Bruit et Systèmes Stochastiques

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Cette année, je vous propose de faire du bruit ;-)

Systèmes stochastiques

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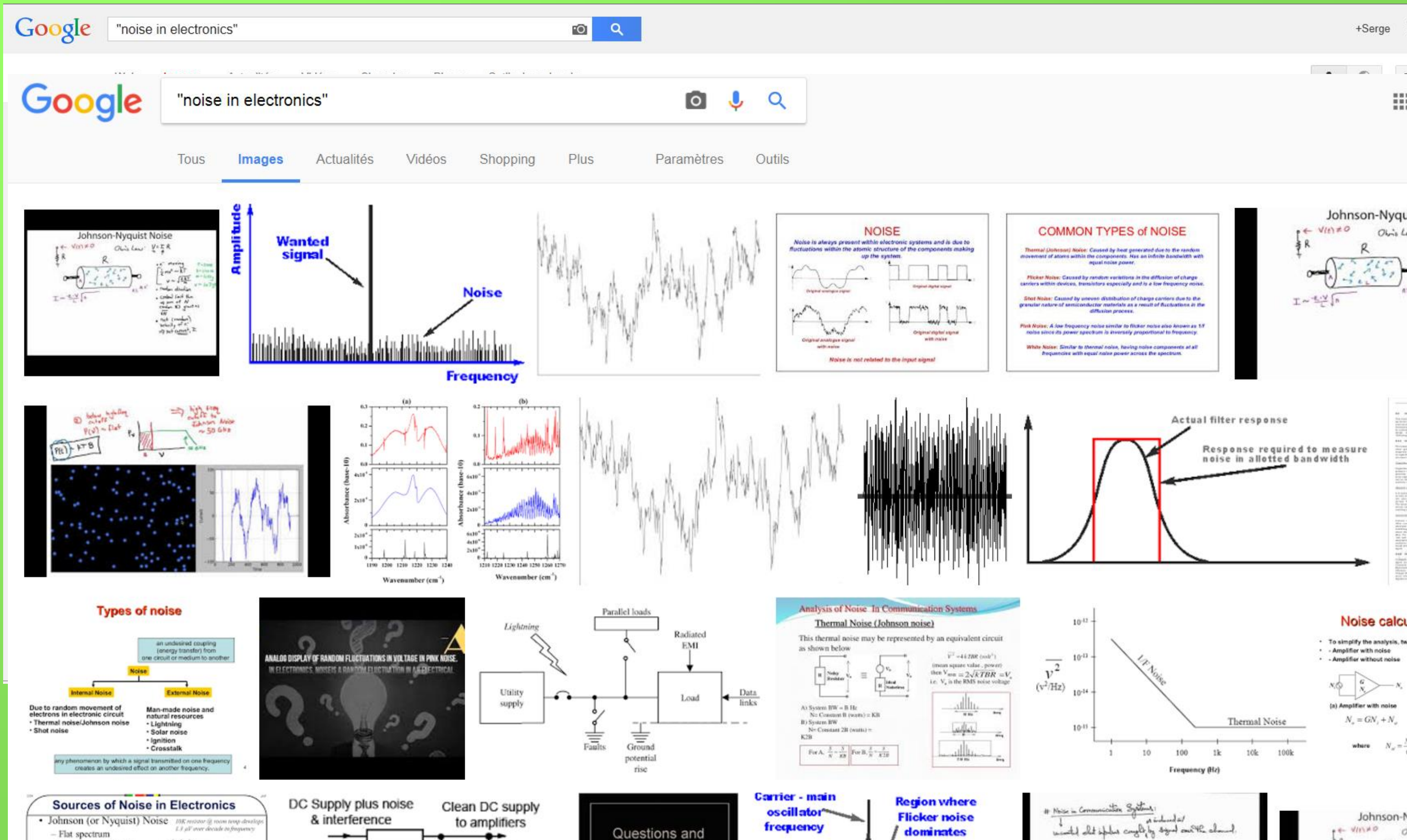
Noise in electronics



Programme de l'enseignement "bruit"

- Introduction et présentation générale
- Théorie du bruit blanc
- Autres bruits : bruit en 1/f , bruit de quantification
- Propriétés statistiques et spectrales du bruit
- SNR - Facteur de bruit - Figure de bruit
- Bruit dans un transistor
- Bruit dans un amplificateur opérationnel

Introduction et présentation générale

Sommaire

- généralités sur le bruit - problématique
- bruit dans les systèmes de communications
- analyse du bruit dans une modulation d'amplitude
- le bruit de quantification
- les analyseurs de spectres
- analyse du bruit dans les circuits: amplificateurs opérationnels et transistors

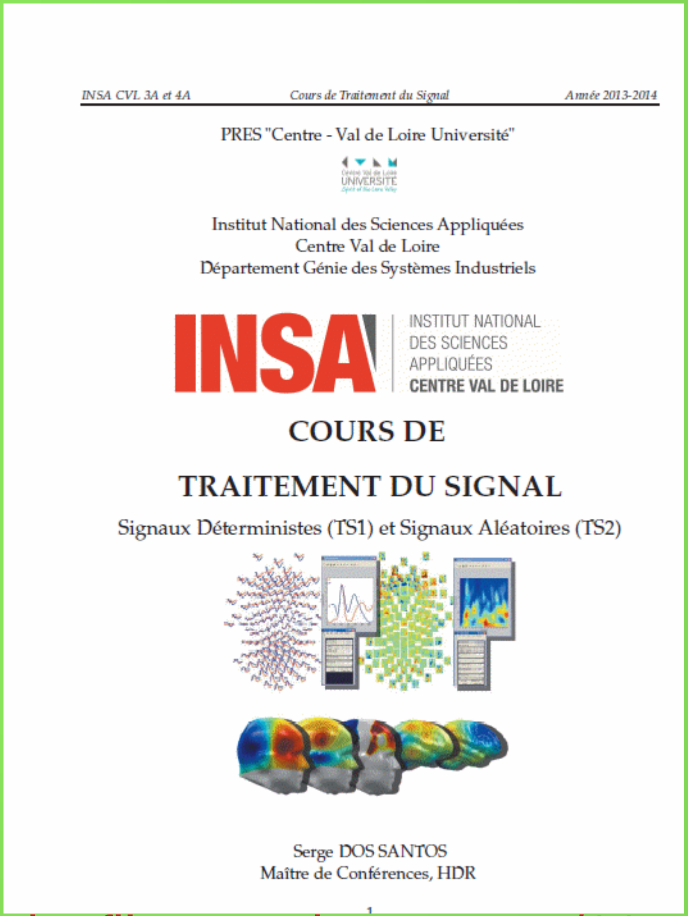
La Physique du bruit

Quelques généralités

Problématique

Les acquis de l’année dernière … on espère ;-)

- Nécessité de décrire les signaux…
  - déterministes **et aléatoires**
- … avec le même formalisme :
  - la représentation temporelle
  - la représentation spectrale


INSA CVL 3A et 4A — Cours de Traitement du Signal — Année 2013-2014

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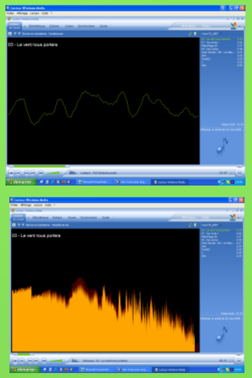
COURS DE

TRAITEMENT DU SIGNAL

Signaux Déterministes (TS1) et Signaux Aléatoires (TS2)

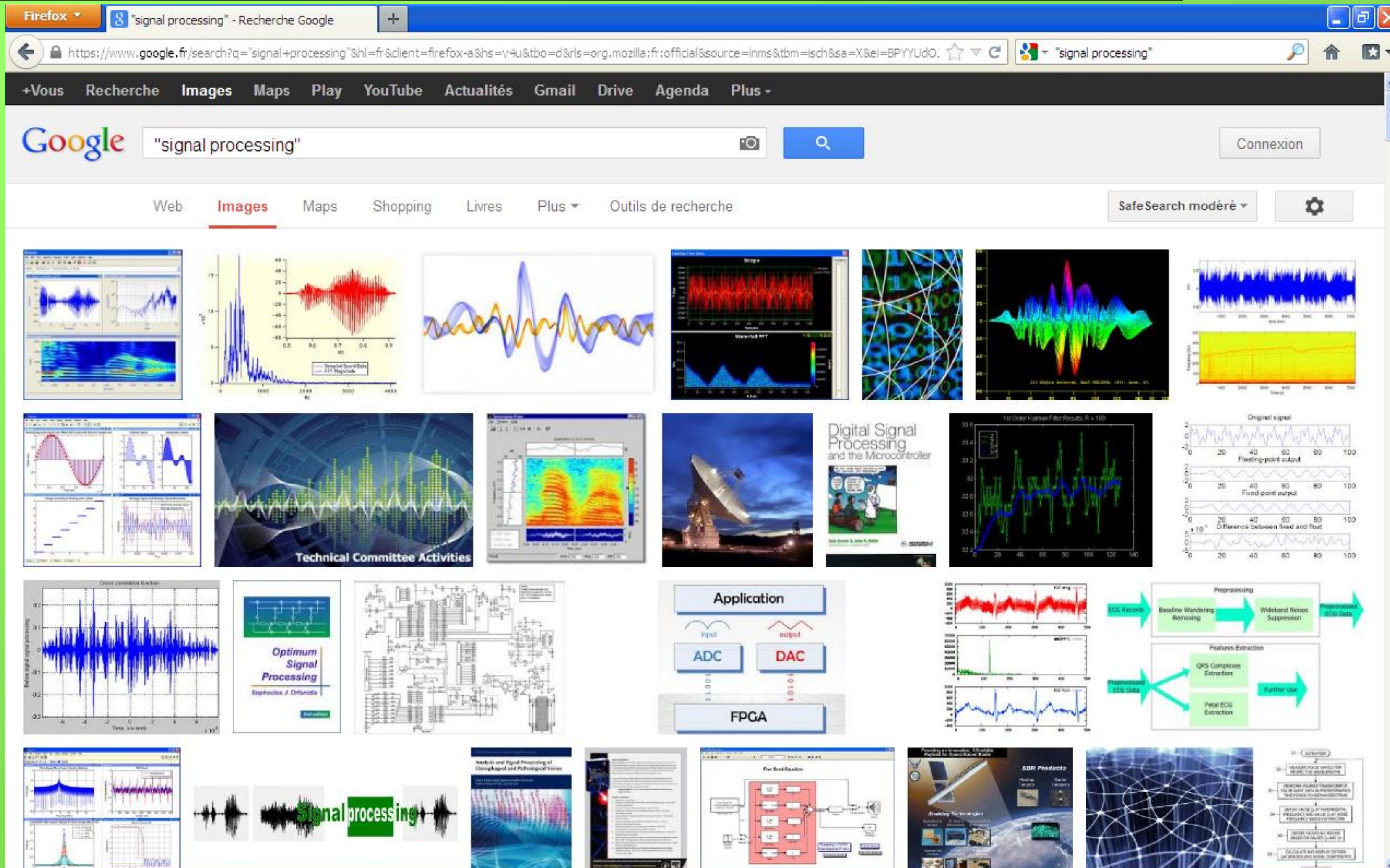
Serge DOS SANTOS
Maître de Conférences, HDR



https://camillecharbonnier.files.wordpress.com/2013/02/slides.pdf

https://celene.insa-cvl.fr/pluginfile.php/7565/mod_resource/content/1/cours_TS_2017_GSI_INSACVL.pdf

Les acquis de l'année dernière … on espère ;-)



https://www.google.fr/search?q=%22signal+processing%22

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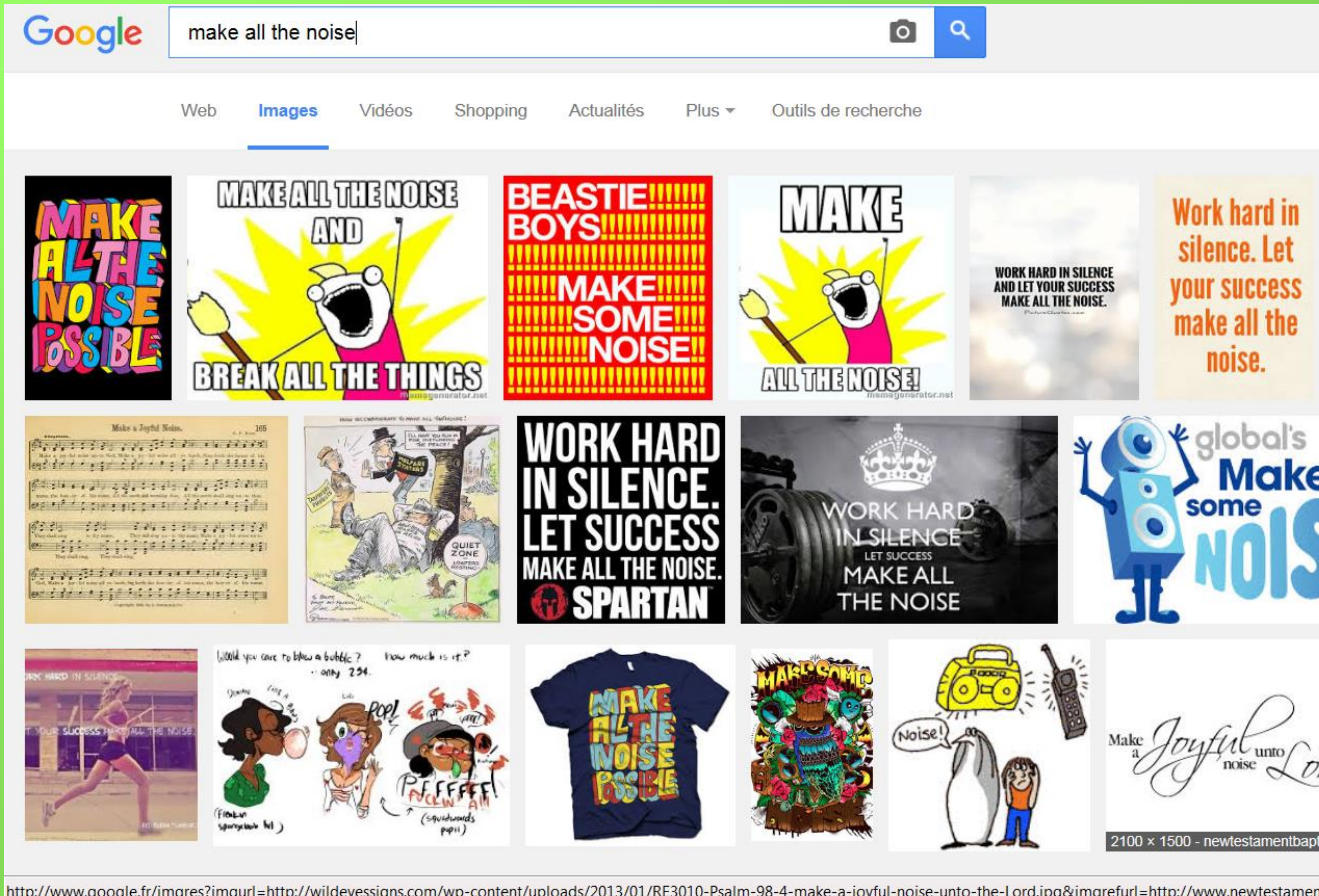

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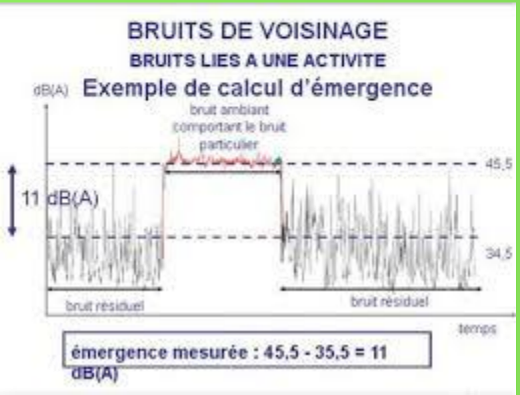

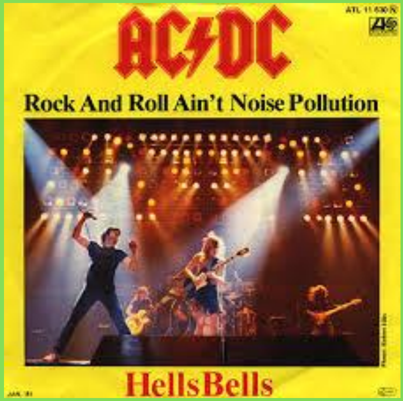

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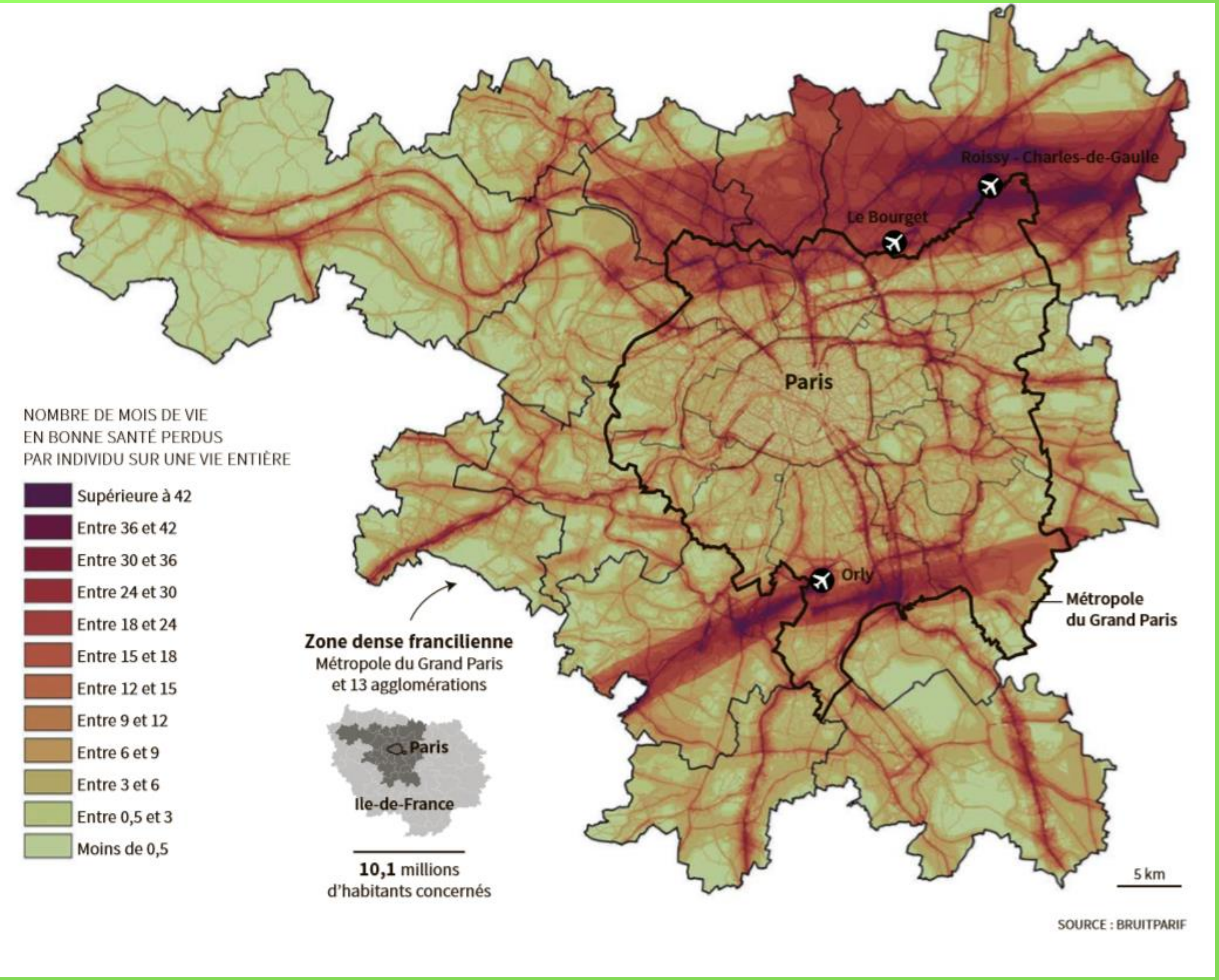
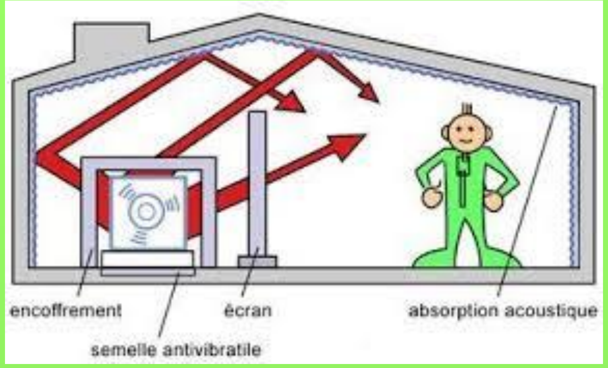
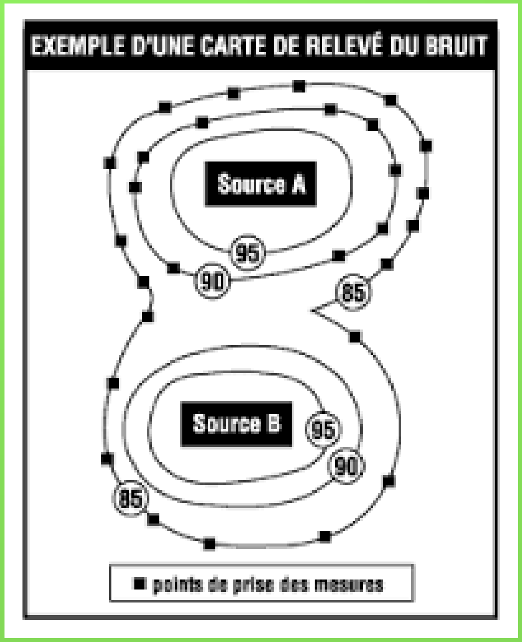
Ou pas !



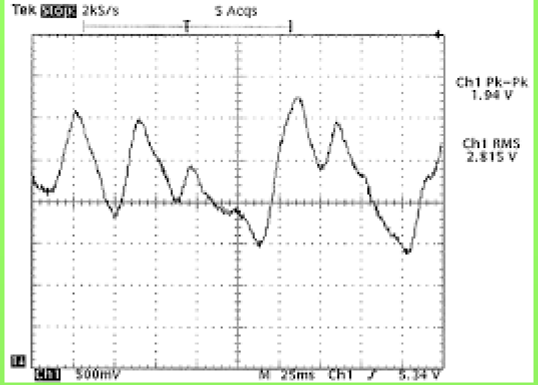
Le Monde,
9 février 2019

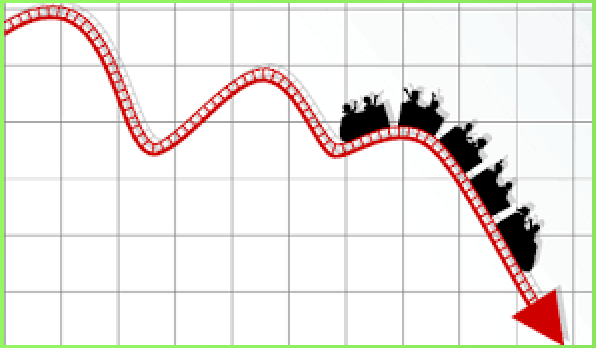
Cartographie de bruit industriel

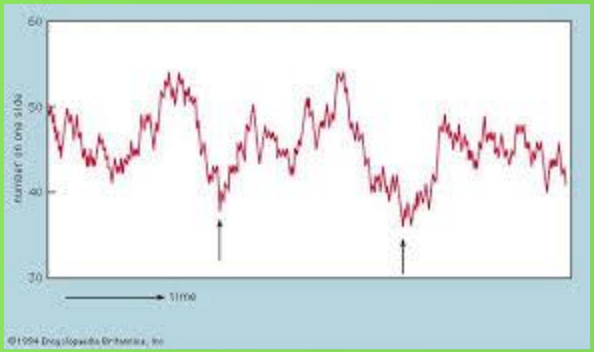


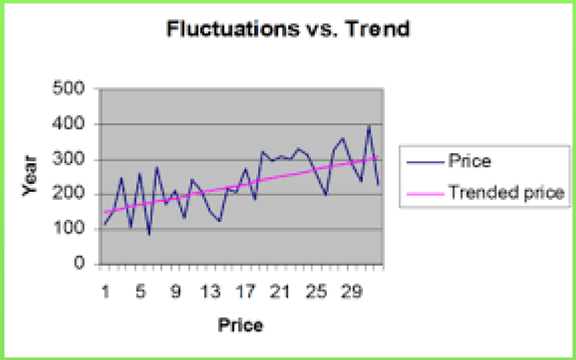


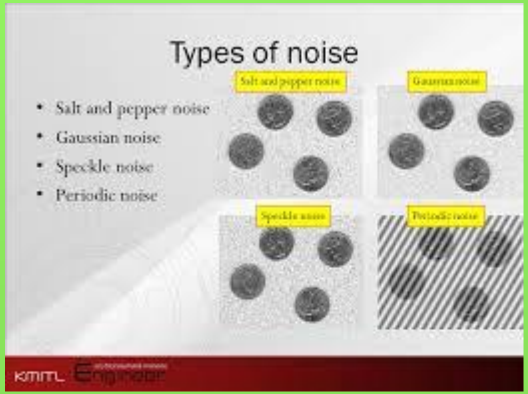
Bruit et fluctuations

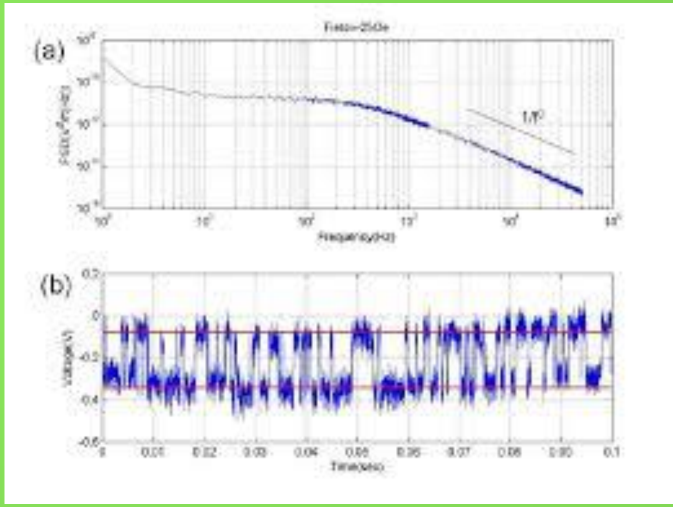


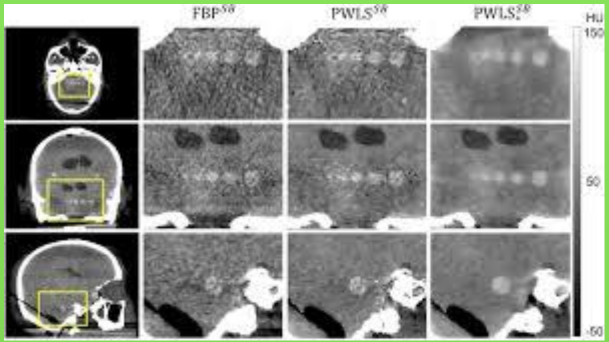










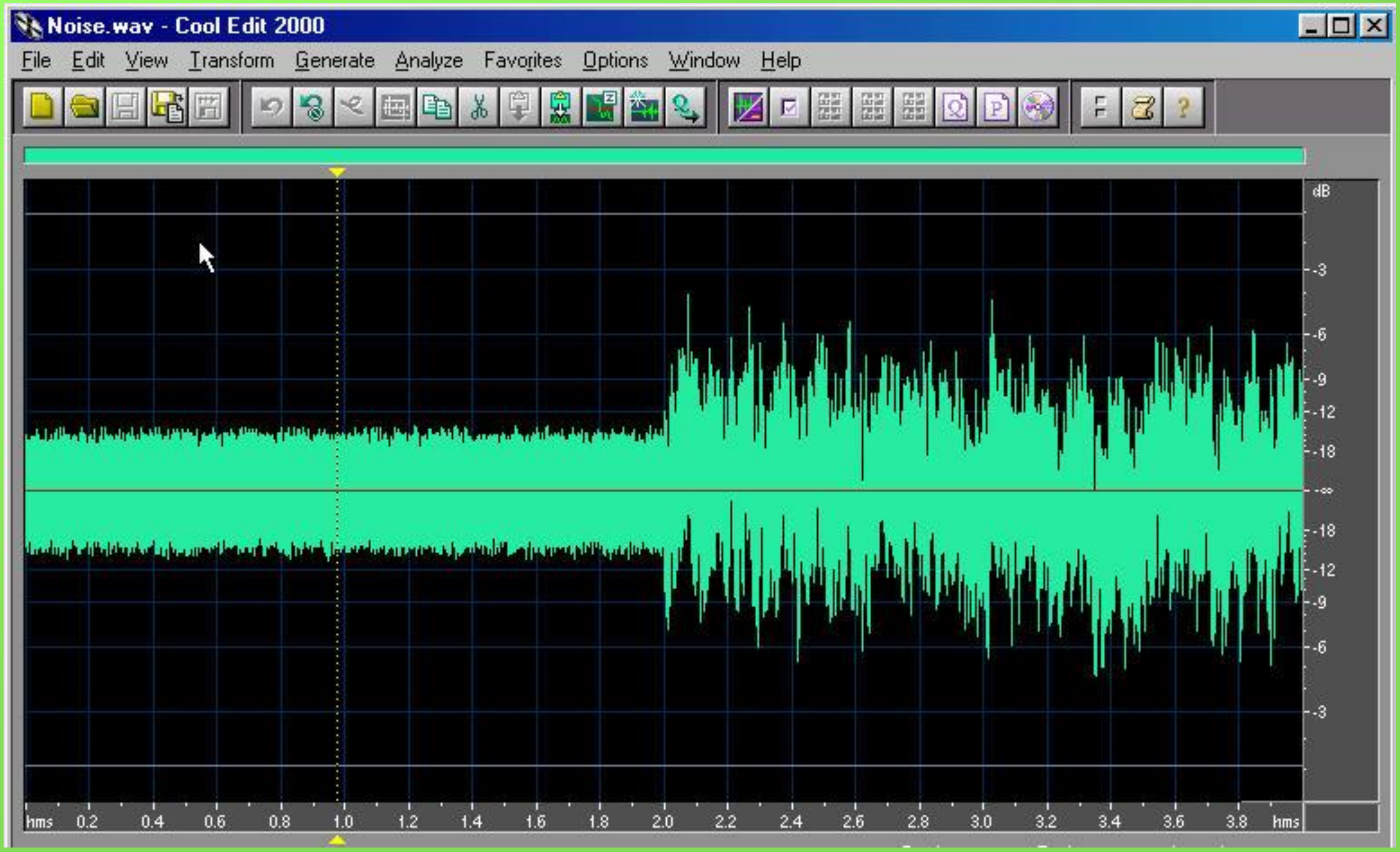


Bruit blanc & bruit en 1/f

- Bruit blanc : intensité (aléatoire) identique à toutes les fréquences

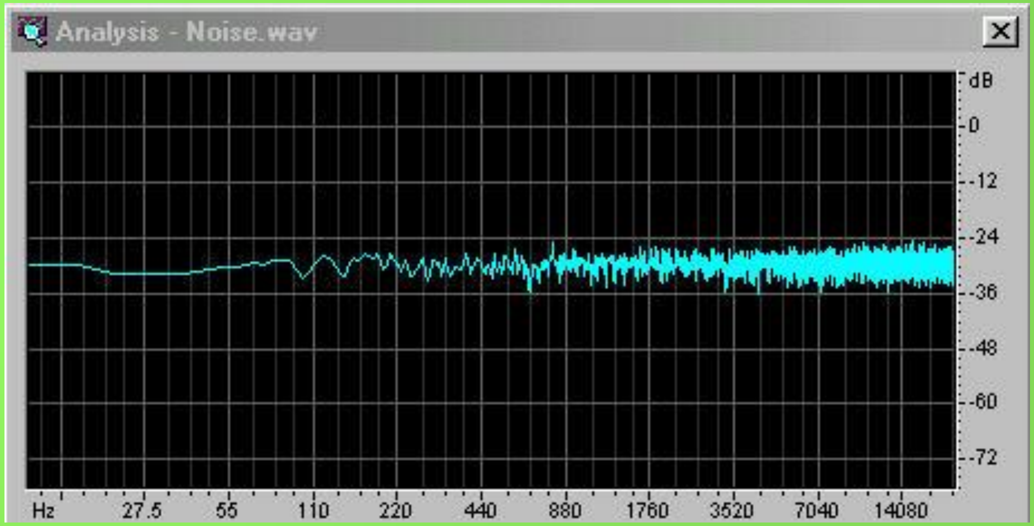
- Bruit en 1/f : puissance acoustique égale dans chaque octave. Décroissance de -3dB par octave
  - Energie acoustique intégrée = intensité*bande
  - Chaque octave est deux fois plus puissante que l'octave précédente

Exemple de bruit blanc et bruit en 1/f

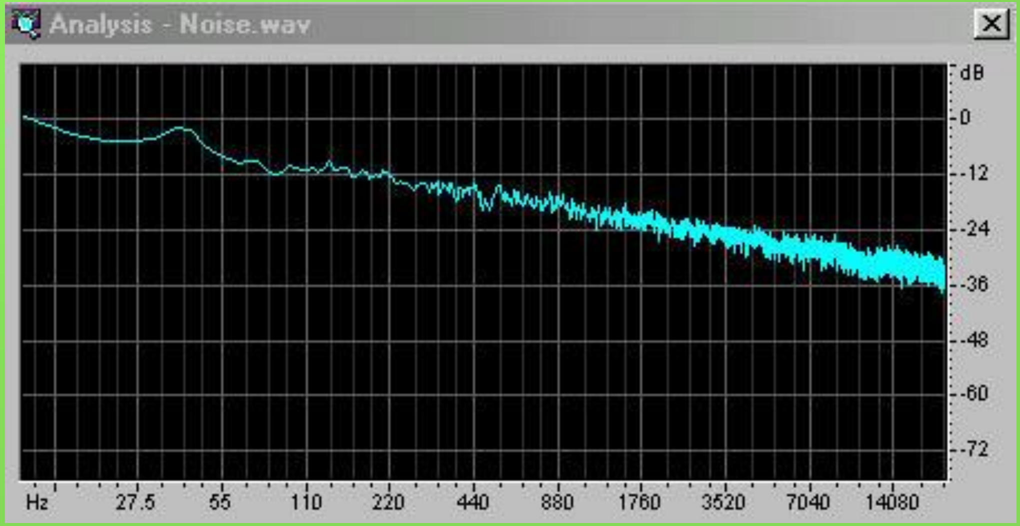


Spectre de puissance: Bruit blanc et “rose” (1/f)

Bruit blanc



Bruit en 1/f



Bruit blanc : distribution normale

- Moyenne et variance du bruit blanc bien définies
  - Déviation standard = racine carré de la variance
- La précision de la moyenne augmente comme l'inverse de la racine carré du nombre de points
- Un sondage d'opinion est précis à 3% si 1000 personnes sont interrogées
  - $0.03 = 1/\sqrt{(1000)}$

Bruit en 1/f- (Bruit Rose)

- On ne peut pas définir la moyenne et la variance d'un bruit en 1/f
- Si la météorologie suit une distribution en 1/f, la notion de climat n'a pas de sens
- La crue du siècle est une crue qui n'arrive qu'une fois sur 100 ans. Elle est 10 fois plus importante qu'une crue décennale
- etc...
- http://www.nslij-genetics.org/wli/1fnoise/index.html

Bruit dans les systèmes électroniques (SEI)

Sources de bruit dans un amplificateur

- Les principales sources de bruit dans un ampli sont :
  - bruit thermique
  - bruit de grenaille
  - bruit flicker (bruit en 1/f)
- Les bruits thermique et de grenaille sont blancs et irréductibles
- Le bruit flicker est “rose” et peut être contrôlé
- Les performances de bruit d’un amplificateur peuvent être quantifiées par
  - sa “Figure de Bruit” (Noise Figure)
  - sa Température de bruit (Noise Temperature)

Sources de bruit

- Bruit ambiant
  - bruit de fond dans un enregistrement
- Interférences Electriques
  - Téléphones cellulaires
- Bruit des amplificateurs
  - Bruit additif de l'amplificateur

Sources de bruit de l'amplificateur opérationnel

- Bruit thermique
  - Composants résistifs
- Bruit de grenaille (Shot noise)
  - Jonctions semi-conductrices
- Bruit flicker ou bruit en 1/f (Flicker Noise)
  - Tous les composants

Thermal Noise

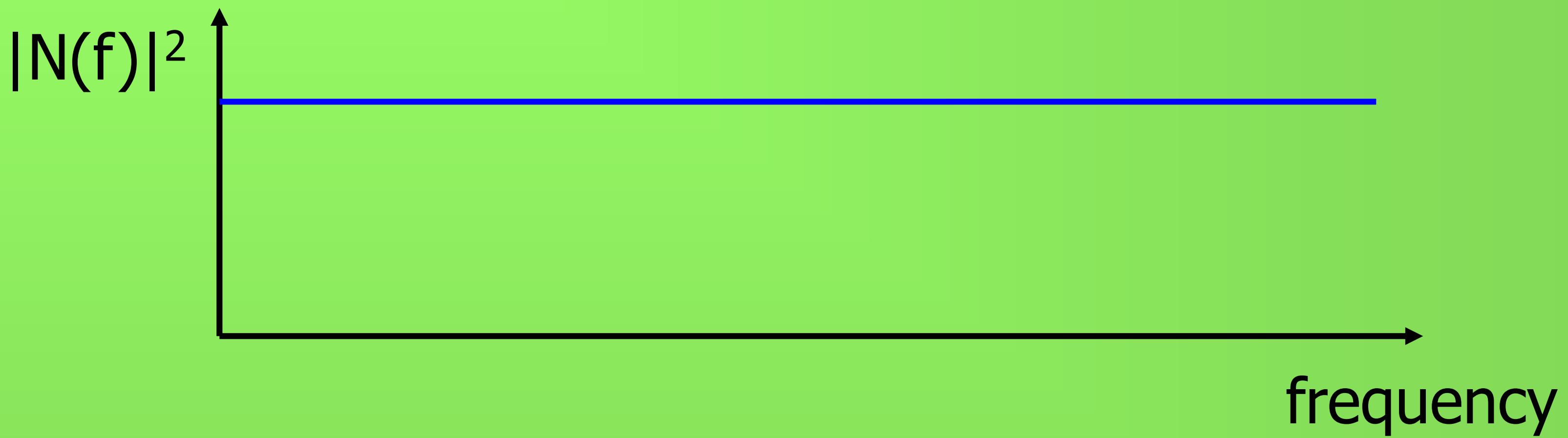
Random motion of electrons in a conductor (Brownian motion) causes thermal noise.

It is a white Gaussian noise voltage of magnitude:

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

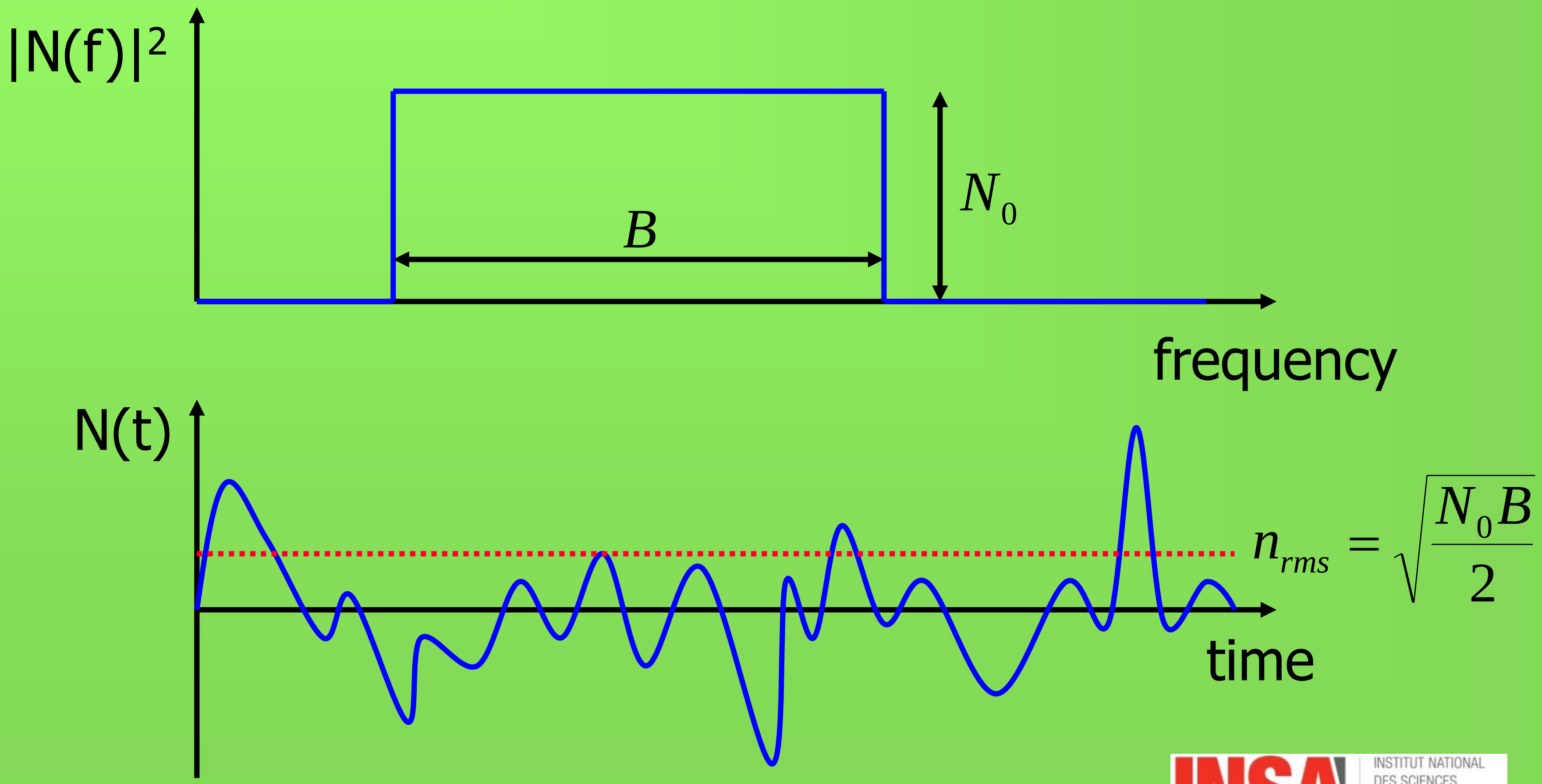
k = Boltzmann's constant
T = Temperature [Kelvin]
R = Resistance
B = Bandwidth

White Noise



- Flat spectrum extending to infinity implies a signal with infinite r.m.s. voltage – obviously impossible.
- In practice, interest is restricted to a finite band of frequencies.

Band-Limited White Noise



Band-Limited Thermal Noise

- The r.m.s. voltage level of a band-limited white noise signal is proportional to the square root of the bandwidth.
- For thermal noise:

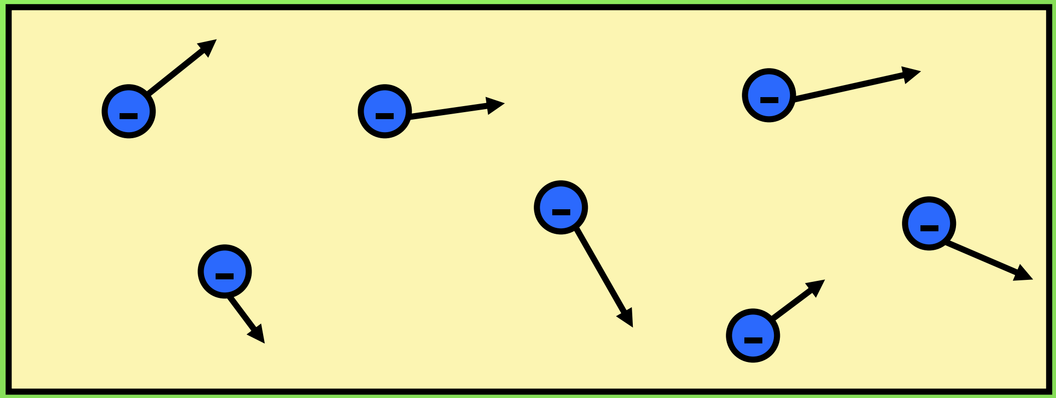
$$v_n = \sqrt{4kTRB} \quad [\mathrm{V}]$$

or,

$$v_n = \sqrt{4kTR} \quad [\mathrm{V}/\sqrt{\mathrm{Hz}}]$$

Shot Noise

Dominates in semiconductor devices when carriers are diffusing. (In conductors, thermal noise is usually much bigger)



Current α number of carriers per second

$$\text{Eg. } 1\,\mu\text{A} \equiv 6 \text{ million carriers per } \mu\text{s}$$

Shot Noise Current

- The average number of carriers flowing past a point per second is proportional to the current.
- In any observation interval, the actual number of carriers will vary around this average – this variation is shot noise.

$$i_n = \sqrt{2qIB} \quad [\mathrm{A_{rms}}] \quad \text{or} \quad i_n = \sqrt{2qI} \quad [\mathrm{A_{rms}}/\sqrt{\mathrm{Hz}}]$$

Flicker Noise

- Imperfections in the fabrication of a component cause flicker noise.
- Unlike thermal noise and shot noise, flicker noise is not white; it is pink.
- Also, it can be reduced depending on the quality of the component.

Flicker Noise Current

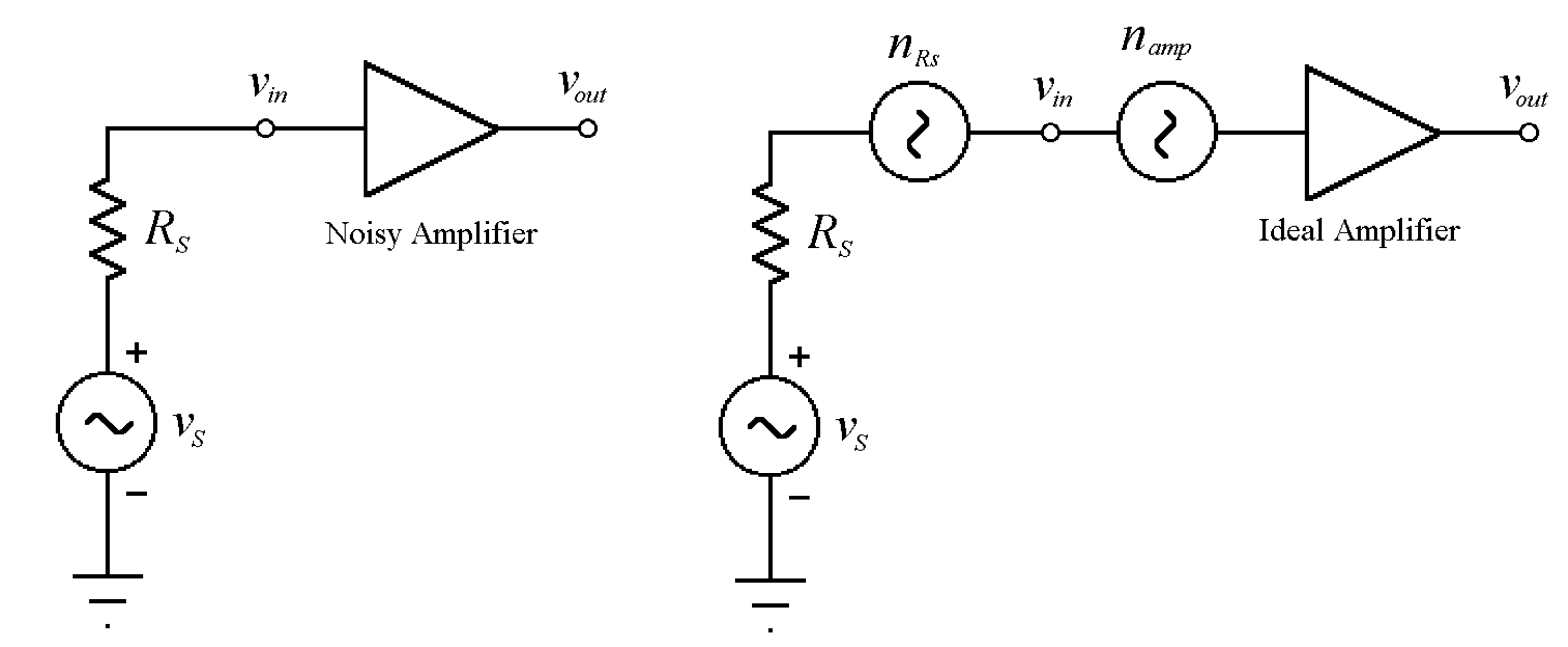
$$i_n = \sqrt{\frac{KIB}{f}} \ \ [\mathrm{A_{rms}}] \quad \text{or} \quad i_n = \sqrt{\frac{KI}{f}} \ \ [\mathrm{A_{rms}}/\sqrt{\mathrm{Hz}}]$$

f = frequency,

K = component dependent constant.

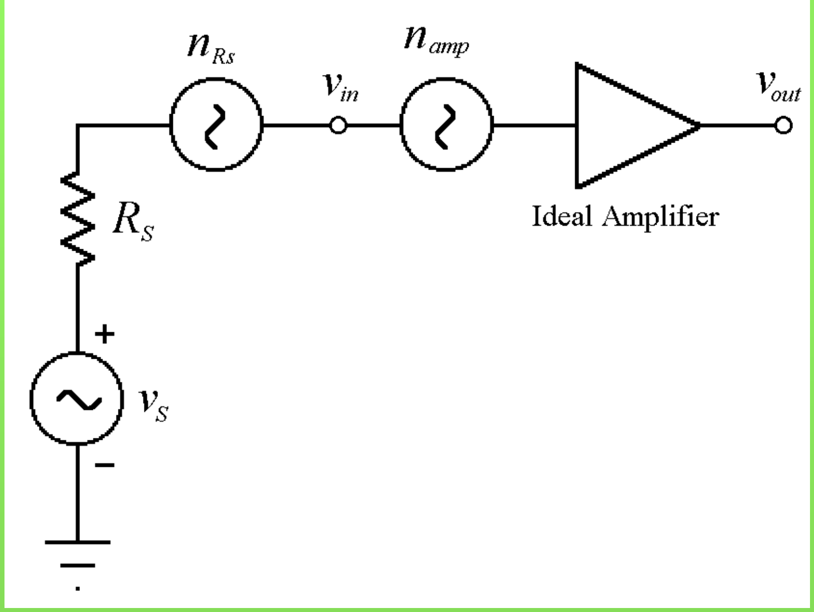
Note that the noise power is inversely proportional to frequency – i.e. pink noise.

Noise in Amplifiers



A noisy amplifier   Equivalent circuit

Noise Figure



Equivalent circuit of a noisy amplifier with a noisy input.

Noise from R_S:

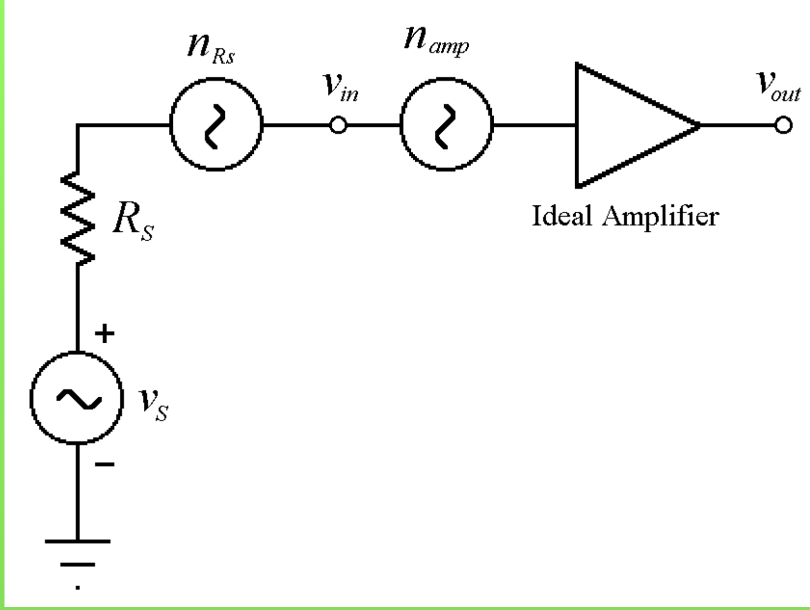
$$n_{Rs} = \sqrt{4kTR_S} \quad [\mathrm{V}/\sqrt{\mathrm{Hz}}]$$

Signal-to-noise ratio for v_{in}:

$$SNR_{in} = 10\log_{10}\left[\frac{v_S^2}{4kTR_S}\right]$$

Noise voltage level at the output will be the r.m.s. sum of the resistor noise and the amplifier noise.
(Add power, not voltage)

$$n_{out} = \sqrt{4kTR_S + n_{amp}^2}$$



Equivalent circuit of a noisy amplifier with a noisy input.

Output signal-to-noise ratio is, therefore:

$$SNR_{out} = 10\log_{10}\left[\frac{v_S^2}{4kTR_S + n_{amp}^2}\right]$$

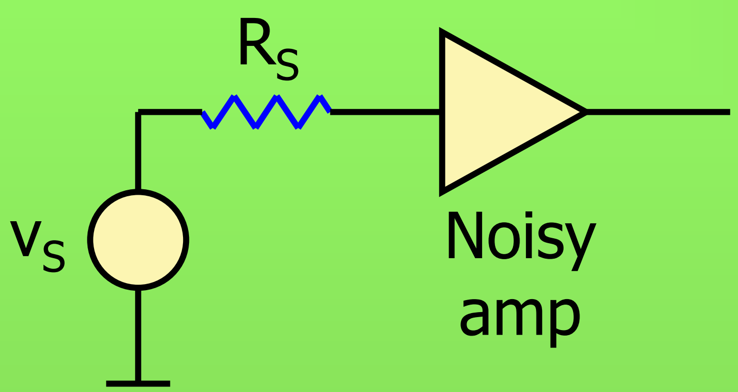
$$SNR_{in} = 10\log_{10}\left[\frac{v_S^2}{4kTR_S}\right]$$

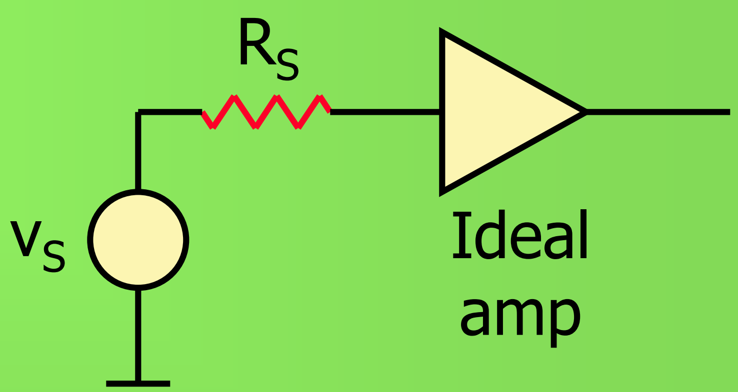
$$SNR_{out} = 10\log_{10}\left[\frac{v_S^2}{4kTR_S + n_{amp}^2}\right]$$

The Noise Figure of the amplifier is the ratio between the output and input signal-to-noise ratios:

$$NF = 10\log_{10}\left[\frac{4kTR_S + n_{amp}^2}{4kTR_S}\right] = 10\log_{10}\left[1 + \frac{n_{amp}^2}{4kTR_S}\right]$$

Noise Temperature





If R_S is cooled to zero:

$$SNR_{out} = 10\log_{10}\left[\frac{v_S^2}{n_{amp}^2}\right]$$

R_S is heated to T_n but amp is ideal

$$SNR_{out} = 10\log_{10}\left[\frac{v_S^2}{4kT_nR_S}\right]$$

The noise temperature of the amplifier is the value of T_n where:

$$10\log_{10}\left[\frac{v_S^2}{n_{amp}^2}\right]=10\log_{10}\left[\frac{v_S^2}{4kT_nR_S}\right]$$

$$\Rightarrow 4kT_nR_S = n_{amp}^2$$

Noise temperature and noise figure are related since:

$$NF = 10\log_{10}\left[1+\frac{n_{amp}^2}{4kTR_S}\right]=10\log_{10}\left[1+\frac{4kT_nR_S}{4kTR_S}\right]$$

$$=10\log_{10}\left[1+\frac{T_n}{T}\right]$$

Bruit dans les systèmes de communication

Sommaire

- Interférences
- Types de bruits
- Bruit électrique
- Bruit gaussien
- Bruit blanc
- Bruit bande étroite
- Bande passante de bruit équivalente
- Rapport signal sur bruit

Interférences

Elles sont dues aux:

- Réflexions
- Couplages par diffraction du signal dans l'atmosphère
- Polarisations croisées: deux systèmes émettant à la même fréquence
- Interférences dues à un filtrage non performant (bandes se chevauchant, etc..

Types of Noise

1- Manmade (artificial): These could be eliminated via better design

- Machinery
- Switches
- Certain types of lamps

2- Natural

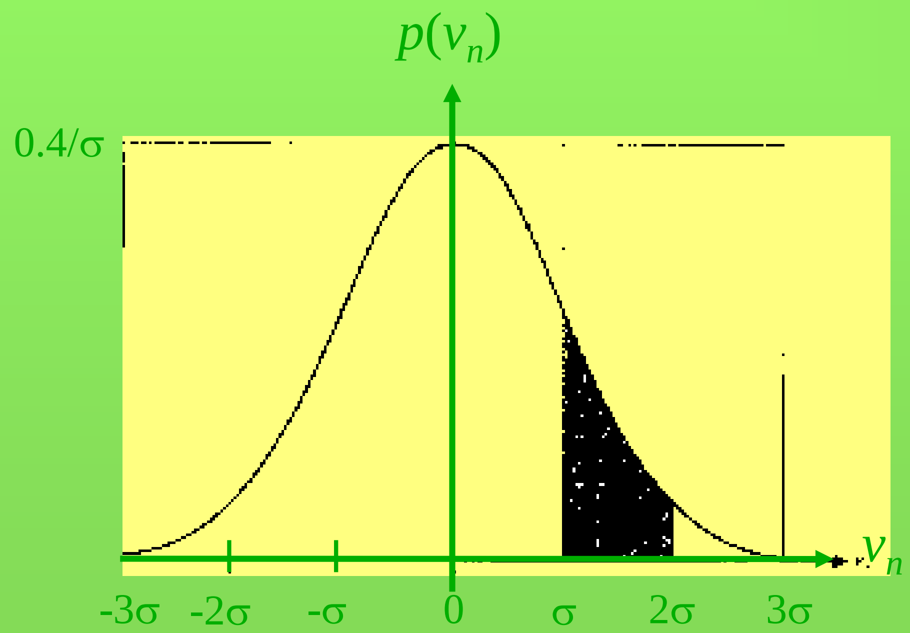
- Atmospheric noise: causing crackles on our radios
- Cosmic noise (space noise):

Noise in Electrical Components

- Thermal noise: Random free electron movement in a conductor (resistor) due to thermal agitation
- Shot noise: Due to random variation in current superimposed upon the DC value. It is due to variation in arrival time of charge carriers in active devices.
- Flicker noise: Observed at very low frequencies, and is thought to be due to fluctuation in the conductivity of semiconductor devices.

Gaussian Noise

Each noise types outlined before (except flicker noise) is the result of a large number of statistically independent and random contributions. The distribution of such random noise follow a Gaussian distribution with zero mean.



Probability density function of zero mean and standard deviation σ

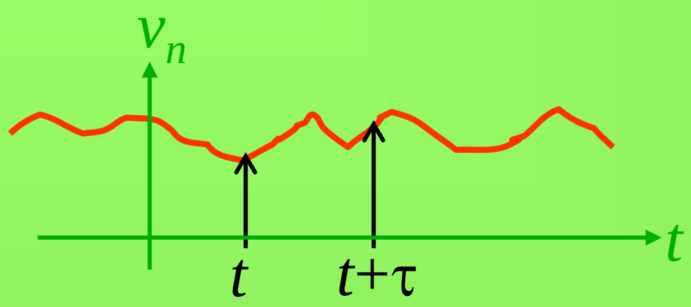
$$p(v_n) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left(-\frac{v^2{}_n}{2\sigma^2}\right)}$$

Where σ^2 is the variance of noise voltage v_n

For zero mean, normalised noise power or mean square voltage:

$$P_n = \overline{v_n^2} = \sigma^2$$

White Noise



The time-average autocorrelation function of the noise voltage is:

$$R_v(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T v_n(t)v_n(t+\tau)\,dt$$

Assumptions:

- $v_n(t+\tau)$ is random value that does not depend on $v_n(t)$.
- The above condition holds no matter how small τ is, provided it is not zero.

White noise $w(t)$

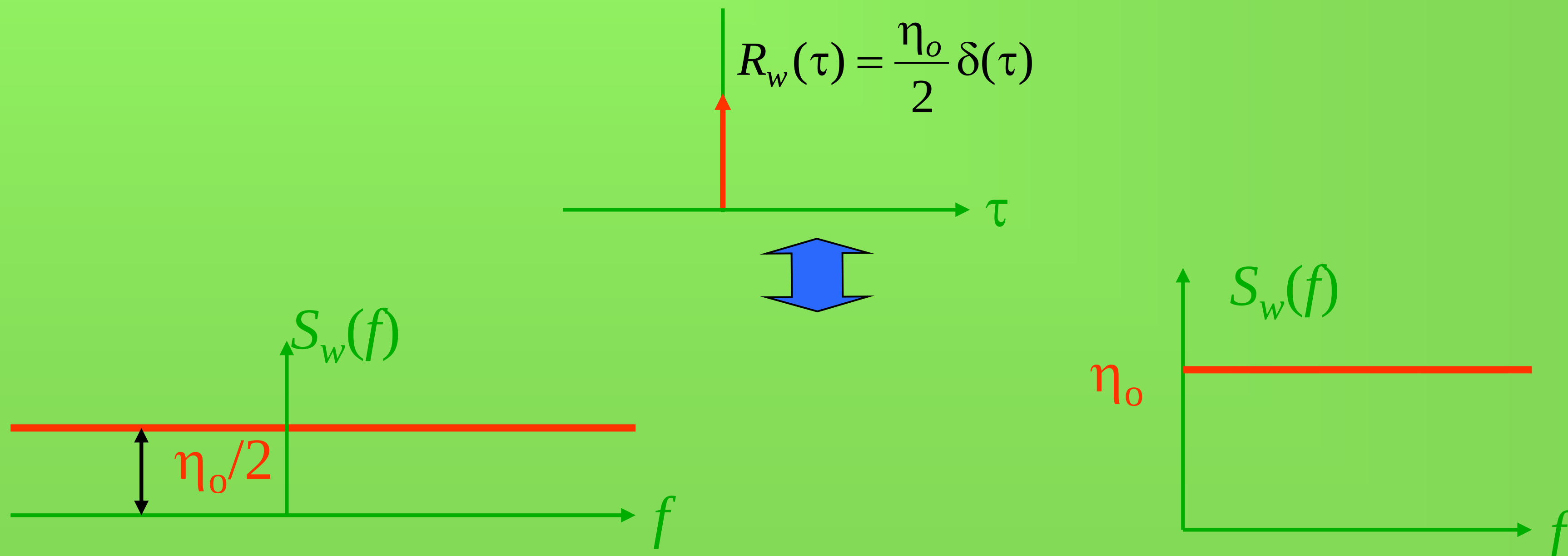
(i.e perfect randomness, which can not be attained in real systems)

White Noise - *cont.*

The autocorrelation of white noise is:

$$R_w(t) = \begin{cases} P_n & \tau = 0 \\ 0 & \tau \neq 0 \end{cases}$$

$R_w(t)$ is a zero width of height P_n with an area under the pulse = $\eta_o/2$



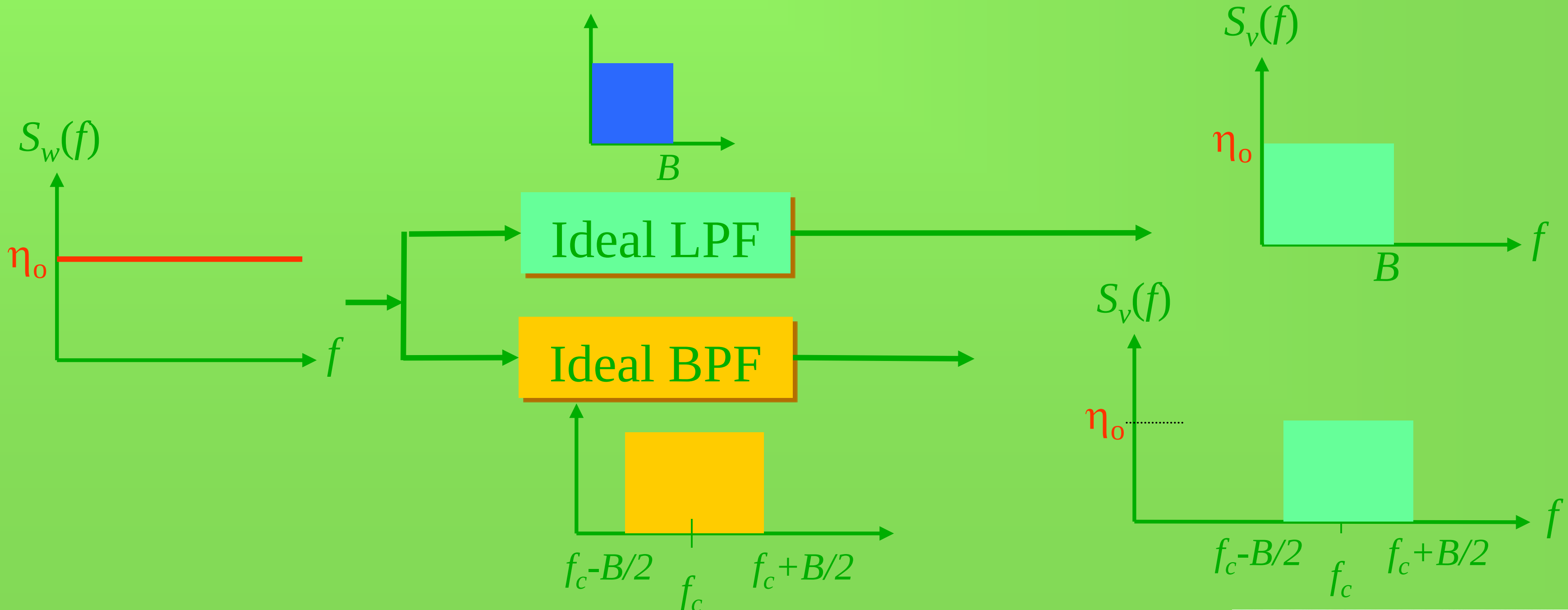
Double-sided power spectral density

Single-sided power spectral density

Narrowband Noise

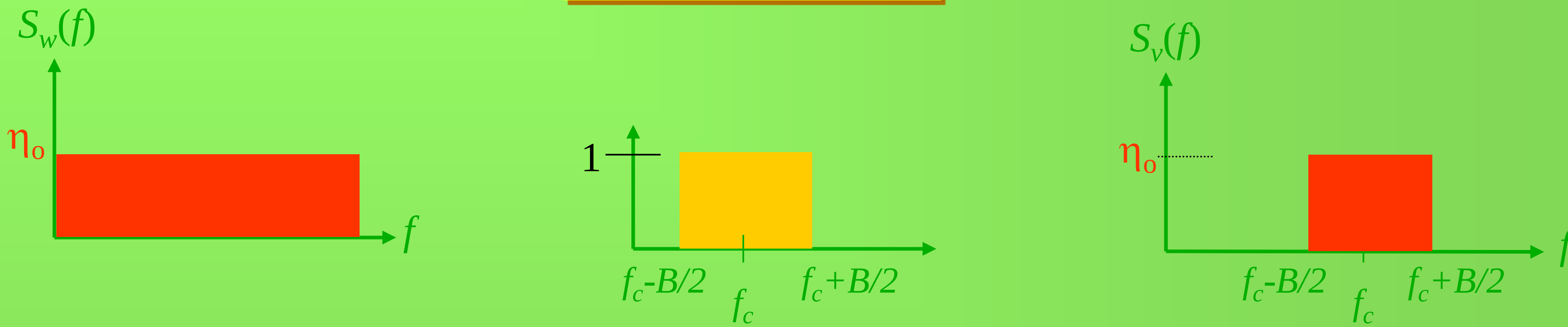
White noise $w(t) \leftrightarrow S_w(f)$ → **Communication Receiver** $H(f)$ → Narrow band noise $v_n(t) \leftrightarrow S_v(f)$

$$S_v(f) = S_w(f)\left|H(f)^2\right|$$



Narrowband Noise - *cont.*

White noise $w(t) \leftrightarrow S_w(f)$ → **Bandpass Filter** $H(f)$ → Narrow band noise $v_n(t) \leftrightarrow S_v(f)$



Bandlimited noise $v_n(t) = x(t)\cos\omega_c t - y(t)\sin\omega_c t$

$x(t)$ and $y(t)$ have the same power as the band pass noise $v_n(t)$

$$P_{x(t)} = P_{y(t)} = \int_{-B/2}^{B/2} S_v(f)\,df = \int_{-B/2}^{B/2} \eta_o |H(f)|^2\,df = \eta_o \int_{-B/2}^{B/2} 1\,df \equiv \eta_o B = P_n = \sigma^2$$

NOISE AND COMMUNICATIONS

- Where does noise originate in a communication system?

  1. Channel
  2. Equipment

- **DEFINE:**

  -undesired random variations that interfere with the desired signal and inhibit communication.

- REMEDIES?

  1. Reduce Bandwidth
  2. Increase transmitter power
  3. Low Noise Amplifiers

TYPES OF NOISE

- TWO CATEGORIES:

  1. External Noise

  2. Internal Noise

EXTERNAL NOISE

- 1. Equipment Noise:
  - automobile engines
  - electric motors
  - computers
  - light dimmers (interrupteurs)
- 2. ATMOSPHERIC NOISE (STATIC)
  - Lightning
  - Noise Blanking
- 3. SPACE NOISE
  - Radiation from the Sun (solar noise)
  - Stellar or Sky Noise (stars)

INTERNAL NOISE

- What devices or components generate noise?

- transistors, diodes, tubes, resistors

- electronic systems and equipment

TYPES OF INTERNAL NOISE

- Thermal Noise

  - random motion of electrons in a conductor due to heat.

- POWER DENSITY of thermal noise is constant with frequency. (White Noise)

$$P_N = kTB$$

$$\begin{aligned} P_N &= noise\ power\ in\ watts \\ k &= Boltzman's\ cons\tan t \\ T &= absolute\ temperature\ in\ K \\ B &= noise\ power\ Bandwidth \end{aligned}$$

THERMAL NOISE (BRUIT THERMIQUE)

- Half power bandwidth (3 dB)
- Average power
- How can thermal noise power be reduced?

  - decrease temperature

  - reduce bandwidth

BRUIT DE TENSION (NOISE VOLTAGE)

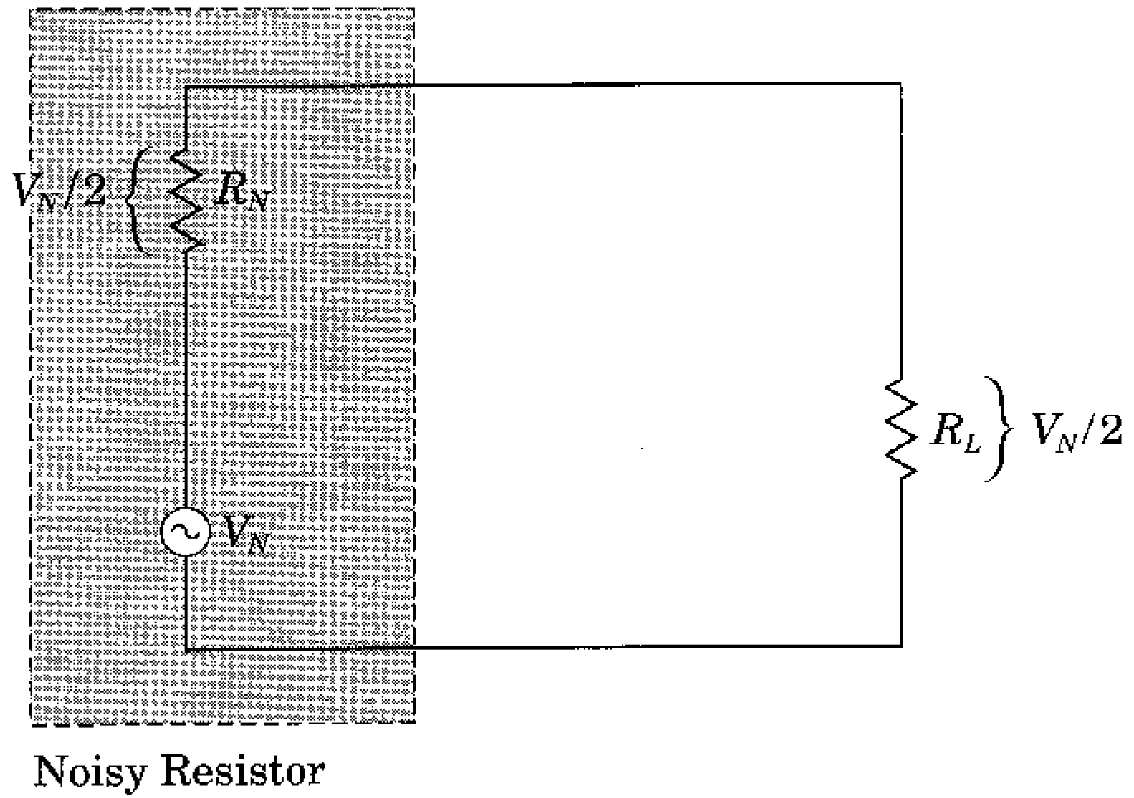
- PUISSANCE DE BRUIT THERMIQUE

$$P = V^2 \div R$$

$$V = \sqrt{PR}$$

- TENSION DE BRUIT THERMIQUE

Thermal Noise Voltage



Transparency 4 (Figure 1.10)

$$V_L = \sqrt{PR}$$

$$= \sqrt{kTBR}$$

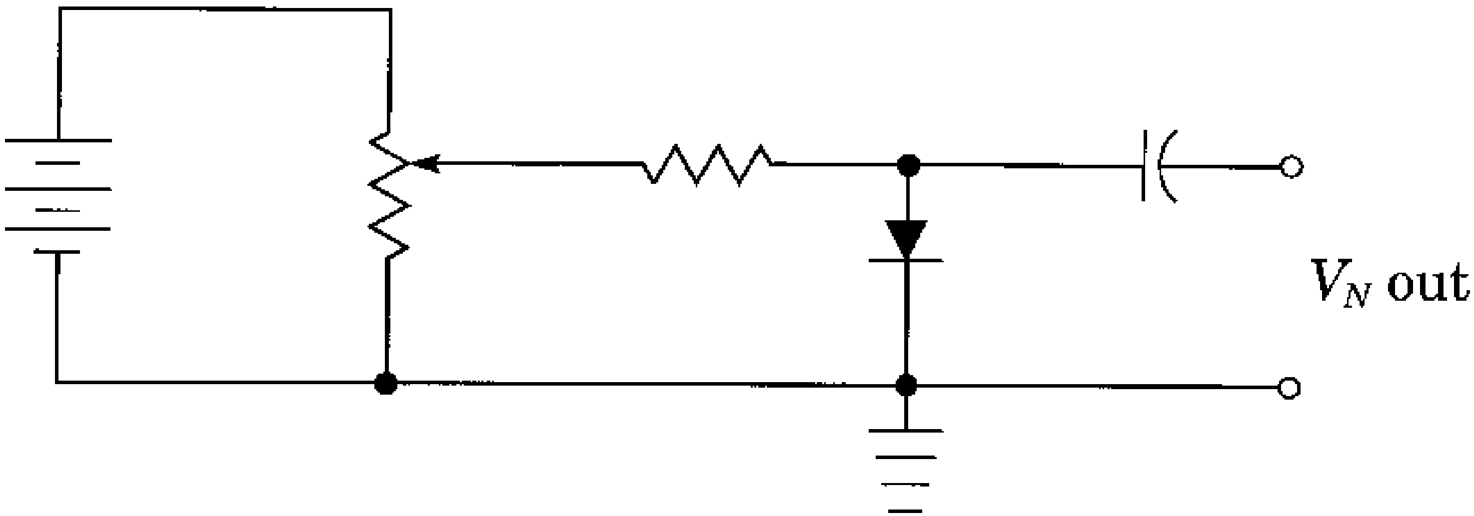
$$adaptation\ d'impédance:$$

$$V_N = 2\sqrt{kTBR} = \sqrt{4kTBR}$$

SHOT NOISE (BRUIT DE GRENAILLE)

- Random variations of current flow in active devices.
- Examples?
- -Transistors, diodes, tubes
- - due to quantum movement or flow of carriers (holes and electrons)(pulses)
- Energy spread over frequency similar to thermal noise.

Diode Noise Generator



$$I_N = \sqrt{2qI_O B}$$

Transparency 5 (Figure 1.11)

OTHER INTERNAL NOISE

- Partition Noise
  - where currents separate Ex. BJT
- Excess Noise (Pink Noise)
  - concentration of noise energy at low frequencies
- Transit Time Noise
  - at cutoff frequencies, junction delay

THE SUM OF NOISE FROM DIFFERENT SOURCES

- Take the square root of the sum of the squares of the individual voltages (if not correlated)
- Write the equation for total noise voltage

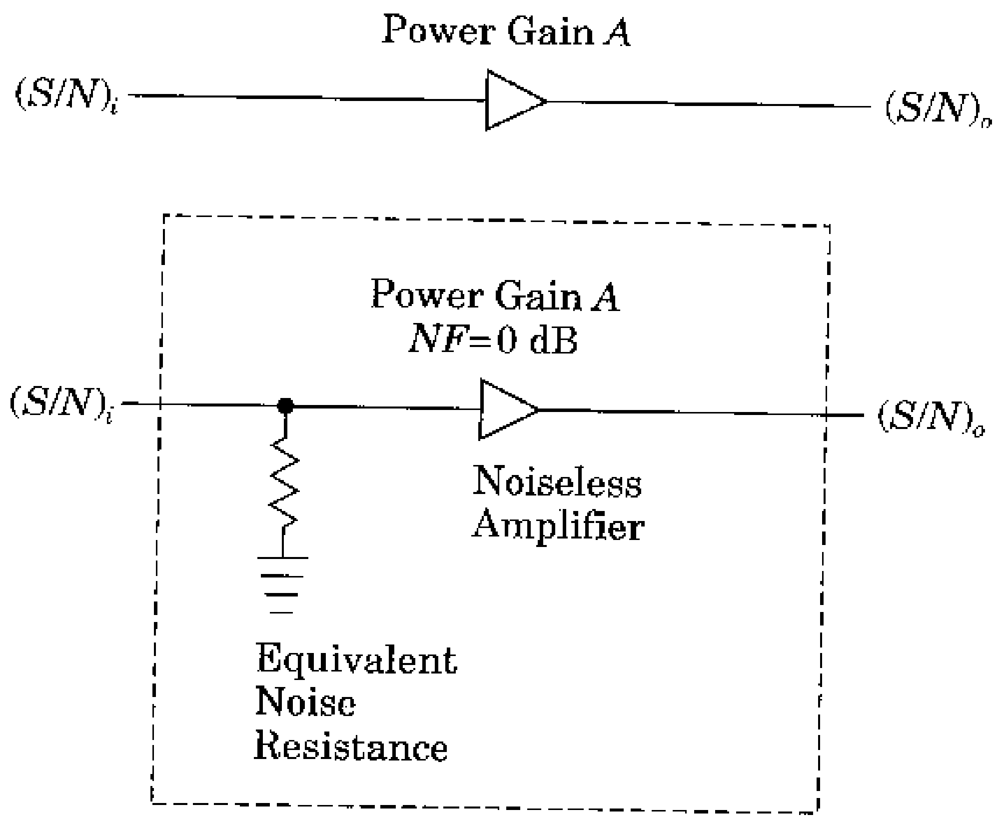
SIGNAL TO NOISE RATIO

- Noise power alone is not enough information
- Ratio of Signal to Noise is an important communications specification
- S/N is a ratio expressed in dB
- S/N (dB) = 10 log PS/PN
- S/N(dB) = 20 log VS/VN

S/N AND NOISE FIGURE

- (S+N)/N
- SINAD (S+N+D)/(N+D) Used for F.M.
- Both are power ratios
- Noise Figure = NF = (S/N)i/(S/N)o
- If expressed in dB NF= (S/N)I(dB)-(S/N)o (dB)

Equivalent Noise Resistance

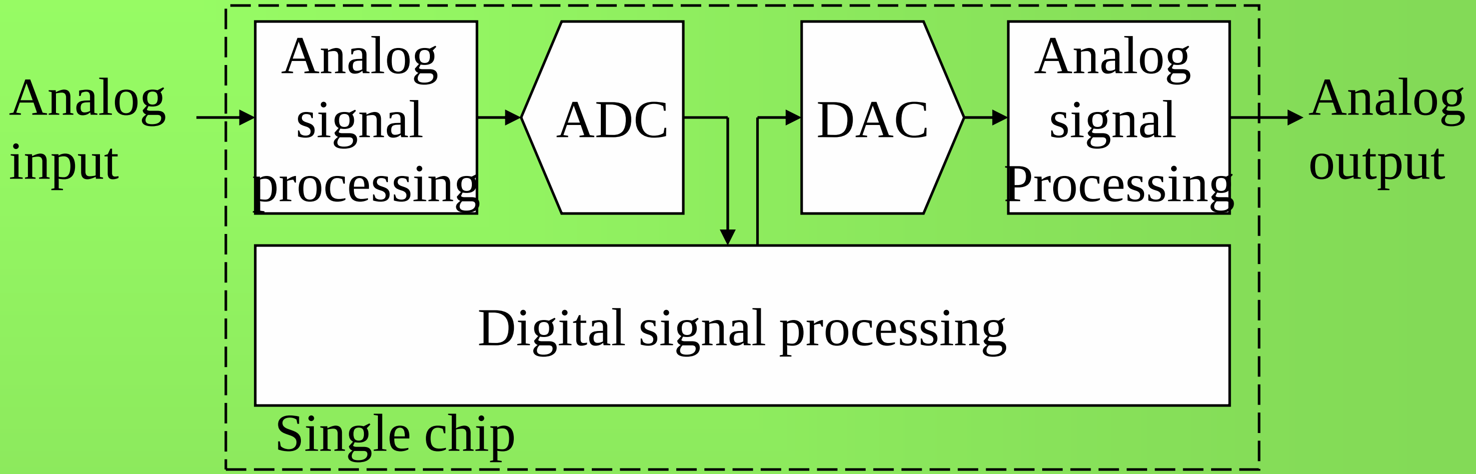


Transparency 6 (Figure 1.13)

Convertisseurs Analogique-Numérique

- le fonctionnement du CAN
- Spécifications du CAN
- Effets Non Idéaux

Pourquoi une conversion Analogique/Numérique?



- Par nature les signaux sont analogiques
- CAN nécessaire pour les DSP
- Le Digital signal processing nécessite:
  - SNR proche de l ’infini
  - système bas coût
  - système répétitif

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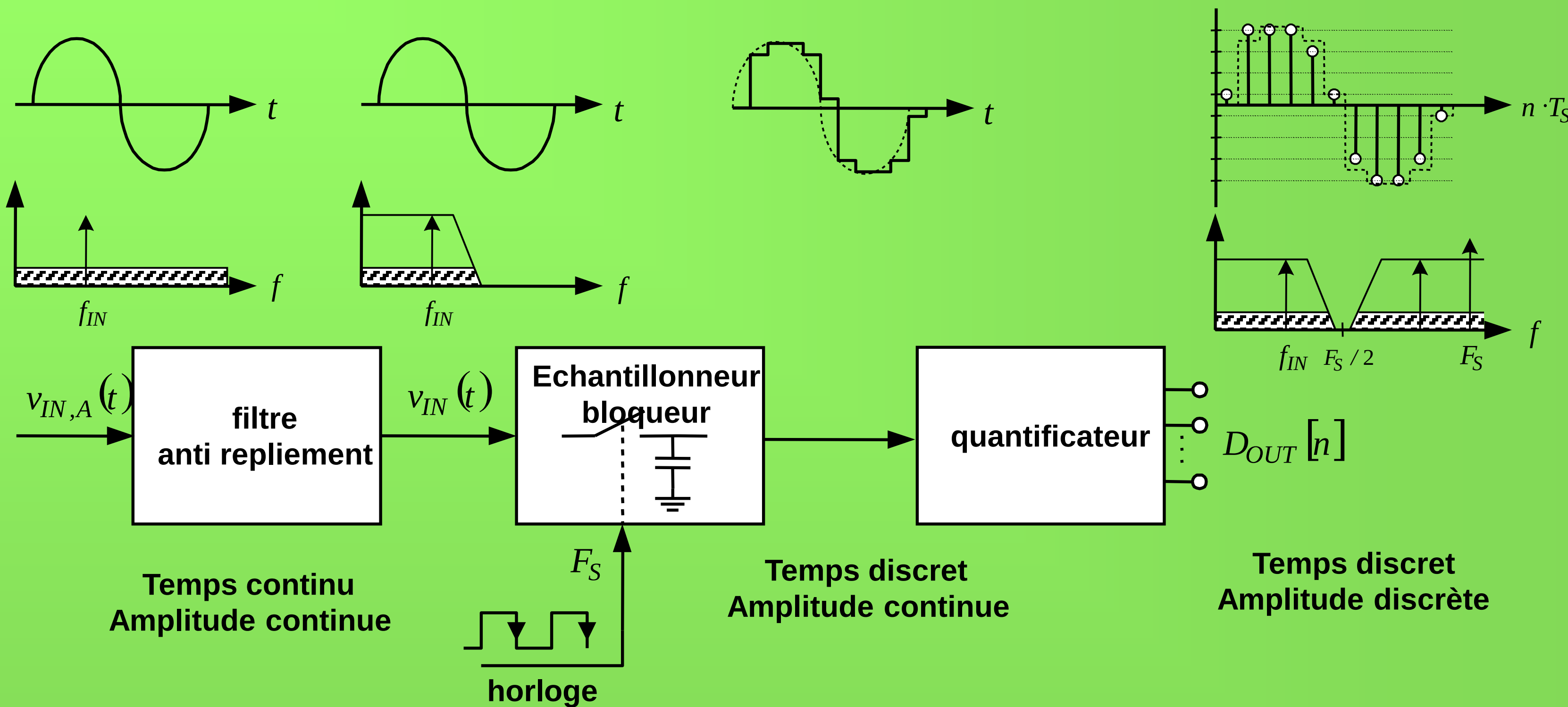
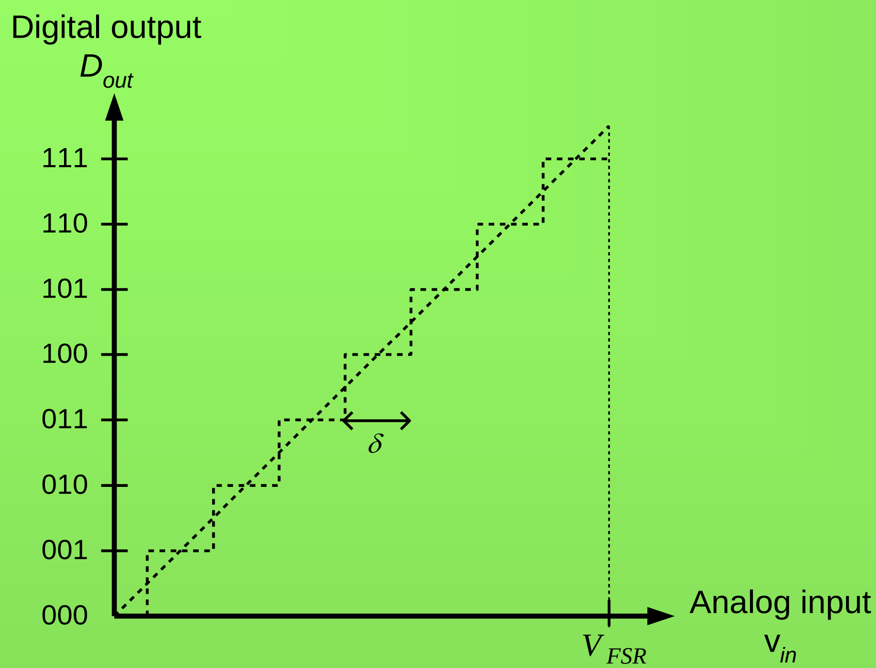
Principe du CAN

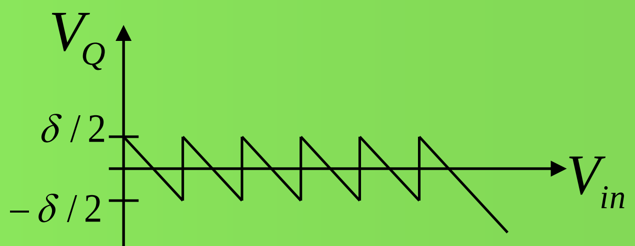


$$D_{OUT}^{ideal}[n] = G_{ideal} \cdot v_{IN}(n \cdot Ts) + q(n)$$

$$D_{OUT}^{real}[n] = G_{ideal} \cdot (1+\varepsilon) \cdot v_{IN}(n \cdot Ts) + q(n) + e_{offset}(n) + e_{noise}(n) + e_{jitter}(n) + e_{distortion}(n)$$

Bruit de quantification





- Convertisseur N-bit :
- FSR (Full Scale Range)

$$\delta = \frac{V_{FSR}}{2^N}$$

Bruit de quantification (2)

- énergie du bruit:

$$V_{Q(RMS)} = \sqrt{\frac{1}{\delta}\int_{-\delta/2}^{\delta/2} V_Q^2 dV_Q} = \sqrt{\frac{\delta^2}{12}}$$

- énergie du signal:

$$V_{in(RMS)} = \frac{\delta \cdot 2^N}{2\sqrt{2}}$$

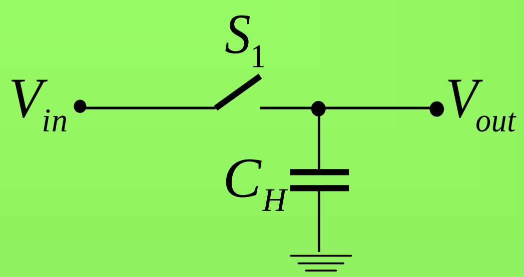
- SNR pour un CAN idéal:

$$SNR = 20\log\left(\frac{V_{in(RMS)}}{V_{Q(RMS)}}\right)$$

$$SNR = 20\log\left(2^N \cdot \sqrt{\frac{3}{2}}\right)$$

$$SNR = 6.02 \times N + 1.76[dB]$$

Bruit de l'échantillonneur (kT/C)



$$V_{KTC}(RMS) = \sqrt{\frac{kT}{C_H}}$$

$$SNR_{KTC} = 20\log\left(\frac{V_{FSR}}{2} \cdot \sqrt{\frac{C_H}{2 \cdot kT}}\right)$$

Par exemple

$$C_H = 1pF,\; V_{FSR} = 1V$$

$$SNR_{KTC} = 74.9dB \approx 12.1Bit$$

grande précision => grand C_H

analyse du bruit dans les circuits:
amplificateurs opérationnels et transistors

Noise Analysis

- Motivation:
  - Noise is a major limitation in analog circuit performances (e.g. in A/D and D/A converters or in RF receiver and transceivers or in audio circuits);
  - Noise sources are distributed all over the circuit.
- Purpose of Noise Analysis:
  - calculate the total noise power at the designated circuit output;
  - evaluate the contribution of each single noise source at the designated output.

Noise spectral density

- Noise in electronic circuits is generally specified in terms of its rms value

$$i_n = \sqrt{\lim_{T \to \infty} \frac{1}{T} \int_0^T \left[i_n(t) - i(t)\right]^2 \, dt} \qquad v_n = \sqrt{\lim_{T \to \infty} \frac{1}{T} \int_0^T \left[v_n(t) - v(t)\right]^2 \, dt}$$

- Such quantity in most electronic circuits can be calculated integrating a given spectral density $\frac{v_n^2}{\Delta f}$ or $\frac{i_n^2}{\Delta f}$ over the bandwidth of interest B=[fa,fb]

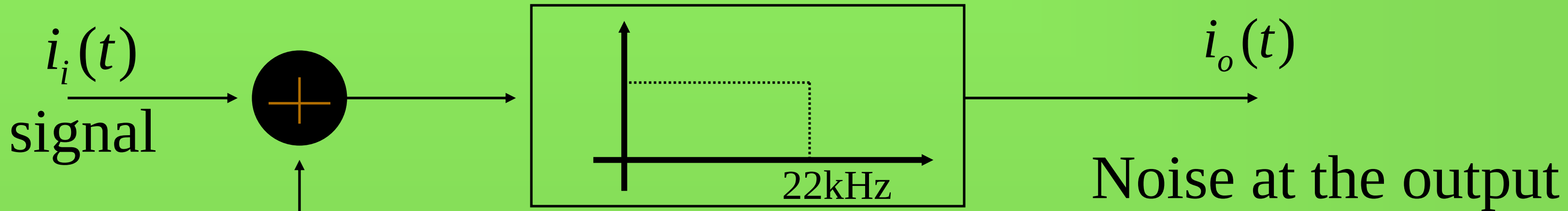
$$i_n^2 = \int_{f_a}^{f_b} \left(\frac{i_n^2}{\Delta f} \right) df \qquad v_n^2 = \int_{f_a}^{f_b} \left(\frac{v_n^2}{\Delta f} \right) df$$

Example: noise calculation

- Def. <u>white noise</u>: spectral density is independent of frequency

$$\frac{\overline{i_n^{\,2}}}{\Delta f} = S_0 = const \qquad \overline{i_n^{\,2}} = \int_{f_a}^{f_b} \left(\frac{\overline{i_n^{\,2}}}{\Delta f} \right) df = S_0 \left(f_b - f_a \right)$$

- Example: white noise after a low pass filter



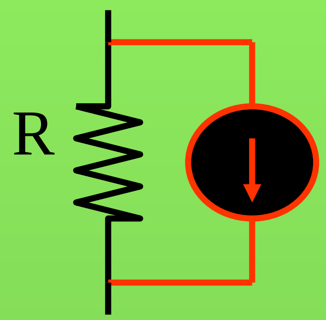
$$\sqrt{\frac{\overline{i_{n,i}^{\,2}}}{\Delta f}} = 18 \frac{pA}{\sqrt{Hz}}$$

Input noise

$$i_{n,o} = \sqrt{\left(18 \frac{pA}{\sqrt{Hz}} \right)^2 (22kHz - 0Hz)} = 2.7nA$$

Noise Models

- Thermal noise
  - due to random **thermal fluctuation**;
  - typical of all **resistive** elements;
  - modeled as parallel current generator producing white noise (= independent from freq.) with spectral density:



$$\frac{i_n^{\,2}}{\Delta f} = 4\,kT\,G$$

- » where k = 1.381E-23 J/K is the Boltzman constant,
- » T is the temperature in Kelvin,
- » G = 1/R is the conductance.

Noise Models (cont.)

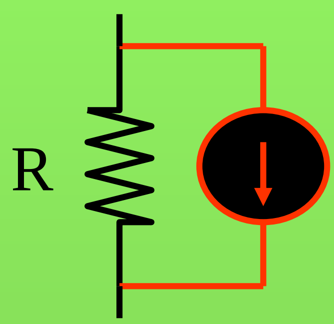
- Shot noise
  - due to the discrete nature of charge flow
    - ; e.g. in Diodes, BJT and FET channels;
  - modeled as white noise with spectral density:

$$\frac{i_n^{\;2}}{\Delta f} = 2\, q\, I$$

    - where q = 1.9E-21C is the charge of one electron, and I is the current through the device
- Flicker noise
  - Due to random capture and release of charge
  - Spectral density proportional to 1/f (very slow change: secs; it is basically a slow change in the DC level)
  - typical of mosfet gates

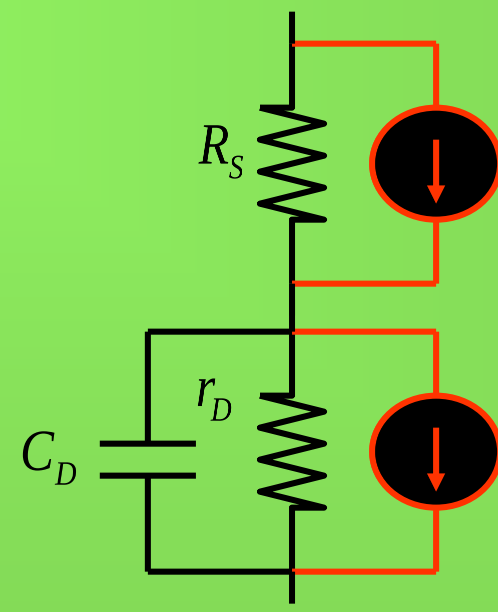
AC device models including noise sources

Resistor



$$\frac{\overline{i_R^{\,2}}}{\Delta f} = 4\,kT\,\frac{1}{R}$$

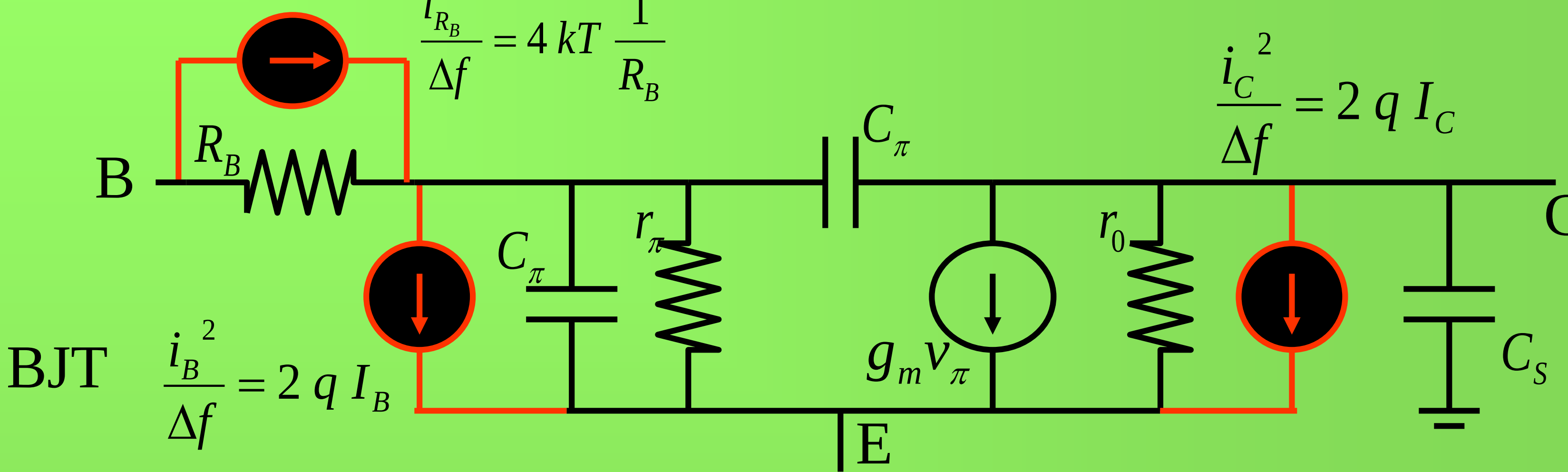
Diode



$$\frac{\overline{i_{Rs}^{\,2}}}{\Delta f} = 4\,kT\,\frac{1}{R_S}$$

$$\frac{\overline{i_D^{\,2}}}{\Delta f} = 2\,q\,I_D$$

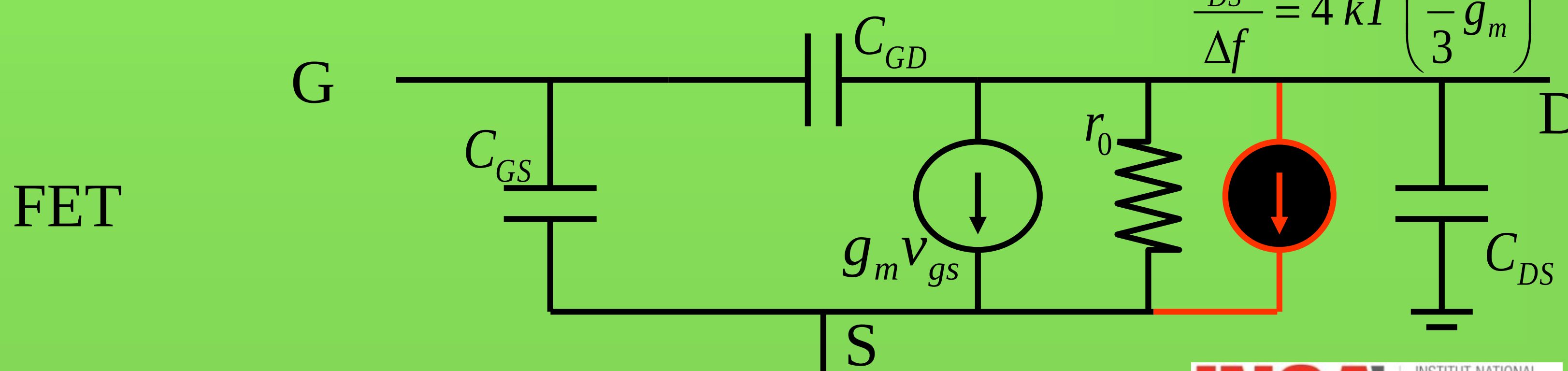
Noise models for devices (cont.)



$$\frac{\overline{i_{R_B}^{\,2}}}{\Delta f} = 4\,kT\,\frac{1}{R_B}$$

$$\frac{\overline{i_B^{\,2}}}{\Delta f} = 2\,q\,I_B$$

$$\frac{\overline{i_C^{\,2}}}{\Delta f} = 2\,q\,I_C$$



$$\frac{\overline{i_{DS}^{\,2}}}{\Delta f} = 4\,kT\left(\frac{2}{3}\,g_m\right)$$

Conventional noise analysis

- Valid for circuits in **small signal** operation (linear)
- Find the transfer impedance Zi from each noise source i to the output
- The noise power density produced at the output by noise source i is given by
- Assuming noise sources are all un-correlated, the total noise power density at the output is

$$\frac{\overline{v_i^2}}{\Delta f} = |Z_i|^2 \frac{\overline{i_i^2}}{\Delta f}$$

$$\frac{\overline{v^2}}{\Delta f} = \sum |Z_i|^2 \frac{\overline{i_i^2}}{\Delta f}$$

Limitations of the noise analysis

- This noise analysis is only for linear circuits
  - good for small signal operation
  - but not good for oscillators or power amplifiers that work in large signal nonlinear regime
- It assumes stationary noise
  - e.g. not good for RF systems with mixers where noise is cyclostationary

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