuating occupancy of traps in the oxide modulates the conducting surface channel all along the channel.
- The relations between the flicker noise in a MOSFET and its geometry and bias conditions depend on the fabrication process. In most cases, the flicker noise, when referred to the input, is independent of the bias voltage and current and is inversely proportional to the product of the active gate area and the gate oxide capacitance per unit area.
- For the **NMOS** devices, the flicker noise was found to be dominant below 10 kHz.
  For the **PMOS** devices, it was found to be dominant below 1 kHz.
  The PMOS device noise is approximately 5 times less than the NMOS device noise.
- Because the JFET has less flicker noise, it is usually preferred over the MOSFET in low-noise applications at low frequencies.
- Compared to the silicon JFET, the **Gallium-Arsenide (GaAs) JFET** is potentially lower in noise. However, the GaAs JFET can exhibit very high flicker noise, making this device useful only for high frequencies.
- The JFET gate current is commonly assumed to be zero when the gate-to-channel junction is reverse-biased. For a high source impedance, the effect of the gate current on the noise might not be negligible. In the design of low noise JFET circuits, particular attention must be paid to the variation of the gate current with drain-to gate voltage.
  In general, the gate current increases with drain-to-gate voltage.
  For low-noise applications, the FET should have a high transconductance parameter.
  For the JFET, this requires a large drain-to-source saturation current and a small threshold or pinch-off voltage.
 The channel thermal noise decreases as the drain bias current increases.

Noise Figure of Radio Receivers

- As far as noise is concerned, the part of a super-heterodyne receiver between the antenna and the output of the last IF stage can be regarded as an amplifier and all the cascaded stage amplifiers noise analysis mentioned above can be applied.
- The fact that a receiver mixer stage shifts the frequency of the noise, this does not change the situation and the above statement. It merely causes the noise to lie in a different place in the spectrum from the input noise.
- The receiver Noise Figure is always defined at the input of the final detector (last IF stage output) because the noise output of a detector (but not of a mixer) is affected by the presence of a signal. For example, an FM signal will suppress weak noise, but will be suppressed itself by strong noise.
- The only exception is when the receiver has no (or poor) RF image rejection.
  In this case the Noise Figure of the receiver is 3dB worse than it would be if the same receiver has good RF image rejection, because the image noise appears at the output along with noise associated with the desired received signal.
  This effectively doubles (by 3dB) the noise power at the output of the IF amplifier.
- The output of the noisy receiver will be determined by the noise available from the source, the gain of the receiver, and the addition of noise generated by circuits within the receiver.
- In a receiver, for the signal to be detected, it must be higher than the Noise Floor.
  For this reason, the term minimum discernable signal (MDS) is often used together with noise floor definition.
  Usually MDS should be 3dB higher (or more) than the receiver noise floor.
- The sensitivity of a receiver is determined by its gain, by its internal noise level referred to the antenna input, and by the required Signal to Noise Ratio (SNR).

Types of Noise sources

There are several types of noise sources in electrical circuits. However, here we discuss only about the important noise sources.

1. Thermal or Johnson - Nyquist Noise
2. Shot Noise
3. 1/f Noise (also called Flicker or Pink noise)
4. White Noise
5. Burst Noise (Popcorn noise)
6. Generation-Recombination Noise (G-R noise)
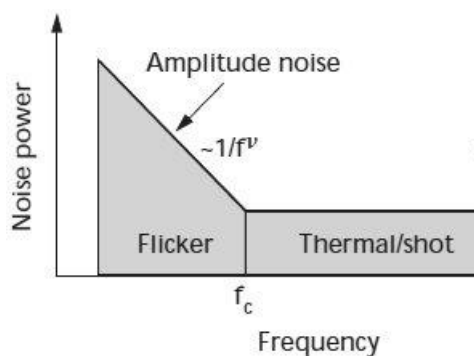
Power spectrum of various noise types

1. Thermal Noise (Johnson-Nyquist Noise)

- This is the noise generated by thermal agitation of electrons in a conductor.
- Also called Johnson-Nyquist Noise, is the random white noise (flat with frequency) generated by thermal agitation of electrons in a conductor or electronic device.
  It is produced by the thermal agitation of the charges in an electric conductor and is proportional to the absolute temperature of the conductor.
- Any substance with temperature above zero Kelvin (absolute zero) contains some electrons that are free to move about in that substance. The amount of energy contained by these electrons increases as the temperature increases, and an increase in energy means an increase in the average speeds of the free electrons.
  However, moving electrons constitute an electric current. Since the currents increase with temperature, the noise power likewise increases with temperature. Further, as the pulses are random, they are spread out over a very broad range of frequencies.
  It develops that, if we look at the power contained in a given passband, the value of that power is independent of the actual center frequency of the passband.
- Thermal Noise it manifests itself in the input circuits of audio equipment such as microphone pre amps, or antenna input of a receiver, where the signal levels are low.
- The Thermal Noise level is the limiting minimum noise any circuit can attain at a given temperature.
  Note that thermal Noise Power, per Hertz, is equal throughout the frequency spectrum, depends only on **k** and **T**.
- Thermal noise in the resistance of the signal source is the fundamental limit on achievable signal sensitivity.
- Thermal Noise has a Gaussian amplitude distribution in the time domain and is evenly distributed across the spectrum.
- Thermal noise spectral breadth and its sources' ubiquity lead it to dominate other noise types in many applications.
- The instantaneous amplitude of thermal noise has a Gaussian, or normal, distribution.

- The average value is zero and the **rms** value is given by $V_n = \sqrt{4kTRB}$
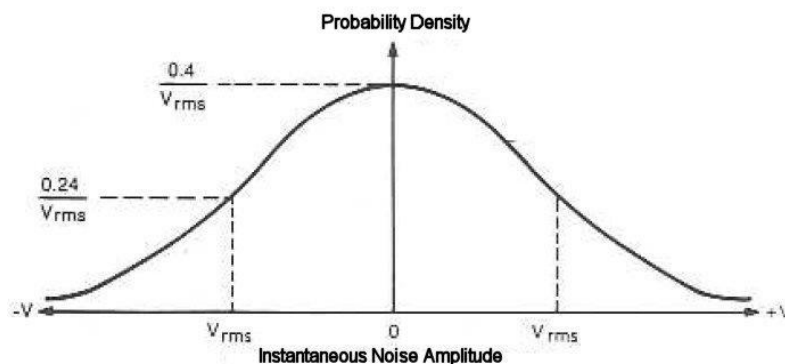
Probability density function for thermal noise (Gaussian distribution)

- The probability of obtaining an instantaneous voltage between any two values is equal to the integral of the probability density function between the two values.
  The probability density function is greatest at zero magnitude, indicating that values near zero are most common.
- The **crest factor of thermal noise** is normally assumed to be 4.

2. Shot Noise

- Shot Noise normally occurs when there is a potential barrier (voltage differential).
- PN junction diode is an example that has potential barrier. When the electrons and holes cross the barrier, Shot Noise is produced.
- For example, a diode, a transistor, and vacuum tube, all will produce Shot noise.
- Shot noise is caused by the fact that current flowing across a junction isn't smooth, but is comprised of individual electrons arriving at random times. This non-uniform flow gives rise to broadband white noise that gets worse with increasing average current.
- A junction diode will typically have two components of noise. One is Thermal Noise, and the other is Shot Noise.
- Note that if the active device provides amplification, the noise also gets amplified along with the signal.
- On the other hand, a resistor normally does not produce Shot Noise since there is no potential barrier built within a resistor. Current flowing through a resistor will not exhibit any fluctuations. However, current flowing through a diode produces small fluctuations. This is due to electrons (in turn, the charge) arriving in quanta, one electron at a time. The current flow is not continuous, but limited by the quantum of the electron charges.
- Shot Noise is proportional to the current passing through the device.
- For a fixed bandwidth, the noise current is independent of frequency so that shot noise has a flat power distribution, i.e., it is **white noise**.
- It is commonly assumed that the amplitude distribution of shot noise can be modeled by a Gaussian or normal distribution. Therefore, the relation between the crest factor and rms value for shot noise is the same as it is for thermal noise.

3. Flicker Noise - 1/f (one-over-f) Noise

- The imperfect contact between two conducting materials causes the conductivity to fluctuate in the presence of a DC current.
  This phenomenon generates what is called **Flicker Noise** or **Contact Noise**.
- Flicker Noise it occurs in any device where two conductors are joined together, e.g., the contacts of switches, potentiometers, relays, etc. In resistors, it is caused by the variable contact between particles of the resistive material and is called **Excess Noise**.
- The power in Flicker Noise is proportional to the square of the current I_f which is inversely proportional to the frequency. Because of this, in electrical engineering flicker noise is commonly referred to as **1/f noise**, read "**one-over-f noise**."
  Because it increases at low frequencies, it is also referred to as **Low Frequency Noise**.
- Another name that is sometimes used is **Pink Noise**. This name comes from the optical analog of pink light which has a power density that increases at the longer wavelengths, i.e., at the lower frequencies.
- Flicker Noise may be present in the carbon composition resistor. It results from the variable contact between the carbon particles of the resistive material.
  This noise is present only when a DC current flows in the resistor.
- Metal film resistors generate the least excess noise, carbon composition resistors generate the most, with carbon film resistors lying between the two.
- Flicker noise in BJT's occurs in the base bias current. In FET's, it occurs in the drain bias current. In BJT's, flicker noise can increase significantly if the base-to-emitter junction is

subjected to reverse breakdown. This can be caused during power supply turn-on or by the application of too large an input voltage. A diode in parallel with the base-to-emitter junction is often used to prevent it.

- Flicker Noise is found in many natural phenomena such as nuclear radiation, electron flow through a conductor, or even in the environment.
- Flicker Noise is associated with crystal surface defects in semiconductors and is also found in vacuum tubes due to the oxide coating on the cathode.
- The noise power is proportional to the bias current, and, unlike Thermal and Shot Noise, Flicker Noise decreases with frequency. An exact mathematical model does not exist for flicker noise because it is so device-specific. However, the inverse proportionality with frequency is almost exactly 1/f for low frequencies, whereas for frequencies above a few kilohertz, the noise power is weak but essentially flat.
- Flicker Noise is essentially random, but because its frequency spectrum is not flat, it is not a white noise. It is often referred to as pink noise because most of the power is concentrated at the lower end of the frequency spectrum.
- Flicker Noise is more prominent in MOSFETs (smaller the channel length, greater the Flicker Noise), and in bulky carbon resistors. The objection to carbon resistors mentioned earlier for critical low noise applications is due to their tendency to produce flicker noise when carrying a direct current. In this connection, metal film resistors are a better choice for low frequency, low noise applications.
- 1/f Flicker Noise is usually defined by the corner frequency f_c, point where Flicker Noise is equal with White Noise.
- Under "typical" operating conditions, precision bipolar processes (BJT) offer the lowest 1/f corners: around 1Hz to 10Hz.
- The corner for devices fabricated in high-frequency bipolar processes is often 1Hz to 10kHz.
- The 1/f corner frequency in MOSFETs goes as the reciprocal of the channel length, with typical values of 100kHz to 1MHz, and even up to 1GHz for latest nano-meter channel length processes.
- Devices built on III-V processes, such as GaAs FET's and Indium-Gallium-Phosphorous HBT, offer extremely wide bandwidths but yield higher frequency 1/f corners in the region of 100MHz.

The 1/f fluctuation phenomena in physical systems generally can be characterized by their Gaussian amplitude distribution density and by a power spectral density **Sx(f)** which follows a f^{-a} law in a wide range of frequencies **f** with an exponent **a** close to unity. Where **x** denotes the fluctuating quantity. The "constant" **a** frequently is not a constant in the whole range of frequencies **f**, with found values between 0.8 and 1.4.

- Thus 1/f-noise may be considered to be a stationary Gaussian random process.
- Another characteristic feature attributed to 1/f-noise is the typical dependence of the power spectral density **Sx(f)** of the current fluctuation on the DC current.
- 1/f-noise depends on temperature, as the current depends on temperature.
  Besides this indirect temperature influence, earlier studies concluded that no other direct temperature dependence exists.
  At last, 1/f noise is commonly regarded as to be independent on temperature.

4. White Noise

- White Noise is the noise that has constant magnitude of power over frequency.
- Examples of White Noise are Thermal Noise, and Shot Noise.

5. Burst Noise

- **Burst Noise** or **Popcorn Noise** is another low frequency noise that seems to be associated with heavy metal ion contamination. Measurements show a sudden shift in the bias current level that lasts for a short duration before suddenly returning to the initial state. Such a randomly occurring discrete level burst would have a popping sound if amplified in an audio system.
- When viewed on an oscilloscope, Burst Noise appears as fixed-amplitude pulses of randomly varying width and repetition rate. The rate can vary from less than one pulse per minute to several hundred pulses per second. Typically, the amplitude of burst noise is 2 to 100 times that of the background thermal noise.
- Like 1/f Flicker Noise, Burst (Popcorn) Noise is very device specific, so a mathematical model is not very useful.
- However, this noise increases with bias current level and is inversely proportional to the square of the frequency $1/f^2$.
- Burst Noise is often observed in P-N junctions devices operating under forward conditions. In the simplest of cases, it looks like a random telegraph wave.
- Its magnitude is generally greater than either 1/f-noise, Shot Noise or Thermal Noise. Burst noise is described as a function of biasing conditions and temperature.
  In BJTs, the phenomena are attributed on to defects located in the neighborhood of the emitter-base junction.
  Because it is caused by a manufacturing defect, it is minimized by improved fabrication processes.

6. Generation-Recombination Noise (G-R noise)

- In semiconductors, the charge carrier, electron or hole, contributes to the conductivity, when the electrons and holes localized in impurities or defects do not participate in the conduction.
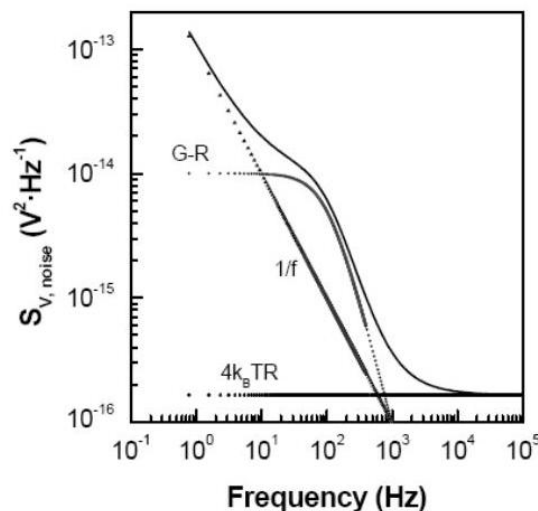
Generation-Recombination (G-R) noise spectrum compared with 1/f-noise and thermal noise

- The transition of an electron or a hole from a localized state to a delocalized one or the creation of an electron-hole pair is called generation, and the inverse process is called recombination.
- Since the elementary generation and recombination processes are random, the number of charge carriers, i.e., electrons or holes in delocalized states, fluctuates around some mean value which determines the mean conductance of the specimen.
  The fluctuations of the charge carriers' number produce fluctuations of the resistance and, consequently, of current and/or voltage if a nonzero mean current is passing through the specimen. This noise is called **generation-recombination noise (G-R noise).**
  It is, perhaps, the most important mechanism of modulation noise, i.e., noise produced by random modulation of the resistance.

Noise Reduction Strategies

Noise is a serious problem, especially where low signal levels are experienced, and there are a number of common-sense approaches to minimize the effects of noise on a system.
In this section we will examine several of these methods.

- Keep the source resistance and the amplifier input resistance as low as possible. Using high value resistances will increase thermal noise voltage.
- Total thermal noise is a function of the bandwidth of the circuit. Therefore, reducing the bandwidth of the circuit to a minimum will also minimize noise. There is also a requirement to match the bandwidth to the frequency response required for the input signal.
- Prevent external noise from affecting the performance of the system by appropriate use of grounding, shielding and filtering.
- Use a Low Noise Amplifier (LNA) as the input stage of the system.
- For some semiconductor circuits, use the lowest DC power supply potentials that will do the job.
- At the transistor level, device noise can be sensed and reduced with negative feedback. Current fluctuations in the transistor contribute to phase and amplitude noise.
  An un-bypassed emitter resistor (RE ~10..30 ohms) reduces noise, but further noise improvement is achieved by sensing the emitter current and feeding back a signal to the base terminal. Successful PM and AM noise reduction of 20 dB has been demonstrated.
- At higher frequencies, the feedback capacitance of the device couples the shot noise of the base/collector junction (BJT) or thermal noise of the channel resistance (MOSFET) to the input and contributes to frequency-dependent noise.
  Optimum noise matching is achieved with BJTs in applications requiring low source resistance, whereas MOSFETs become viable for high source resistance applications.
- In a balanced system both resistive and reactive balance must be maintained.
  The greater the degree of balance, the less noise that will couple into the system.
  Balancing can be used with shielding to provide additional noise reduction.
- The lower the characteristic impedance of a DC power distribution circuit, the less the noise coupling over it.
  Since most DC power buses do not provide a low impedance, a decoupling capacitor should be used at each load.
- From noise point of view, a dissipative filter is preferred to a reactive filter.

- The bandwidth of a system should be limited to that required to receive or transmit a signal in order to minimize the noise.
- A low-frequency system should have a minimum of three separate ground returns. These should be:
  - Signal ground
  - Noisy ground
  - Hardware ground
- The basic objectives of a good ground system are to minimize the noise voltage from two ground currents flowing through a common impedance.
- Suppressing noise at Source:
  - Enclose noise sources in a shielded enclosure
  - Filter all leads leaving a noisy environment
  - Limit pulse rise time
  - Shield and twist noisy leads together
  - Ground both ends of shields used to suppress radiated interference

Noise Figure Measurements – Y-Factor Method

The Noise Figure and Gain measurements could be made using an ON/OFF **noise source** and simple power-ratio measurements.
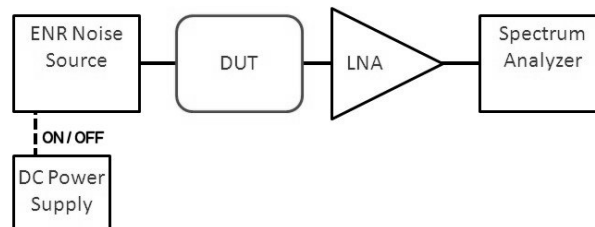
- Every noise source has an associated parameter termed **Excess Noise Ratio**, or **ENR**.
- ENR is the power level difference between hot and cold states, compared to the thermal equilibrium noise power at the standard reference temperature, T_o (290K).
- The noise source is powered ON and provides "hot" noise related to its ENR.
- The noise source is powered OFF, providing a 50-ohm "cold" termination to the input of the DUT.

At room temperature Noise Figure (NF) is defined (in dB) as:

$$NF_{(dB)} = 10log[(T_e + 290)/290]$$

where T_e is the noise temperature of the DUT.

Using the **Y-factor** method, Noise Figure (in dB) is then equal to:

$$NF_{(dB)} = ENR_{(dB)} - 10*LOG(Y-1)$$

where **Y** is the ratio of the output power of the DUT with the noise source in an ON state, to the output power of the DUT with the noise source in an OFF state:

$$Y = P_{ON}1 / P_{OFF}1 = [k*(T_h+T_e*B*G_m*G_a)] / [k(T_o + T_e*B*G_m*G_a)]$$

where:
     k = Boltzmann constant $(1.38*10^{-23})$ (J/K)
     T_h = the output power of the noise source when is turned ON = $\{290[1+10(ENR/10)]\}$ (K)
     T_o = the ambient room temperature when the noise source is turned OFF (K)
     B = the noise bandwidth of the measurement system (Hz)
     G_m = the available gain of the test setup (linear, not in dB)
     G_a = the available gain of the DUT (linear, not in dB)

$$ENR = (T_h - T_o)/T_o$$

where **ENR** in (dB) = $10*\log[(T_h-T_o)/T_o]$

Two additional measurements are performed in order to calculate the gain.

The noise source is connected directly to the test setup, while the power levels P_{ON2} and P_{OFF2}, respectively, are measured with the noise source turned ON and then OFF.

These measurements, which are performed as part of the test-setup calibration, eliminate the bandwidth, gain, and noise figure of the test-setup from the gain equation:

$$G_a = (P_{ON}1-P_{OFF}1) / (P_{ON}2-P_{OFF}2)$$

where:

$$P_{ON}2 = k*(T_h + T_m)*B*G$$
$$P_{OFF}2 = k*(T_o + T_m)*B*G$$

T_m = the noise temperature of the test setup

The condition for the elimination of the bandwidth from the gain equation is that the bandwidth of the test-setup is smaller than the bandwidth of the DUT.

     For ambient temperatures much different than 290K(17°C), a correction factor $(10*\log A)$ should be added to the right side of the Y-factor noise-figure equation, with **A** defined as:

$$A = 1 - [(T_o / 290) - 1]*[Y/10(ENR/10)]$$

The correction is more significant when measuring low noise figures and can, in most cases, be disregarded in order to simplify the measurement.

Corrections for second-stage effects (the test-setup noise figure) are made by use of the following equation:

$$F_{actual} = F_{measured} - [(F - 1)/G_a]$$

where:
 F_{actual} = the actual Noise Factor of the DUT (linear, not in dB),
     $F_{measured}$ = the measured Noise Factor (linear, not in dB),
     F = the Noise Factor of the test-setup (linear, not in dB).

- Impedance mismatch between the DUT, the noise source, and the test-setup may lead to measurement uncertainty. Thus, the impedances should be kept close to 50 ohms as possible by using a well-matched noise source with minimum variation of the output impedance as it is turned from ON to OFF.
- Noise sources with built-in isolators are ideal for less-than-octave frequency ranges, while noise sources with built-in-attenuators are best for wider-than-octave band applications.

- It is common to use a filter (band-pass or low-pass) in making noise measurements. The **noise bandwidth** of a filter is defined as the bandwidth of an ideal filter which passes the same **rms noise** voltage as the filter, where the input signal is **white noise**.
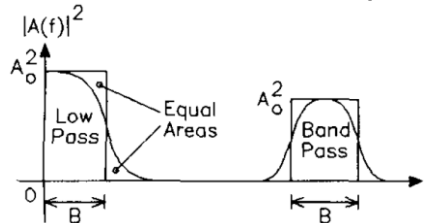
Graphical interpretation of the noise bandwidth using LPF and BPF

- When a noise voltage is measured, the observed value is dependent on the bandwidth of the measuring voltmeter unless a filter is used to limit the bandwidth to a value that is less than that of the voltmeter. It is common to use such a filter in making noise measurements.
- Band-pass filters are used in making spot noise measurements. The filter bandwidth must be small enough so that the input noise voltage as a function of frequency is approximately constant over the filter bandwidth. The spot noise voltage is obtained by dividing the filter noise output voltage by the square root of its noise bandwidth. A filter that is often used for these measurements is a second-order band-pass filter. Such a filter has a 3dB bandwidth of f_c/Q, where f_c is the center frequency and **Q** is the quality factor.
- The noise bandwidth is given by $B = \Pi f_c / 2Q$. This is greater than the 3-dB bandwidth by the factor $\Pi / 2$

Avoidable Noise Measurement Errors:

- Use a 15dB ENR noise source to measure Noise Figures of up to 30dB.
- Use a 6dB ENR noise source for very low noise figure devices to keep the noise detector linearity issues to a minimum.
- Use a noise source with greater internal attenuation if the DUT is match sensitive.
- Do accurate loss compensation of cables connected to the DUT, and calibrate the test setup including the ENR noise source values.
- Report ambient temperature to the Analyzer for accurate ENR interpretations.
- Account for frequency conversion during DSB and SSB measurements.
- When measure low gain, DUT's use a pre-amplifier in front of the Analyzer to improve accuracy, but be careful to not overload the system.
- Reduce the magnitude of all mismatches by using isolators or pad attenuators.
- Minimize the number of adapters, and take care of them.
- Use averaging to avoid display jitter.
- Choose the appropriate bandwidth.
- Avoid DUT non-linearities.

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