

**Conversion Analogique-Numérique
et Numérique-Analogique
Introduction à la Radio Logicielle**

O. VENARD

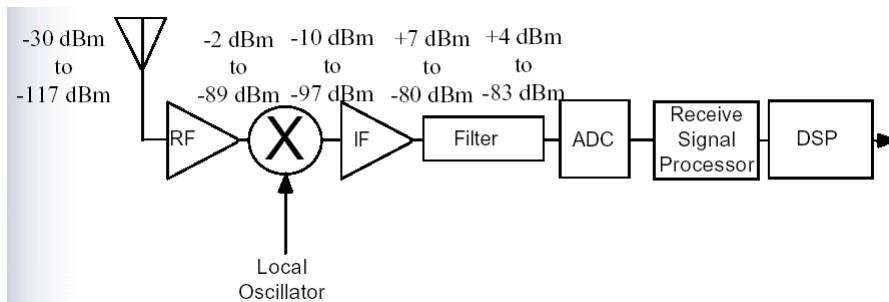
ST5-ARCH

**Année scolaire : 2009-2010
2008-2009
2007-2008**

Conversion Analogique-Numérique Numérique-Analogique

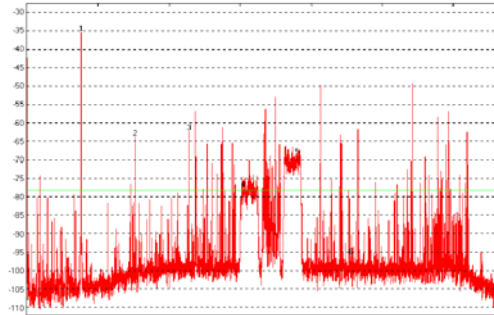
Application à la Radio logicielle

Chaîne de réception



Dynamique 87dB + marge de garde

Spectre radio

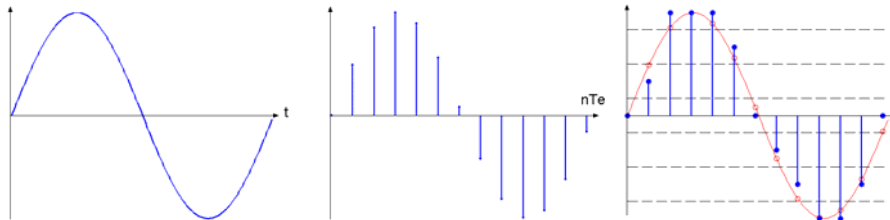


Signal utile + interférents

Echantillonnage

Echantillonnage
discrétisation de
l'axe des abscisses

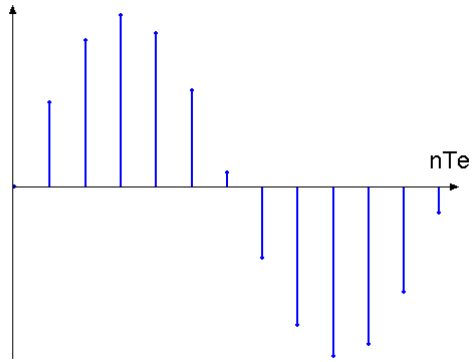
Quantification
discrétisation de
l'axe des ordonnées



réversible

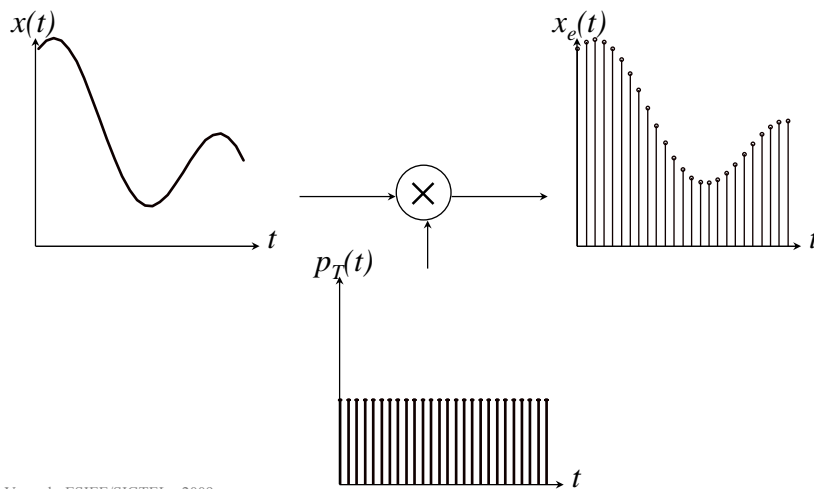
irréversible

Echantillonnage



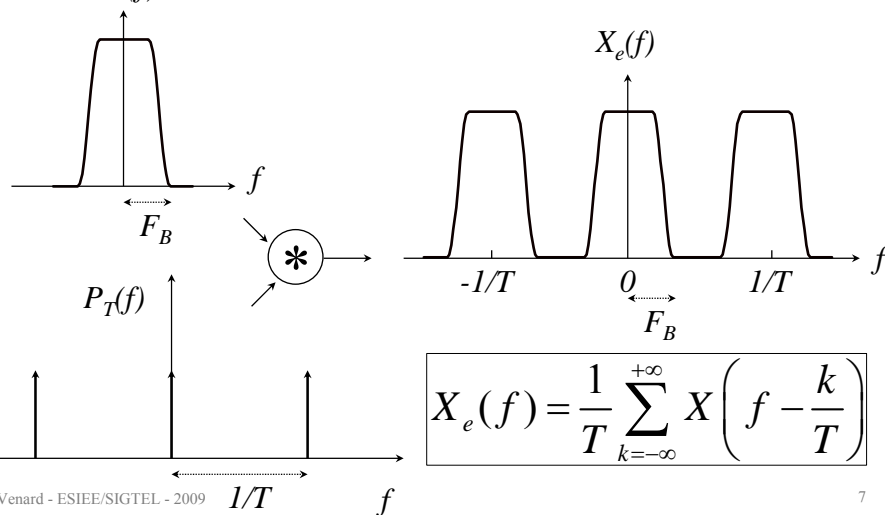
Modèle de l'échantillonnage

$$x_e(t) = x(t) \cdot p_T(t) = x(t) \cdot \sum_{n=-\infty}^{+\infty} \delta(t - nT)$$

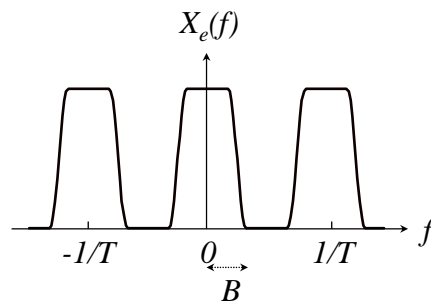


Modèle de l'échantillonnage

$$X_e(f) = X(f) * P_T(f) = X(f) * \frac{1}{T} \sum_{k=-\infty}^{+\infty} \delta\left(f - \frac{k}{T}\right)$$

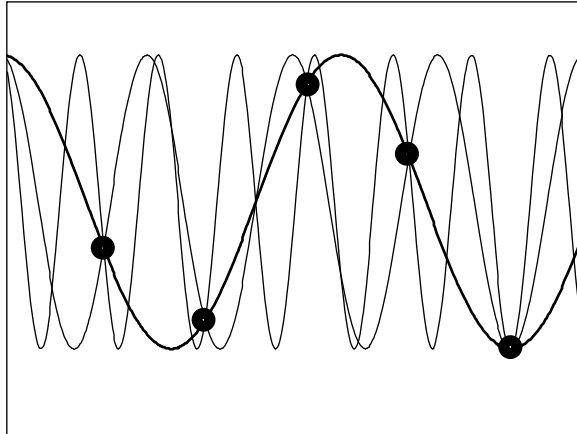


Echantillonnage bande de base (signal passe-bas)



$$F_e = \frac{1}{T} \geq 2B$$

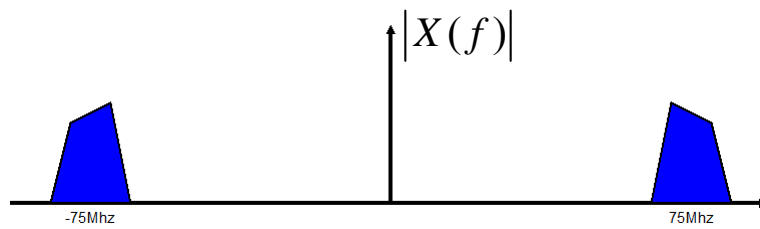
Repliement de spectre



$f_1=2\text{kHz}$
 $f_2=8\text{kHz}$
 $f_3=12\text{kHz}$

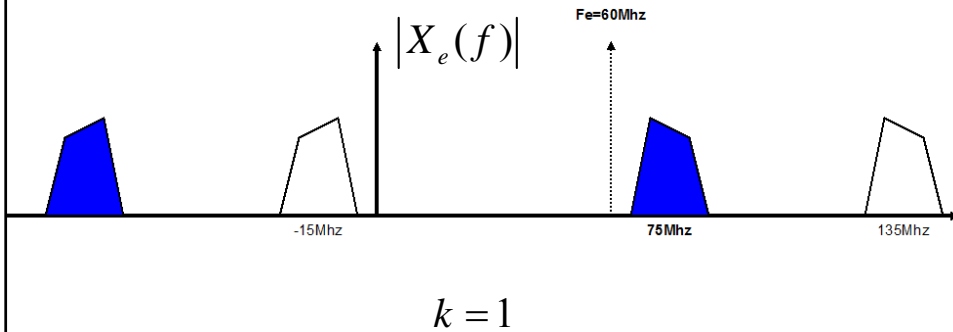
$F_e=10\text{kHz}$

Échantillonnage passe-bande



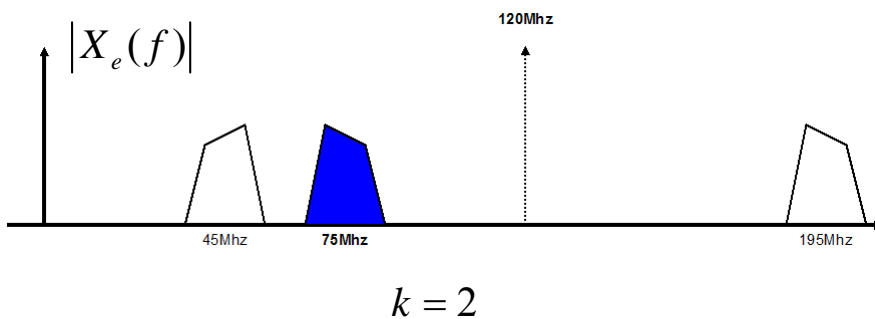
Échantillonnage passe-bande repliement

$$X_e(f) = F_e \sum_{k=-\infty}^{+\infty} X(f - kF_e)$$



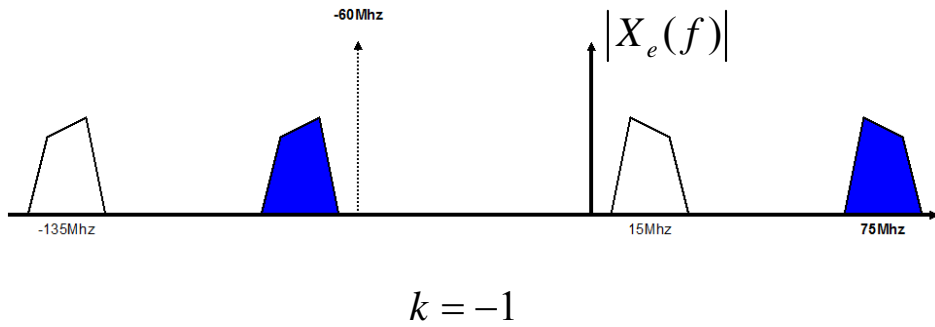
Échantillonnage passe-bande repliement

$$X_e(f) = F_e \sum_{k=-\infty}^{+\infty} X(f - kF_e)$$



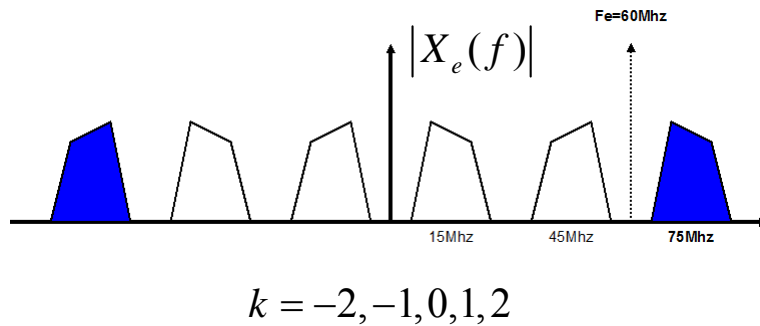
Échantillonnage passe-bande repliement

$$X_e(f) = F_e \sum_{k=-\infty}^{+\infty} X(f - kF_e)$$



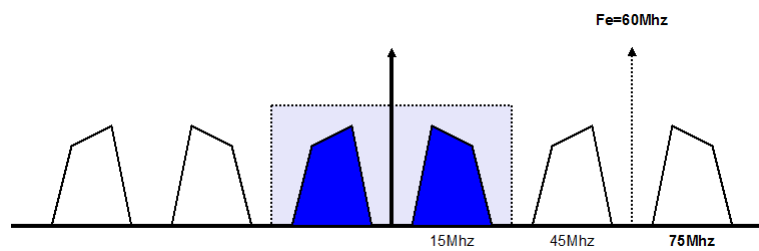
Échantillonnage passe-bande repliement

$$X_e(f) = F_e \sum_{k=-\infty}^{+\infty} X(f - kF_e)$$



ESIEE Échantillonnage passe-bande

$$f' = f - kF_e \text{ avec } -\frac{F_e}{2} \leq f' < \frac{F_e}{2}$$

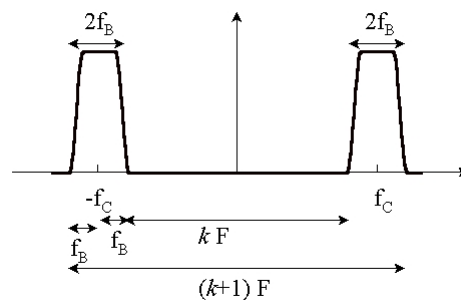


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15

ESIEE Échantillonnage passe-bande

Soit un signal passe-bande $[f_c - f_B; f_c + f_B]$



$$(-f_c + f_B) + kF_e \leq (f_c - f_B)$$

$$(-f_c - f_B) + (k+1)F_e \geq (f_c + f_B)$$

$$\frac{2(f_c + f_B)}{k+1} \leq F_e \leq \frac{2(f_c - f_B)}{k}$$

$$\text{et } F_e \geq 4f_B$$

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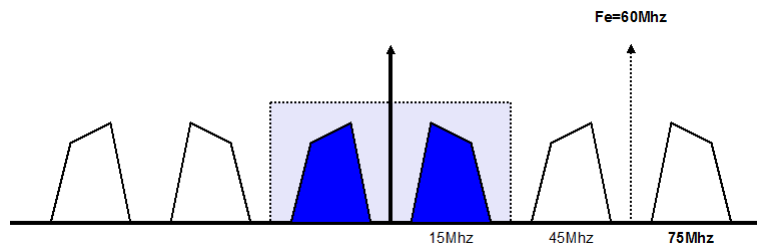
16

ESIEE Échantillonnage passe-bande

$$\frac{2(f_c + f_b)}{k + 1} \leq F_e \leq \frac{2(f_c - f_b)}{k} \quad \frac{2(85MHz)}{k + 1} \leq F_e \leq \frac{2(65MHz)}{k}$$

$$F_e \geq 4f_b \quad F_e \geq 4 \times 10MHz$$

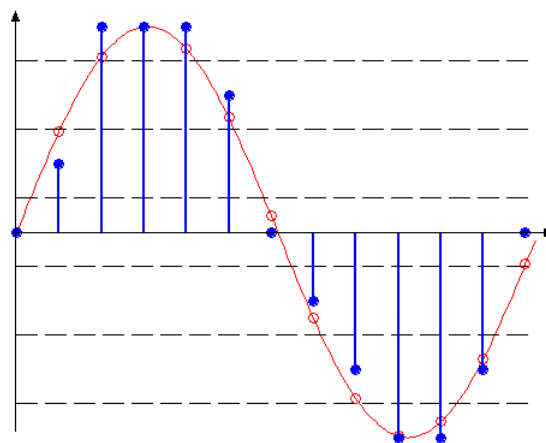
85MHz ≤ F_e ≤ 130MHz pour k = 1,
 56.66MHz ≤ F_e ≤ 65MHz pour k = 2,
 42,5MHz ≤ F_e ≤ 43.33MHz pour k = 3.



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17

ESIEE Quantification



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19

Quantification uniforme

$$\forall x \in [T_n, T_{n+1}]$$

$$Q(x) = x_n$$

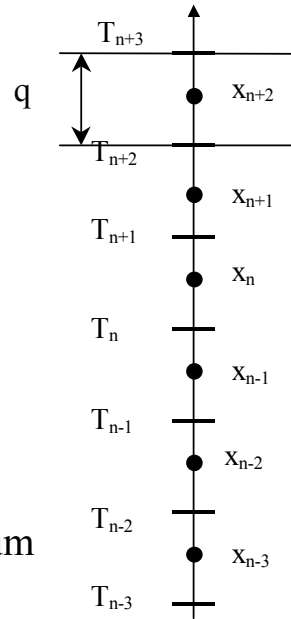
T_n = Seuil de Quantification

x_n = Valeur de Quantification

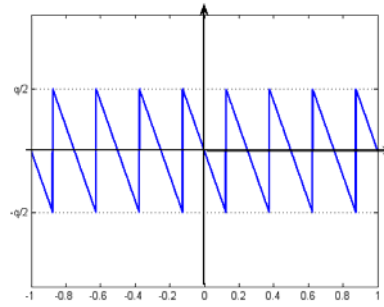
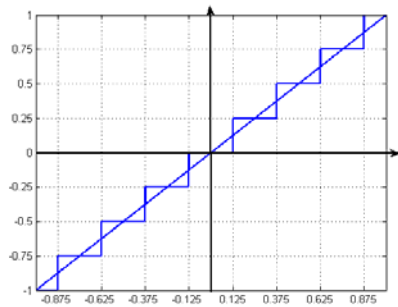
$$\forall n \quad |T_{n+1} - T_n| = q$$

$$\forall n \quad |x_{n+1} - x_n| = q$$

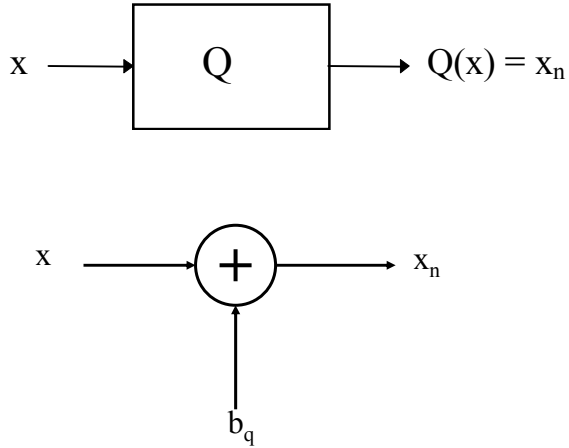
q = pas de quantification = quantum



Quantification par arrondi

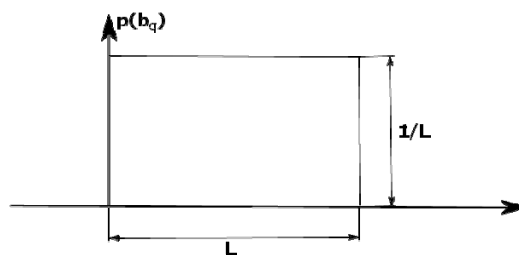


Dégradation



Modèle probabiliste

- Blanc
- Non corrélé
- Distribution uniforme



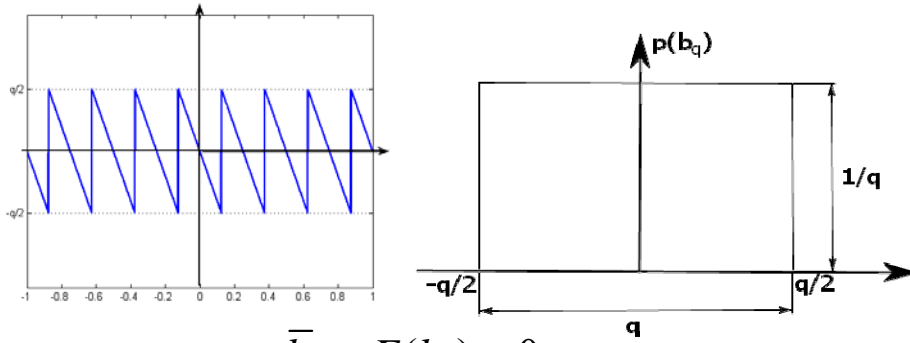
$$b_q = \hat{x} - x$$

$$\bar{b}_q = E(b_q) = \int b_q p(b_q) db_q$$

$$\sigma_{b_q}^2 = E(b_q^2) = \int b_q^2 p(b_q) db_q$$

$$P_{b_q} = \sigma_{b_q}^2 + \bar{b}_q^2$$

Arrondi

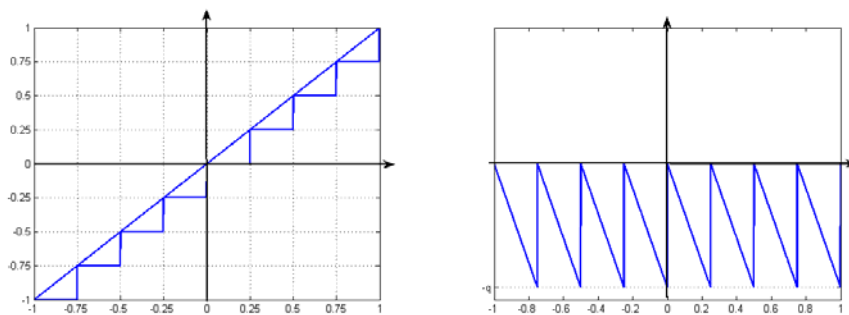


$$\bar{b}_q = E(b_q) = 0$$

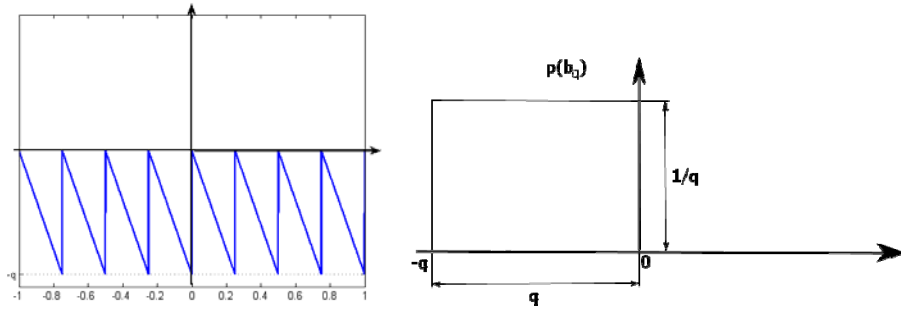
$$\sigma_{b_q}^2 = E(b_q^2) = q^2 / 12$$

$$P_{b_q} = q^2 / 12$$

Quantification par troncature (-∞)



Troncature vers $-\infty$

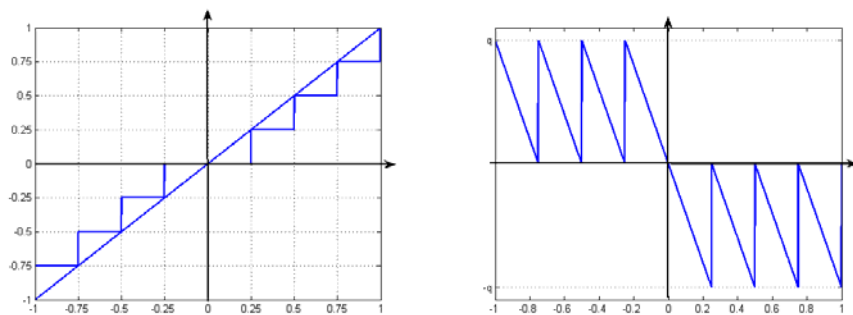


$$\bar{b}_q = E(b_q) = -q/2$$

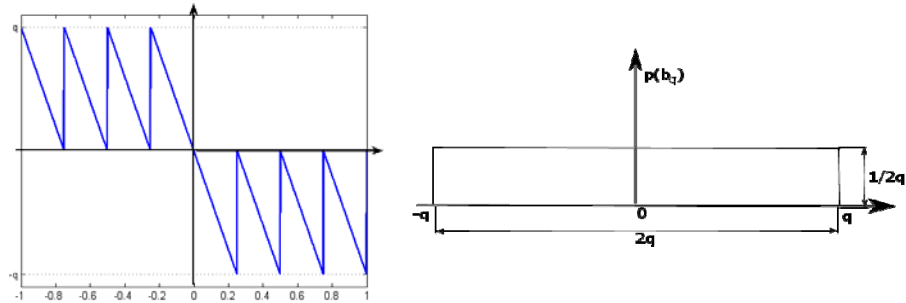
$$\sigma_{b_q}^2 = E(b_q^2) = q^2/12$$

$$P_{b_q} = q^2/3$$

Quantification par troncature (0)



Troncature vers 0



$$\bar{b}_q = E(b_q) = 0$$

$$\sigma_{b_q}^2 = E(b_q^2) = q^2/3$$

$$P_{b_q} = q^2/3$$

Evaluation de la dégradation

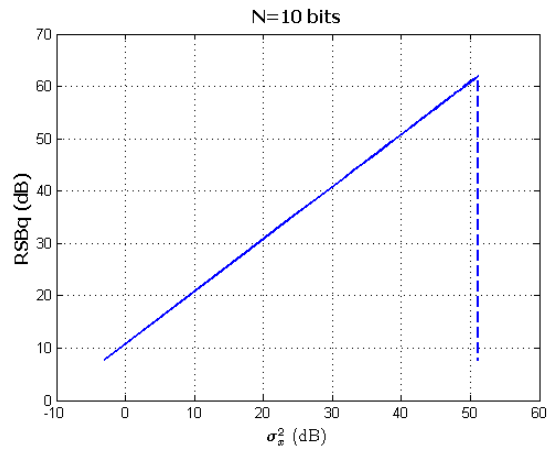
$$q = \frac{2x_{\max}}{2^N - 1} \approx \frac{2x_{\max}}{2^N}$$

$$RSB_q = 10 \log \left(\frac{\sigma_x^2}{\sigma_b^2} \right) = 10 \log \left(\frac{\sigma_x^2}{x_{\max}^2} \right) + 4.77 + 6.02N \text{ dB}$$

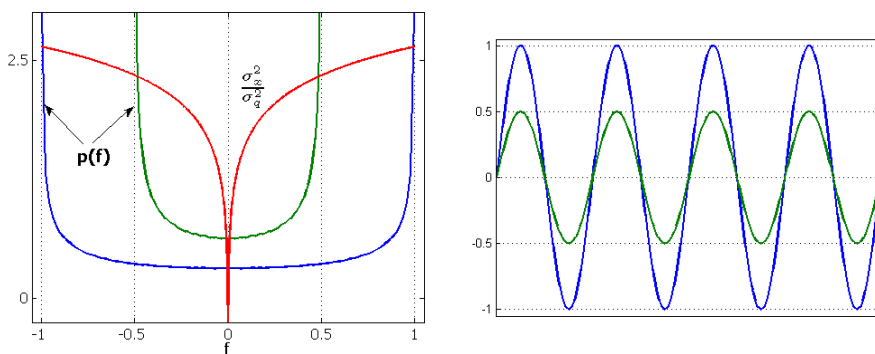
Pour un sinus d'amplitude crête = 1 (quantif par arrondi) :

$$RSB_q = 1.76 + 6.02N \text{ dB}$$

RSBq (10 bits) pour un sinus



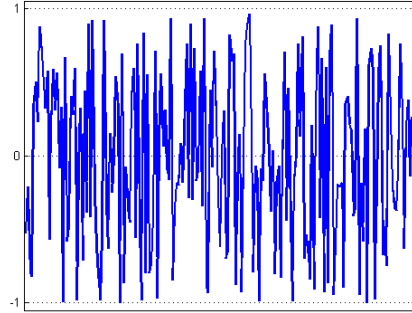
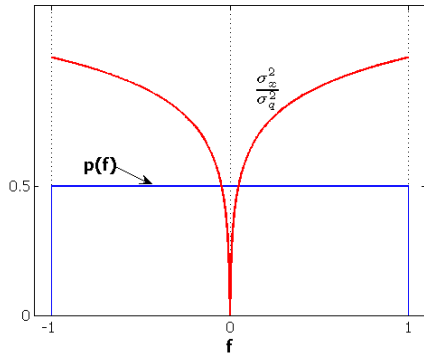
Signal sinusoidal



$$RSB_q = 6.02N + 1.76 \text{ dB}$$

$$\sigma_x = \frac{x_{\max}}{\sqrt{2}}$$

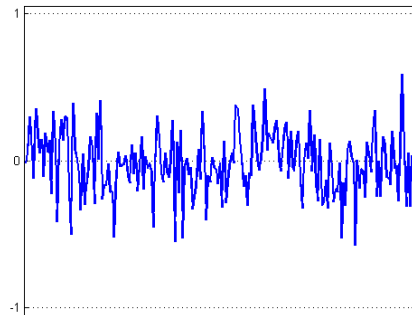
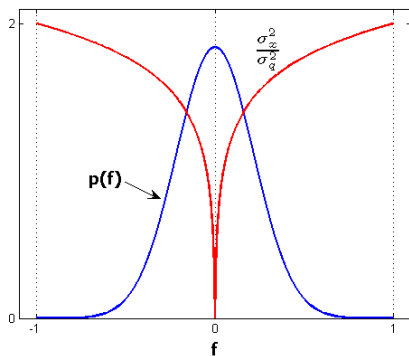
distribution uniforme



$$RSB_q = 6.02N \text{ dB}$$

$$\sigma_x = \frac{x_{\max}}{\sqrt{3}}$$

distribution normale



$$RSB_q = 6.02N - 8.2 \text{ dB}$$

$$\sigma_x = \frac{x_{\max}}{4.45}$$

$$p(|x| > x_{\max}) < 10^{-5}$$

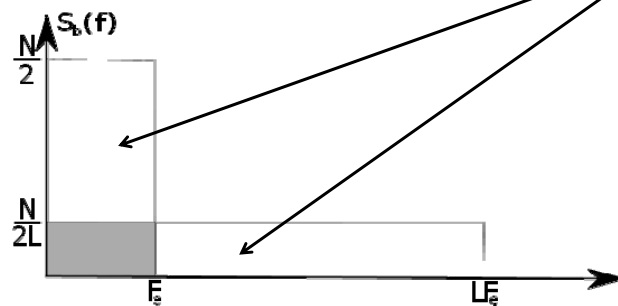
Résumé RSBq

$$RSB_q = 10 \log \left(\frac{\sigma_x^2}{x_{\max}^2} \right) + 4.77 + 6.02N \text{ dB}$$

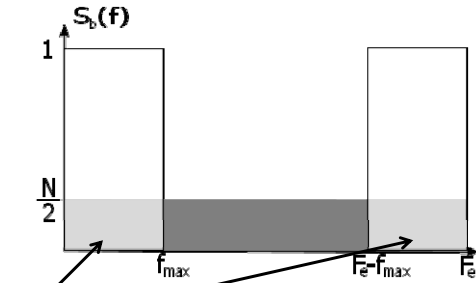
	σ_x	RSBq
sinusoïdal	$\frac{x_{\max}}{\sqrt{2}}$	$6.02N + 1.76 \text{ dB}$
uniforme	$\frac{x_{\max}}{\sqrt{3}}$	$6.02N \text{ dB}$
normale	$\frac{x_{\max}}{4.45}$	$6.02N - 8.2 \text{ dB}$

Puissance du bruit de quantification

$$\sigma_q^2 = \int_0^{F_e} \frac{N}{2} df = \int_0^{LF_e} \frac{N}{2L} df = \frac{N}{2} F_e = \frac{q^2}{12}$$



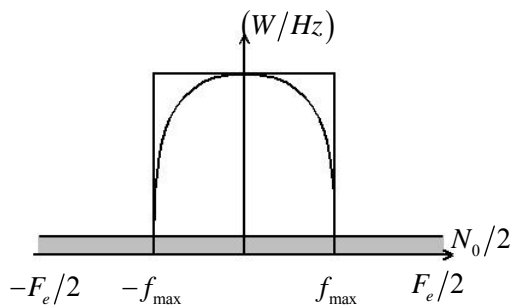
Gain de traitement



$$\sigma_b^2 = \sigma_q^2 \frac{1}{F_e} \int_0^{F_e} |H(f)|^2 df = \frac{2f_{\max}}{F_e} \sigma_q^2 = \frac{\sigma_q^2}{G_T}$$

$$RSB_q = 10 \log \left(\frac{\sigma_x^2}{\sigma_b^2} \right) = 10 \log \left(\frac{\sigma_x^2}{\sigma_q^2 / G_T} \right) = 10 \log \left(\frac{\sigma_x^2}{\sigma_q^2} \right) + 10 \log(G_T)$$

Gain de traitement

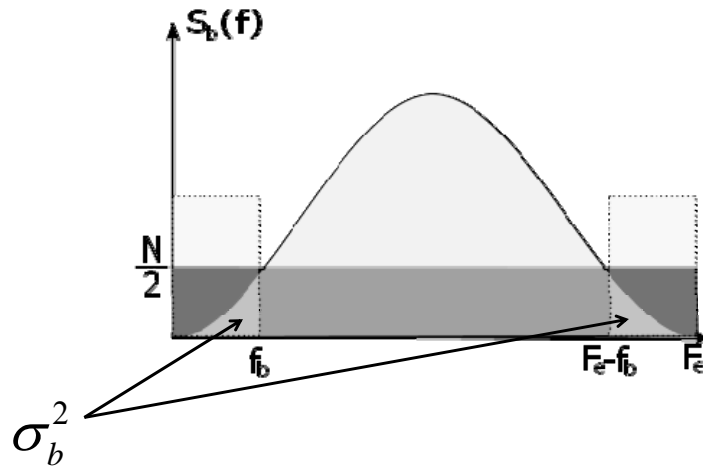


$$G_T = \frac{F_e}{2f_{\max}} = 2^R$$

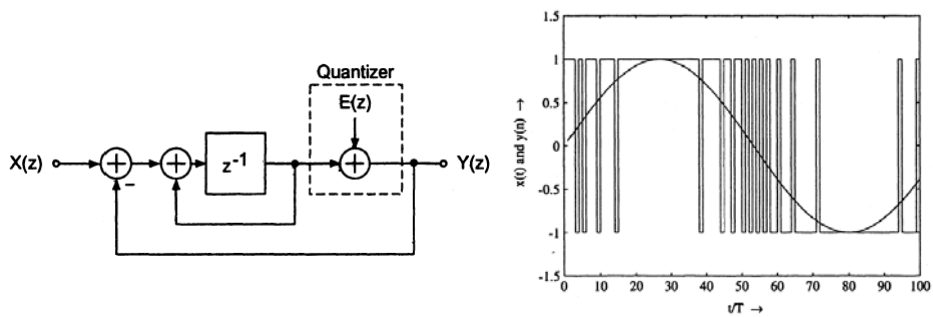
$$RSB_q = 10 \log \left(\frac{\sigma_x^2}{x_{\max}^2} \right) + 4.77 + 6.02N + 10 \log(G_T) \text{ dB}$$

$$RSB_q = 10 \log \left(\frac{\sigma_x^2}{x_{\max}^2} \right) + 4.77 + 6.02N + 3.01R \text{ dB}$$

Mise en forme du bruit



modulateur $\Sigma\Delta$ ordre 1



$$y(n) = x(n - 1) + e(n) - e(n - 1)$$

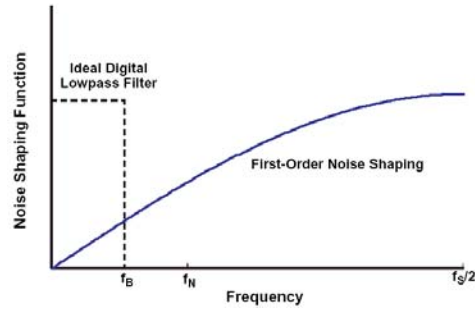
$$Y(z) = z^{-1}X(z) + E(z)(1 - z^{-1})$$

...modulateur $\Sigma\Delta$ ordre 1

$$e_1(n) = e(n) - e(n-1)$$

$$S_{bb}(f) = S_{qq}(f) 4 \sin^2(\pi f / F_s)$$

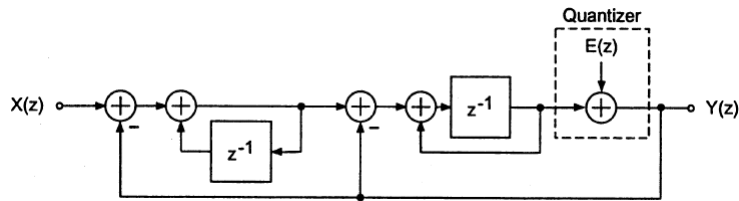
$$\sigma_b^2 = \sigma_q^2 \frac{\pi^2}{3} \left(\frac{1}{G_T} \right)^3$$



$$RSB_q = 10 \log \left(\frac{\sigma_x^2}{x_{\max}^2} \right) - 0.4 + 6.02N + 9.03R \text{ dB}$$

$$G_T = 2^R$$

modulateur $\Sigma\Delta$ ordre 2



$$y(n) = x(n-1) + e(n) - 2e(n-1) + e(n-2)$$

$$Y(z) = z^{-1}X(z) + E(z)(1 - z^{-1})^2$$

$$\sigma_b^2 = \sigma_q^2 \frac{\pi^4}{5} \left(\frac{1}{G_T} \right)^5$$

$$RSB_q = 10 \log \left(\frac{\sigma_x^2}{x_{\max}^2} \right) - 8.1 + 6.02N + 15.05R \text{ dB}$$

$$G_T = 2^R$$

modulateur $\Sigma\Delta$ ordre M

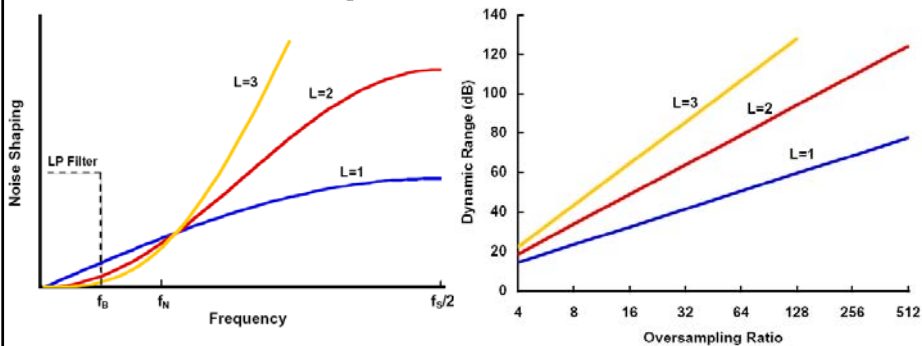
$$\sigma_b^2 = \sigma_q^2 \frac{\pi^{2M}}{2M+1} \left(\frac{1}{G_T} \right)^{2M+1}$$

$$RSB_q = 10 \log \left(\frac{\sigma_x^2}{x_{\max}^2} \right) + (4.77 - 10M + 10 \log(2M + 1)) + 6.02N + (6.02M + 3.01)R \text{ dB}$$

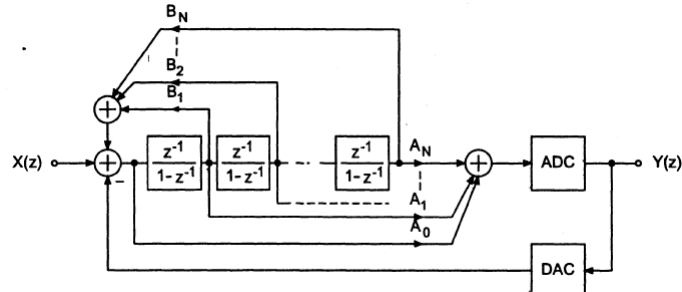
$$G_T = 2^R$$

modulateur $\Sigma\Delta$

$$Y(z) = z^{-1}X(z) + (1 - z^{-1})^L E_Q(z)$$



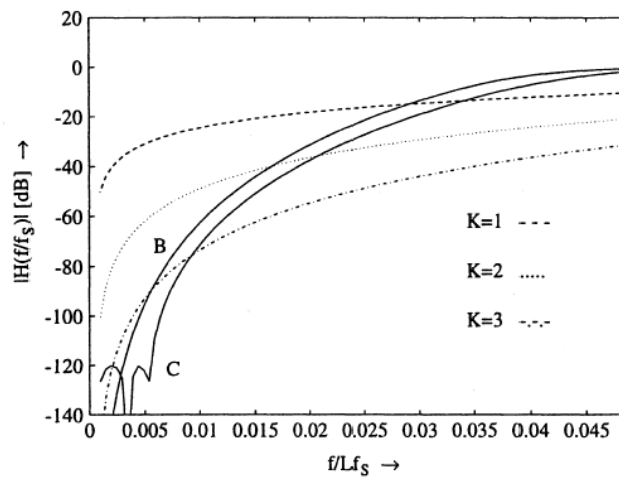
modulateur $\Sigma\Delta$



$$H(z) = \frac{\sum_{i=0}^N A_i (z-1)^{N-i}}{(z-1)^N - \sum_{i=1}^N B_i (z-1)^{N-i}}$$

$$Y(z) = \frac{H(z)}{1+H(z)} X(z) + \frac{1}{1+H(z)} E(z)$$

modulateur $\Sigma\Delta$ filtre de mise en forme



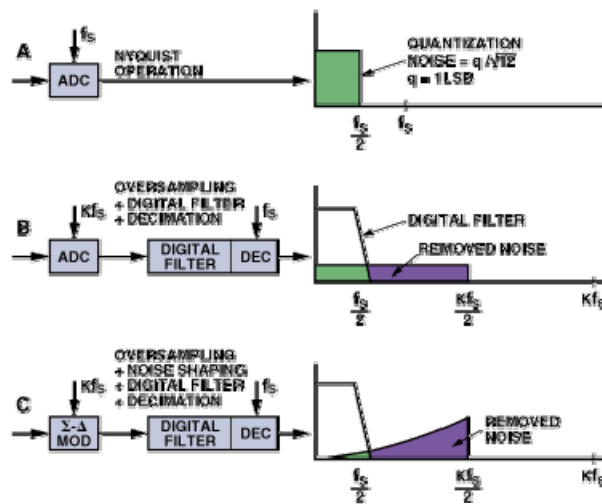
modulateur $\Sigma\Delta$

$$Y(z) = H_X(z)X(z) + H_E(z)E(z)$$

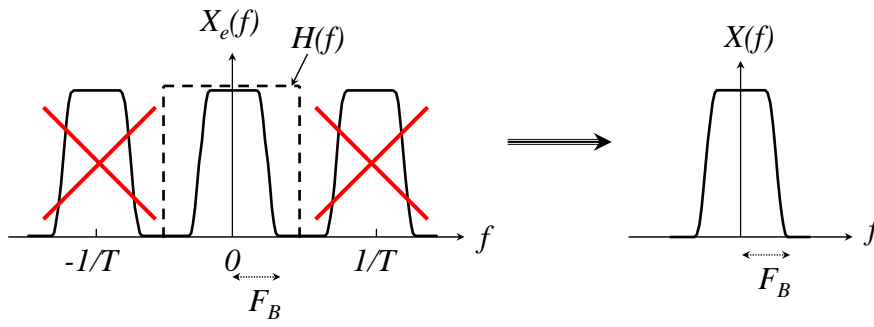
$$H_X(z) = \frac{\sum_{i=0}^N A_i(z-1)^{N-i}}{(z-1)^N - \sum_{i=1}^N B_i(z-1)^{N-i} + \sum_{i=0}^N A_i(z-1)^{N-i}}$$

$$H_E(z) = \frac{(z-1)^N - \sum_{i=1}^N B_i(z-1)^{N-i}}{(z-1)^N - \sum_{i=1}^N B_i(z-1)^{N-i} + \sum_{i=0}^N A_i(z-1)^{N-i}}$$

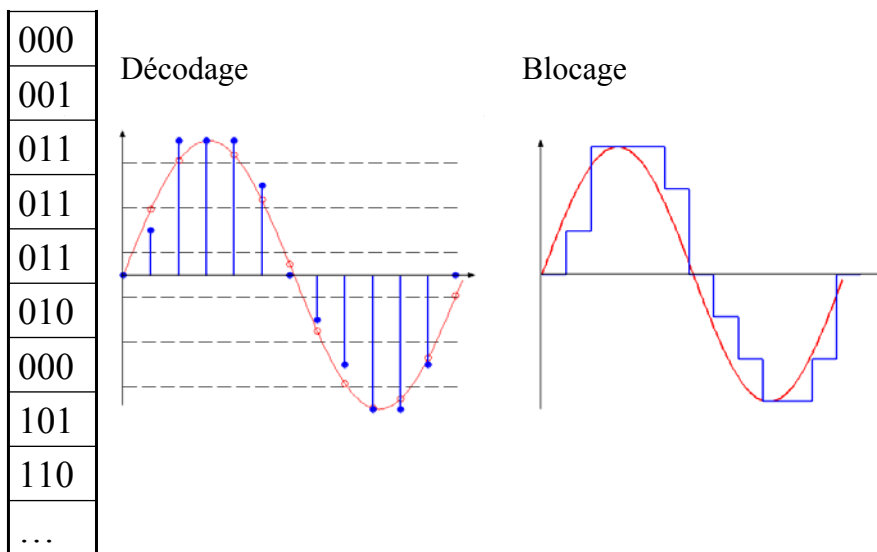
Résumé



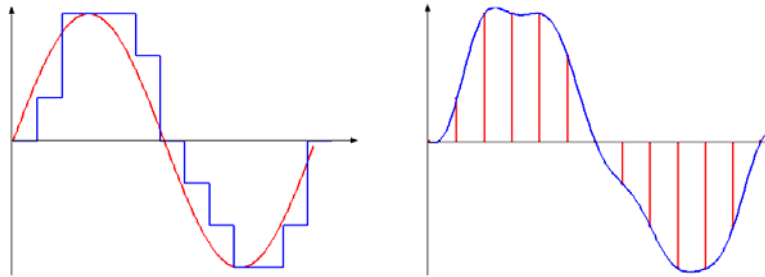
Reconstruction



Du numérique à l'analogique

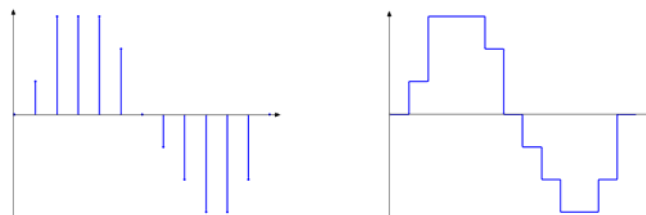
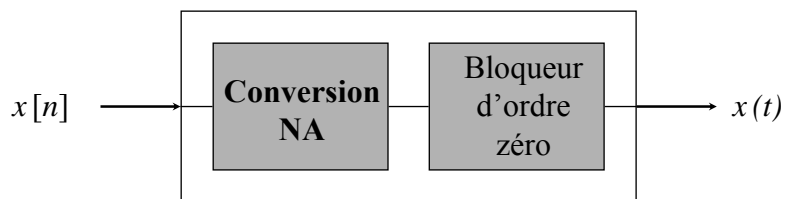


Lissage

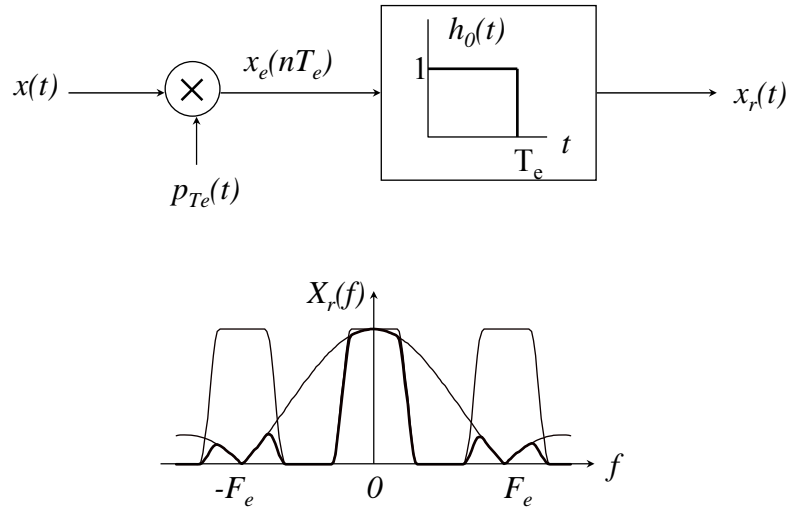


Convertisseur Numérique analogique

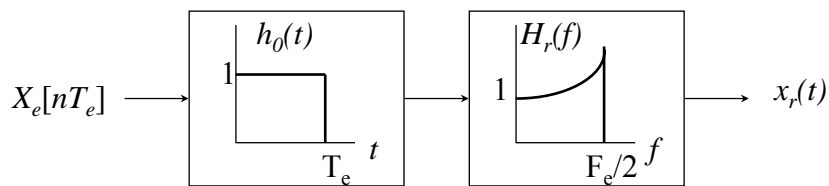
CNA



... suite

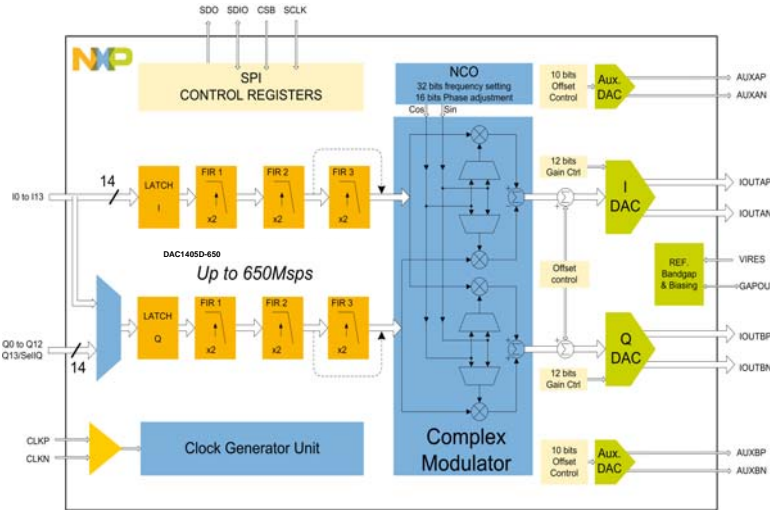


Filtre de lissage

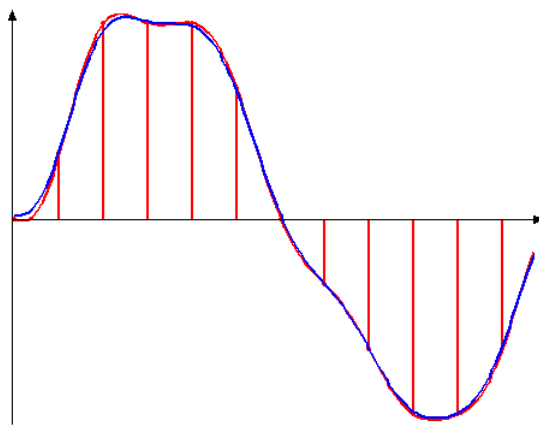


$$H_r(f) = \begin{cases} \frac{1}{\text{sinc}(T_e f)} & \text{pour } |f| \leq F_e/2, \\ 0 & \text{sinon.} \end{cases}$$

Interpolation DAC

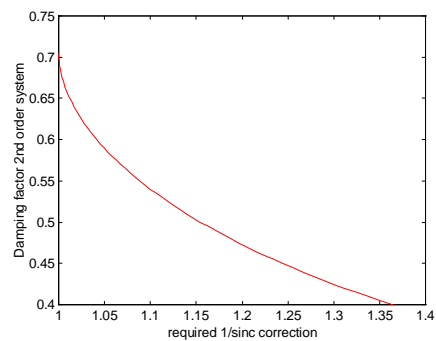
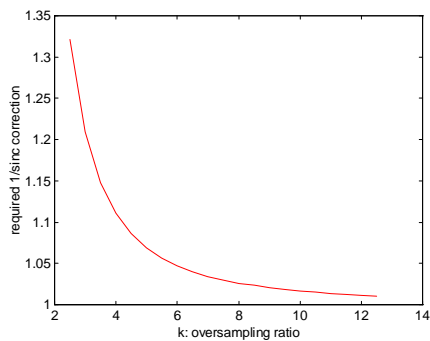


... suite



Abaques

- La correction en 1/sinc peut être approximée par la surtension d'une fonction de transfert d'ordre supérieur à 1



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57

Nombre de bits effectifs (ENOB)

- Le nombre de bits effectifs de précision dépend du RSB

$$RSB_q = 6.02N + A \text{ dB}$$

- Étant donné un RSB, la précision en nombre de bits du signal est :

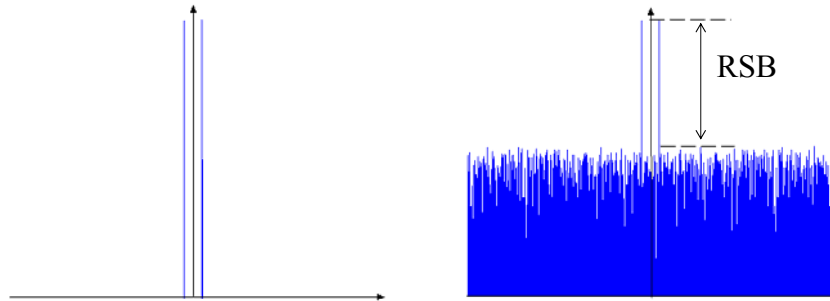
$$N = \frac{RSB - A}{6.02} \text{ bits}$$

- D'où l'importance de la mise en forme du bruit

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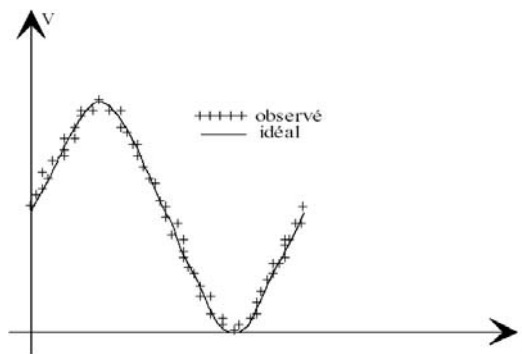
58

...ENOB



$$N_{ENOB} = \frac{RSB - 1.76}{6.02}$$

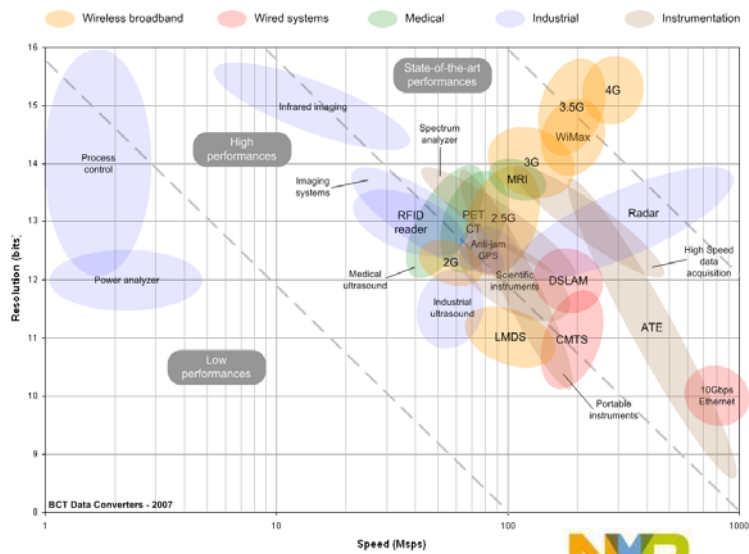
Ajustement de sinus



$$\sigma_e = \left(\frac{1}{N} \sum (x_{obs} - x_{id})^2 \right)^{1/2} \quad ENOB = N - \log_2 \left(\frac{\sigma_e}{q/\sqrt{12}} \right)$$

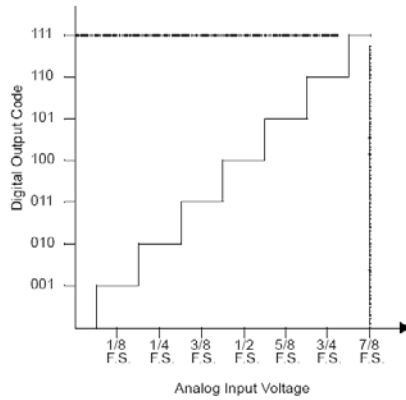
CAN

Les besoins et les moyens



Précision

- Résolution : $x_{min} = q = x_{max} / (2^N - 1)$
- N bits, 2^N états ; 12bits \rightarrow 1 bit = 0.0244% FS
- Temps de conversion : $T_s = 1/F_s$



Fonction de transfert d'un convertisseur analogique numérique

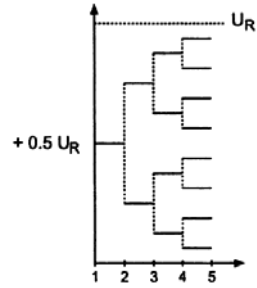
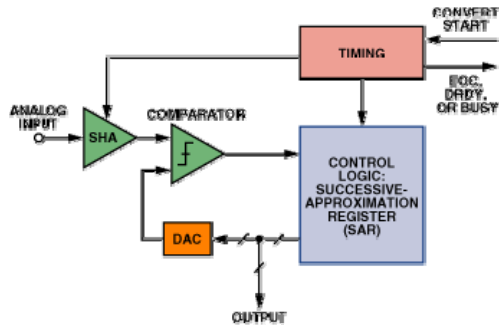
Précision

RESOLUTION N	2^N	VOLTAGE (10 V FS)	ppm FS	% FS	dB FS
2-bit	4	2.5 V	250,000	25	-12
4-bit	16	625 mV	62,500	6.25	-24
6-bit	64	156 mV	15,625	1.56	-36
8-bit	256	39.1 mV	3,906	0.39	-48
10-bit	1,024	9.77 mV (10 mV)	977	0.098	-60
12-bit	4,096	2.44 mV	244	0.024	-72
14-bit	16,384	610 μ V	61	0.0061	-84
16-bit	65,536	153 μ V	15	0.0015	-96
18-bit	262,144	38 μ V	4	0.0004	-108
20-bit	1,048,576	9.54 μ V (10 μ V)	1	0.0001	-120
22-bit	4,194,304	2.38 μ V	0.24	0.000024	-132
24-bit	16,777,216	596 nV*	0.06	0.000006	-144

NOTES: *600 nV is the Johnson Noise in a 10 kHz BW of a 2.2 k Ω Resistor @ 25°C

10 bits and 10 V FS yields an LSB of 10 mV, 1000 ppm, or 0.1%.
All other values may be calculated by powers of 2.

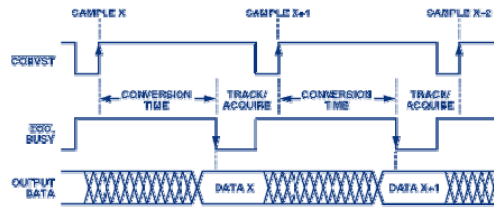
Successive approximation



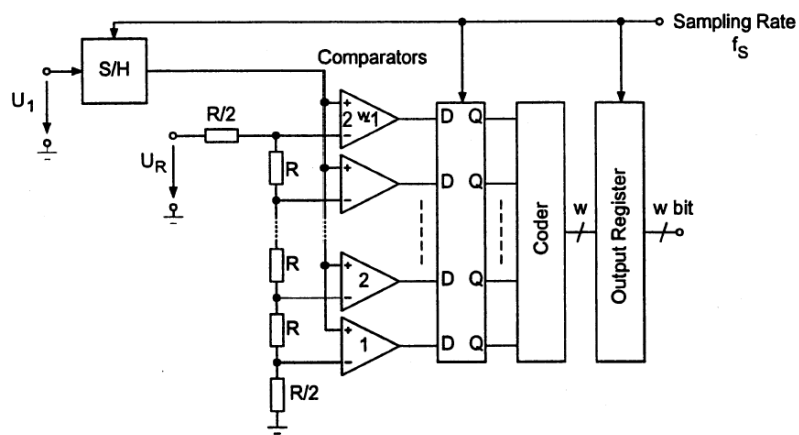
N cycles pour N bits

~ 16 bits @ ~ 3MHz

Bernard Gordon, at Epsco, introduced the first commercial vacuum-tube SAR ADC in 1954—an 11-bit, 50-kSPS ADC that dissipated 500 watts



Convertisseur Flash

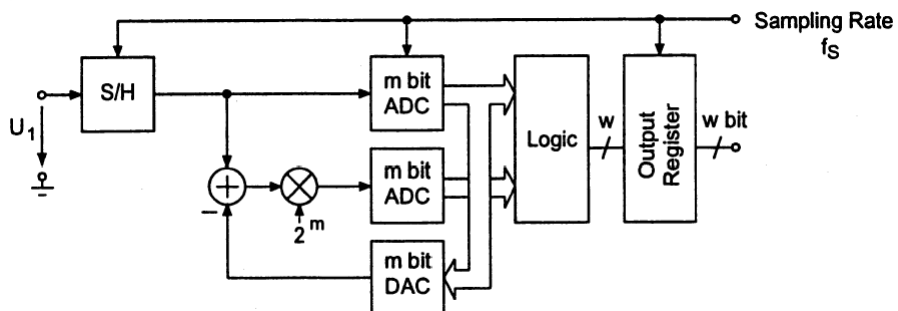


1 à 1500 MHz @ 8 à 10 bits max

Convertisseur Flash

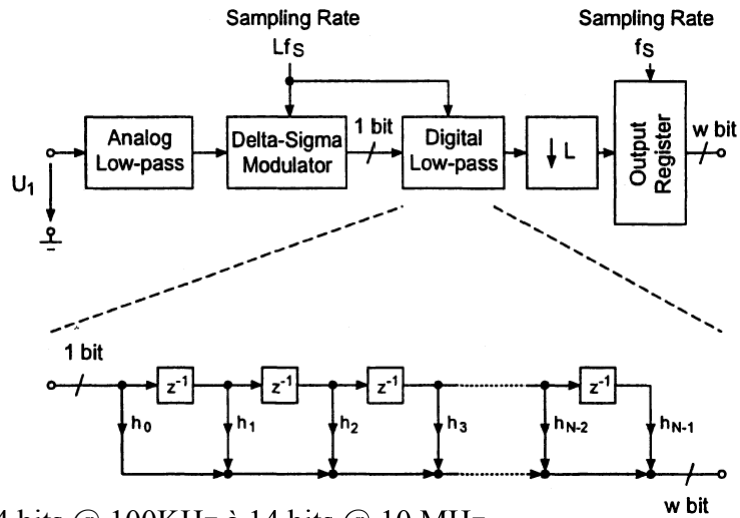
- 1 comparateur par valeur.
- N bits $\rightarrow 2^N - 1$ comparateurs.
- 1 cycle pour N bits
- +1 LSB \rightarrow taille circuit $\times 2$.
- +1 LSB \rightarrow ajustement composant $\times 2$ précis.
- Quelques watts ...

Convertisseur semi-flash



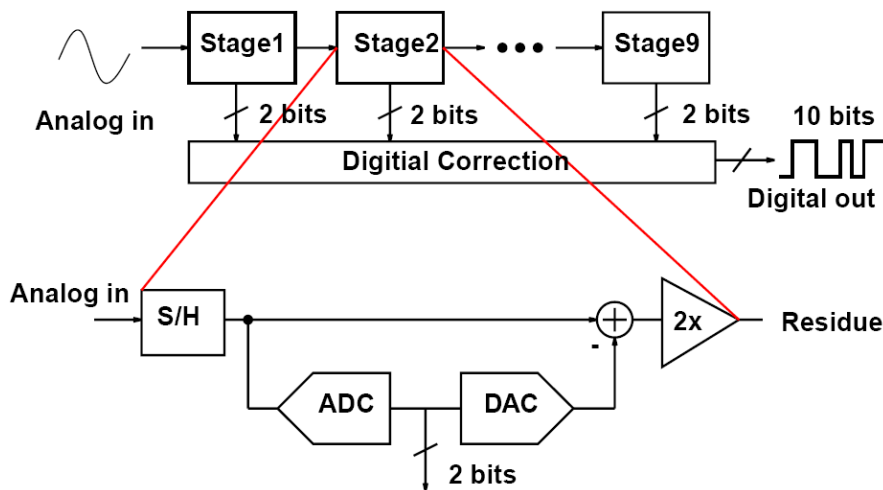
$$N = M + M \text{ bits} \rightarrow 2^{M+1} \text{ comparateurs}$$

Sigma-Delta



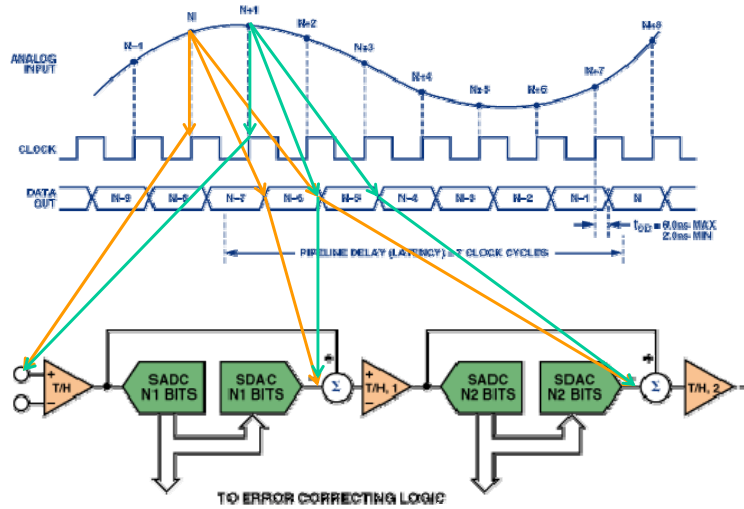
24 bits @ 100KHz à 14 bits @ 10 MHz

Pipeline

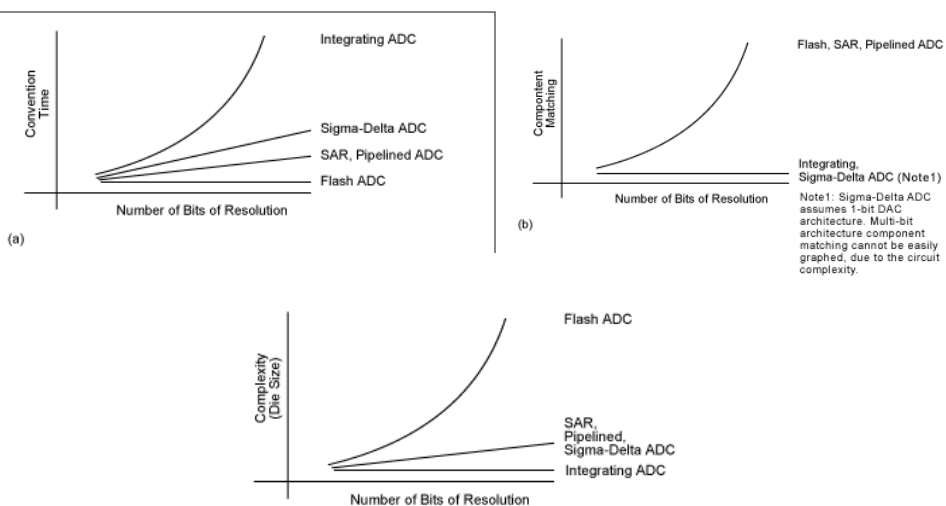


10 à 14 bits @ 150 MHz

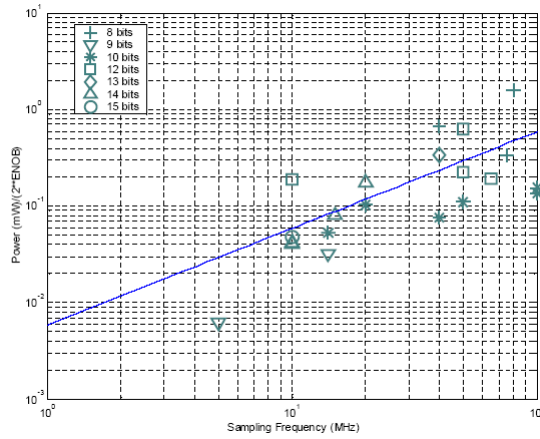
convertisseur Pipeline



Comparison



Consommation



Panorama

Texas Instruments










Resolution (Bits)	Sample Rate									
	< 100 SPS	100SPS to 1kSPS	1 to 10kSPS	10 to 100kSPS	100 to 500kSPS	500kSPS to 1MSPS	1 to 10MSPS	10 to 50MSPS	50 to 100MSPS	> 100MSPS
24	●	●	●	●	●					
22			●		●					
20	●			●						
18					●	●	●			
16		●		●	●	●	●	●		
13 / 14			●	●	●	●	●	●	●	●
11 / 12		●		●	●	●	●	●		●
10				●	●		●	●	●	
8				●	●		●	●	●	

Analog Devices

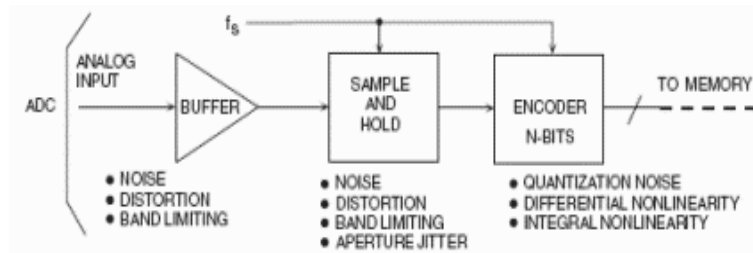
Resolution, Bits	Throughput Rate					
	<10 kSPS	10 kSPS to 100 kSPS	100 kSPS to 1 MSPS	1 MSPS to 10 MSPS	10 MSPS to 100 MSPS	100 MSPS +
17+	●	●	●	●		
14-16	●	●	●	●	●	●
12-13		●	●	●	●	●
10-11		●	●	●	●	●
8-9			●	●	●	●
<8					●	

Panorama

e2v
(ex ATMEL)

Device	Resol	SAR	IB	ENOB	SFDR	C	SPR	PD	P	DS
AT84AD004B	8-bit	500 Msp/s	1 GHz	7 bit	-58 dBc	2	1-1 1-2	1.4W	LQFP144	
AT84AD001B	8-bit	1 Gsp/s	1.5 GHz	7.4bit	-60 dBc	2	1-1 1-2	1.4W	LQFP144	
AT84AS003	10-bit	1.5 Gsp/s	3 GHz	>8bit	>60 dBc	1	1-2	6.5W	EBGA317	
AT84AS004	10-bit	2 Gsp/s	3 GHz	7.8bit	-55 dBc	1	1-2 1-4	6.5W	EBGA317	
TS83102G0B	10-bit	2 Gsp/s	3.3 GHz	8bit	-60 dBc	1	1-1	4.6W	CBGA 152	
TS83102G0BMGS	10-bit	2 Gsp/s	3.3 GHz	8bit	-60 dBc	1	1-1	4.6W	CI-CGA 152	
AT84AS008	10-bit	2.2 Gsp/s	3.3 GHz	>8bit	-58 dBc	1	1-1	4.2W	CI-CGA 152, CBGA 152	
AT84AS001	12-bit	500 Msp/s	1.5 GHz	12bit	72 dBc	1	1-1	2.3W	EBGA192	
EV8AQ160	8-bit	5 Gsp/s	2.5 GHz	7.5bit	52 dBc	4	1-1 1-2	3.9W	EBGA380	

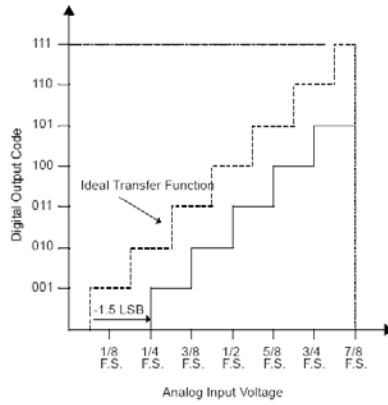
Caractéristiques et imperfections



- Caractéristiques statiques
 - la non-linéarité différentielle
 - la non-linéarité intégrale
 - l'erreur de décalage
 - l'erreur de gain
- Caractéristiques dynamiques
 - ...

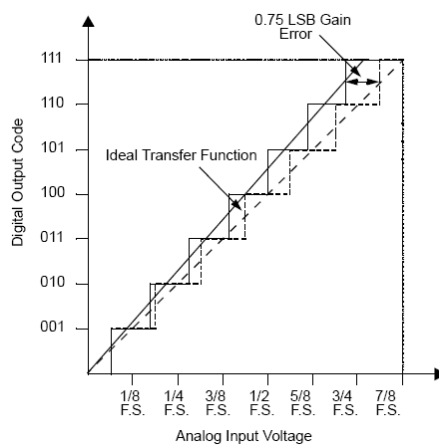
Erreur d'offset

- Écart entre la 1^{ère} transition et sa position théorique (0.5 LSB)

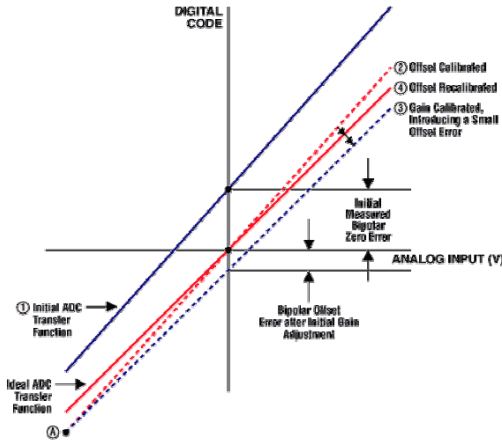


Erreur de gain

- Écart de pente par rapport au gain idéal (1)
- Unité : volt, % FS, LSB

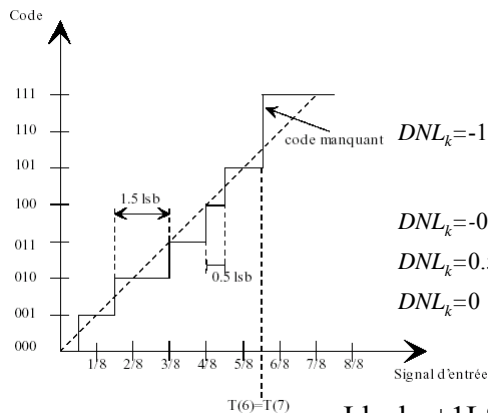


Calibration



Non linéarité différentielle (DNL)

- Écart relatif entre la valeur effective du pas q_i et la valeur théorique q .



$$DNL_k = \frac{q(k+1) - q(k) - q}{q}$$

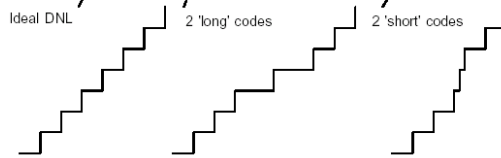
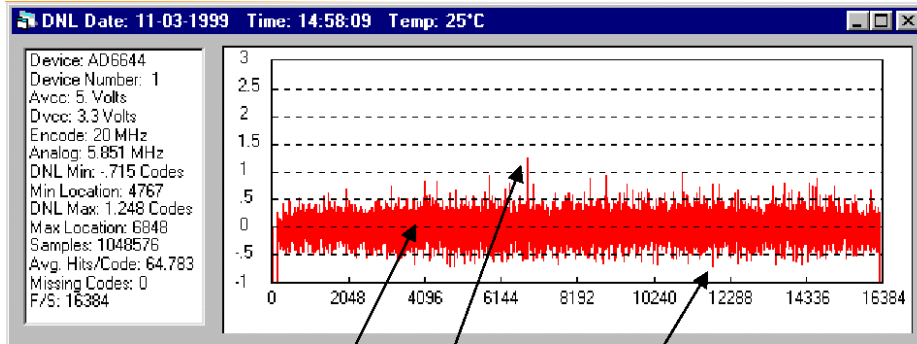
$$DNL = \max_k |DNL_k|$$

$$DNL_k = -0.5$$

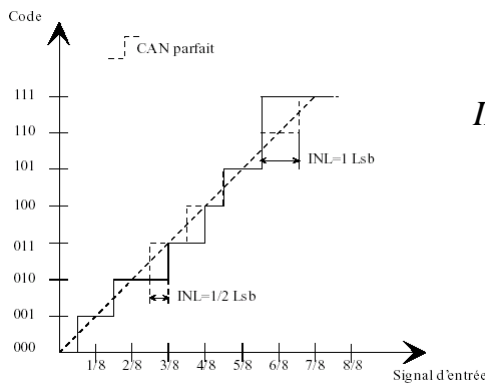
$$DNL_k = 0.5$$

$$DNL_k = 0$$

- Ideal : +1LSB FS => +1bit
- DNL > 1LSB => code manquant



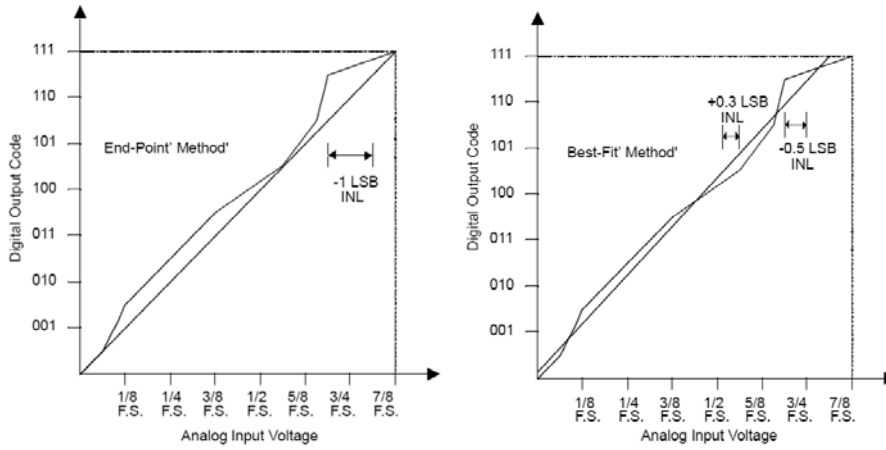
- Qualifie la forme générale d'une fonction de transfert
- $E(k)$: écart entre la transition et la droite de gain



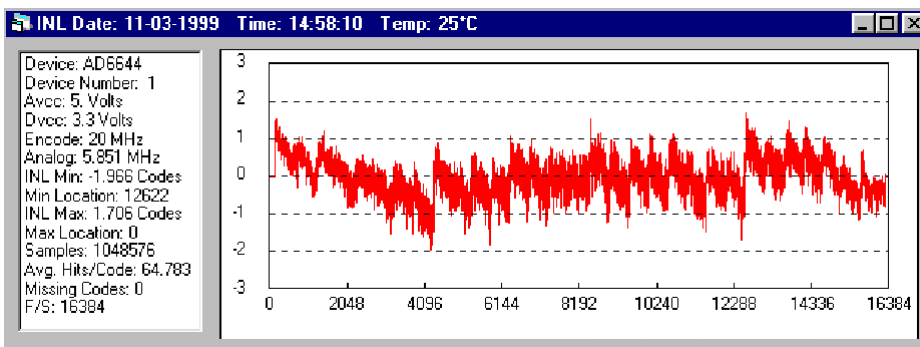
$$INL(k) = E(k) - 1/2LSB$$

$$INL(i) = \sum_{j < i} \frac{\Delta q_j}{q} = \sum_{j < i} DNL(j)$$

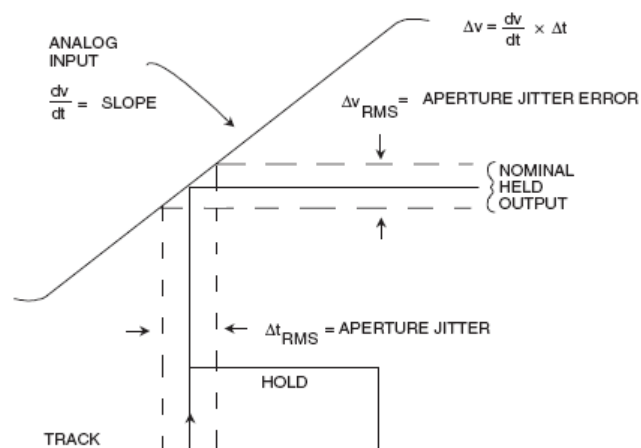
2 mesures ...



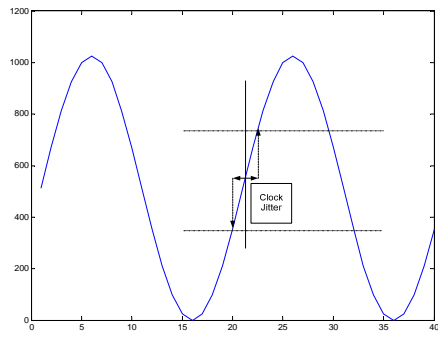
INL



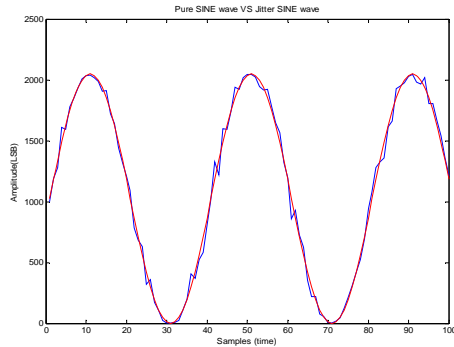
- Signal ou signaux de test:
 - Gigue à l'ouverture
 - Taux de distorsion harmonique
 - Distorsion d'intermodulation
 - SFDR



Gigue à l'ouverture



gigue



Avec et sans gigue

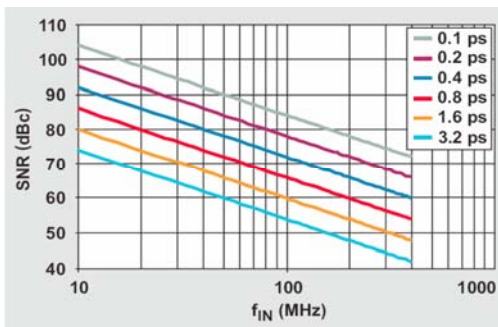
Gigue à l'ouverture

- Gigue à l'ouverture : t_g

$$RSB_g = -20 \log(2\pi f t_g)$$

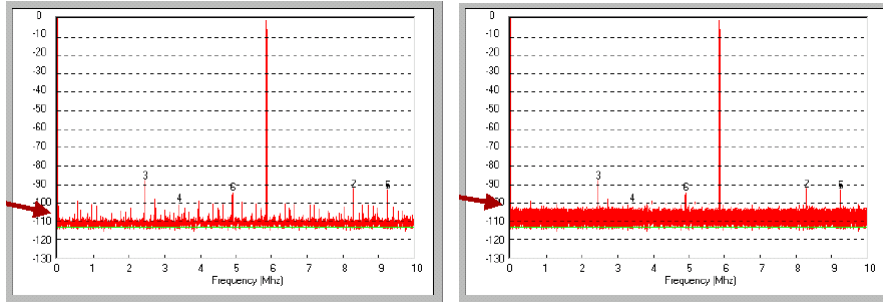
- La gigue et la fréquence du signal d'entrée étant données, la résolution max est :

$$N = \log_2 \left(\frac{2}{\sqrt{3} \pi f t_g} \right) - 1$$



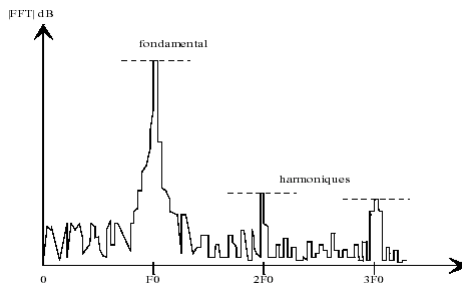
Gigue à l'ouverture

Produit une remontée du plancher de bruit



Distorsion harmonique

- Non linéarité du composant

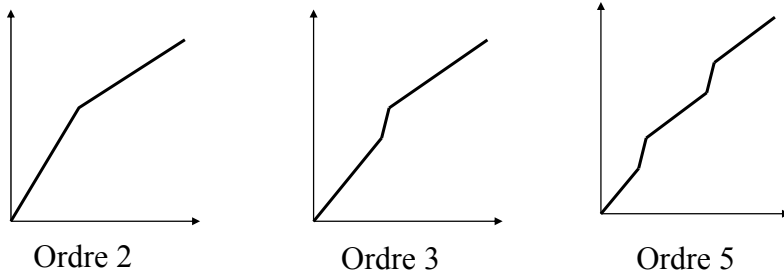


$$THD_{dB} = 20 \log \left(\frac{V_{f_2}^2 + V_{f_3}^2 + \dots + V_{f_n}^2}{V_{f_1}^2} \right)^{1/2}$$

- Interférence large bande

INL et distorsion

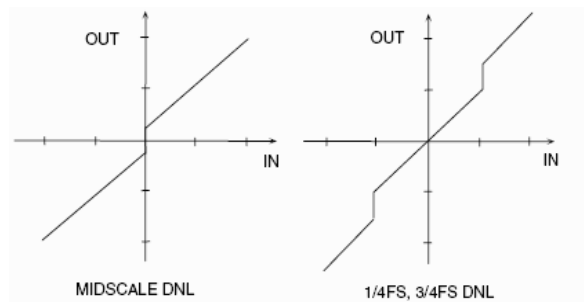
Fonction de transfert du convertisseur



$$V_{out} = K_0 + K_1 V_{in} + K_2 V_{in}^2 + K_3 V_{in}^3 + \dots$$

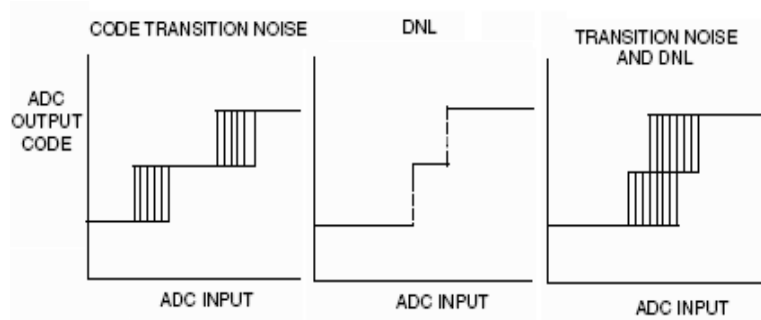
Les coefficients dépendent de la dynamique du signal !

INL et DNL



- Pleine échelle : le cumul des non linéarités -> INL
- Petite échelle : DNL peut-être dominant, pas de proportionnalité amplitude/distorsion

DNL+gigue



- fct de transfert : non bijective autour des zones de transition

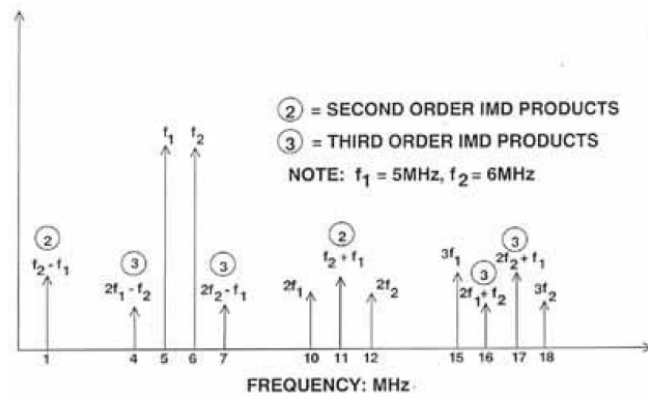
Distorsion d'intermodulation

- 2 signaux tests f_a et f_b :
 - non linéarité à l'ordre 2
 - $(f_a + f_b)$ et $(f_a - f_b)$
 - non linéarité à l'ordre 3
 - $(2f_a + f_b)$, $(f_a + 2f_b)$, $(2f_a - f_b)$ et $(2f_b - f_a)$

$$IMD_{dB} = 20 \log \left(\frac{\sum_{i,j} V_{ij}^2}{V_a^2 + V_b^2} \right)^{1/2}$$

- Interférence Bande étroite

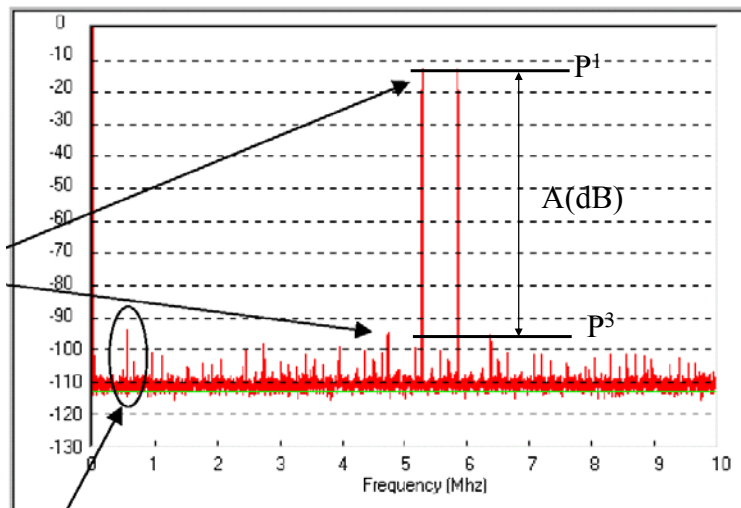
ESIEE Distorsion d'intermodulation



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101

ESIEE IMD



Ordre 3

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102

IP3

$$IP3 = P^1 + \frac{A}{2}$$

$$P^1 = -12dBm, P^3 = -96dBm,$$

$$A = (P^1 - P^3) = 84dB \Rightarrow IP3 = 30dBm$$

SFDR

- Spurious free dynamic range
- Contribution de toutes les sources d'imperfections

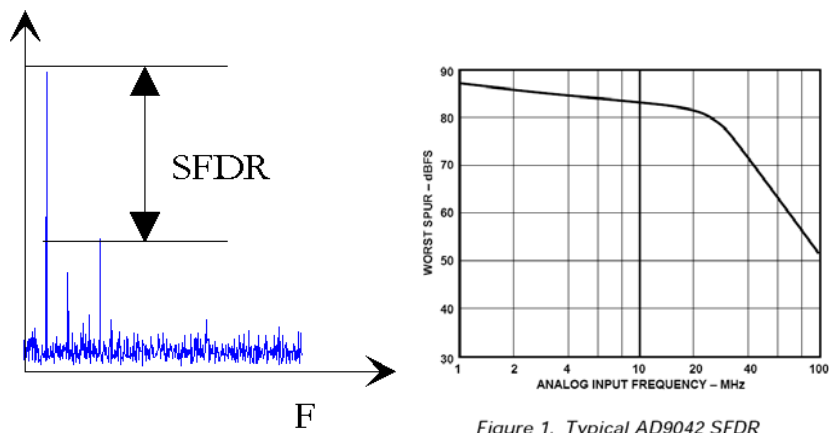
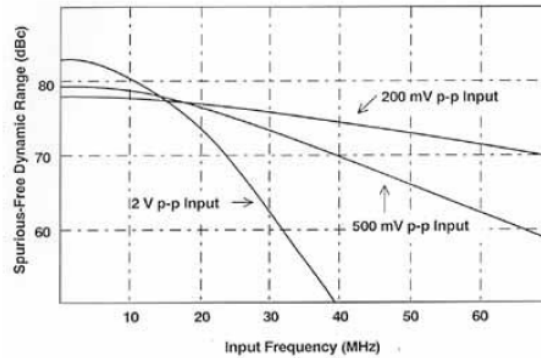


Figure 1. Typical AD9042 SFDR

SFDR

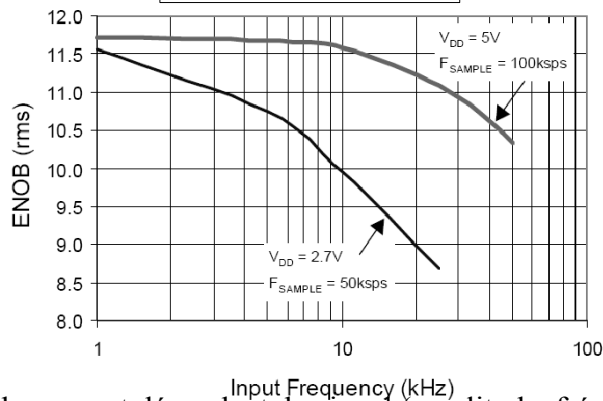
AD9100 HOLD-MODE SFDR MEASURED AT A SAMPLING RATE OF 10MSPS



Dépend du signal.
 Difficulté de qualifier un composant pour les modulations à enveloppe non constante.

SFDR -> ENOB

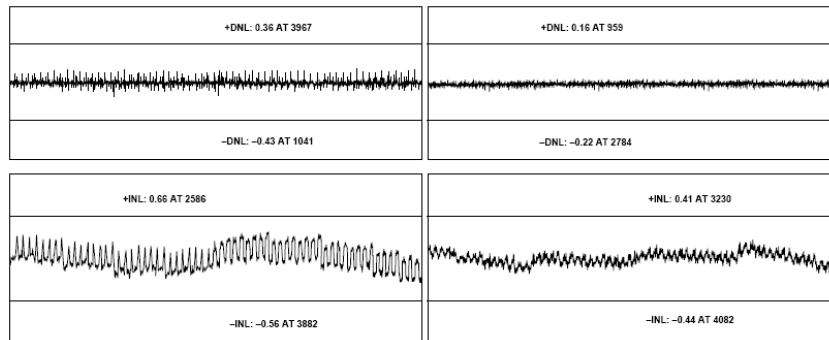
$$N_{ENOB} = \frac{RSB - 1.76}{6.02}$$



SFDR largement dépendant du signal (amplitude, fréquence, largeur de bande).

Subranging converter répétition et cumuls des défauts

AD 9042



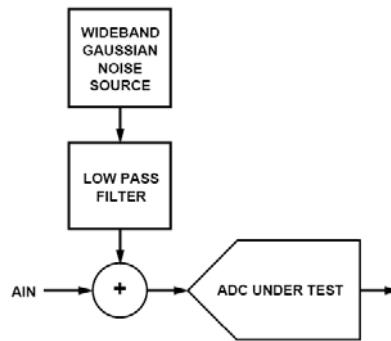
DNL -> SFDR

SFDR et C/I

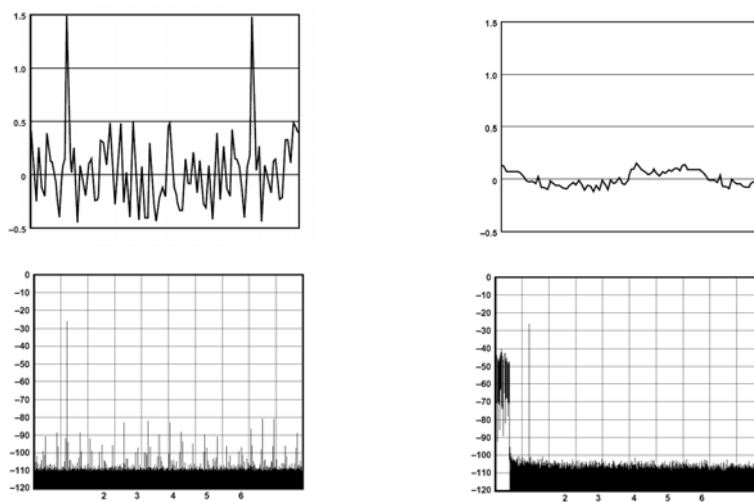
- Caractéristique convertisseur :
 - Pleine échelle : 4.8 dBm.
 - SFDR : -90 dBFS
- Spécifications :
 - C/I : 18 dB
 - Gain de l'antenne au convertisseur : 25 dB
- Sensibilité à l'antenne :
 - $[[[FS+SFDR]-G]+C/I] = -92.2 \text{ dBm}$

Dithering

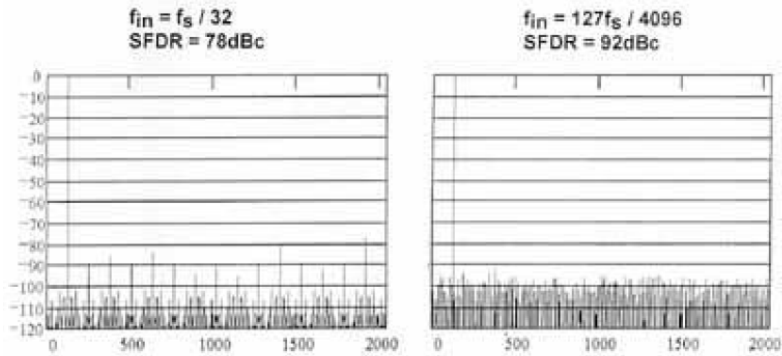
- La solution : ajouter du bruit !



DNL et SFDR



Corrélation bruit de quantification



« Dithering » large bande

Rapport signal sur bruit

$$Bruit_{CAN} = 20 \log \left[(2\pi f t_g)^2 + \left(\frac{1 + \epsilon}{2^N} \right)^2 + \left(\frac{2\sqrt{2}V_{noise}}{2^N} \right)^2 \right]^{1/2}$$

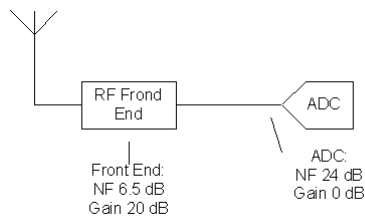
- f : Fréquence signal IF
- t_g : gigue à l'ouverture (rms)
- ϵ : DNL moyen (LSB)
- V_{noise} : bruit thermique (LSB)
- N nombre de bit

Rapport signal sur bruit pour un sinus

$$RSB = 1.76 + 6.02N \Rightarrow 1.76 - Bruit_{CAN}$$

Facteur de bruit

- Puissance d'entrée pleine échelle
- Impédance de terminaison
- Fréquence d'échantillonnage
- Rapport signal sur bruit



Facteur de bruit ADC

$$F = \frac{RSB_{in}}{RSB_{out}} = \frac{P_{sig}/N_{in}}{P_{sig}/N_{out}} = \frac{N_{out}}{N_{in}} \text{ avec } G = 1$$

$$N_{in} = -174 \text{ dBm/Hz}$$

$$N_{out} = P_{sig} - RSB - 10 \log \left(\frac{F_e}{2} \right) \text{ dBm/Hz}$$

$$P_{sig} = 10 \log \left(\frac{V_{rms}^2 / Z_{in}}{10^{-3}} \right)$$

Facteur de bruit

$$\left. \begin{array}{l} \bullet V_{rms}=0.707 \text{ V, } Z_{in}=200 \Omega, P_{sig}=4 \text{ dBm} \\ \bullet RSB=78 \text{ dB} \\ \bullet F_e=80 \text{ MHz} \end{array} \right\} N_{out} = -150 \text{ dBm/Hz}$$

$$F = -150 + 174 = 24 \text{ dB}$$

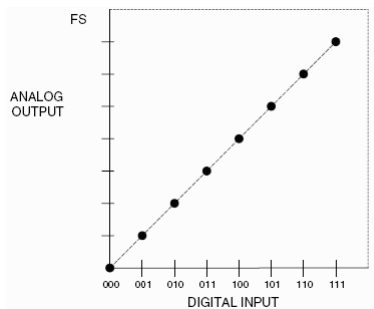
$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} = 4.467 + \frac{251.2 - 1}{100} = 6.969 = 8.4 \text{ dB}$$

Convertisseur numérique-analogique

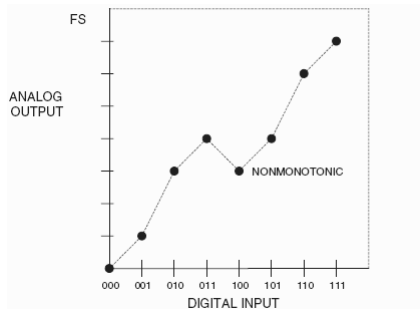
Imperfections

- DNL
- Temps d'établissement
- Glitch
- Distorsion
- SFDR

DNL

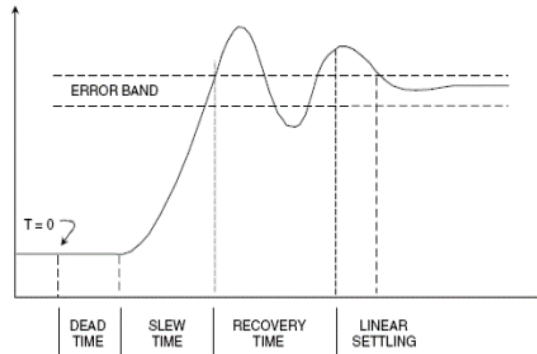


Ideal : +1bit => +1LSB FS



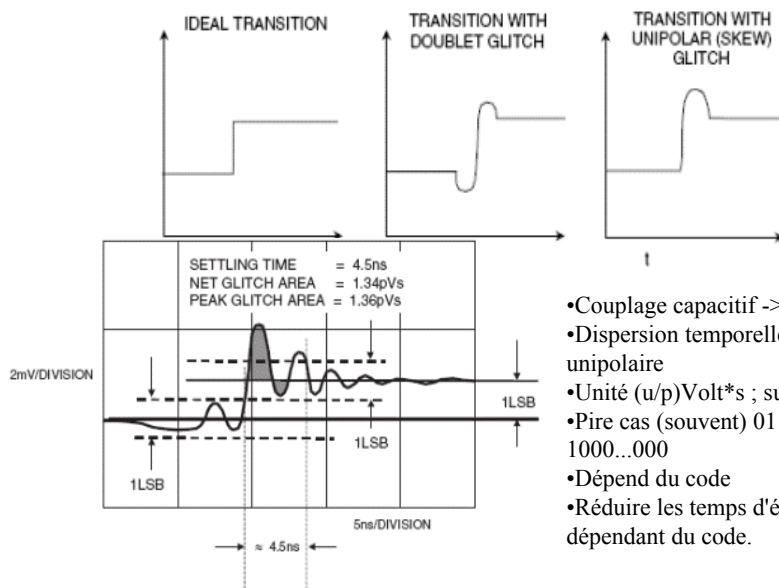
DNL > 1LSB => non monotonique

Temps d'établissement



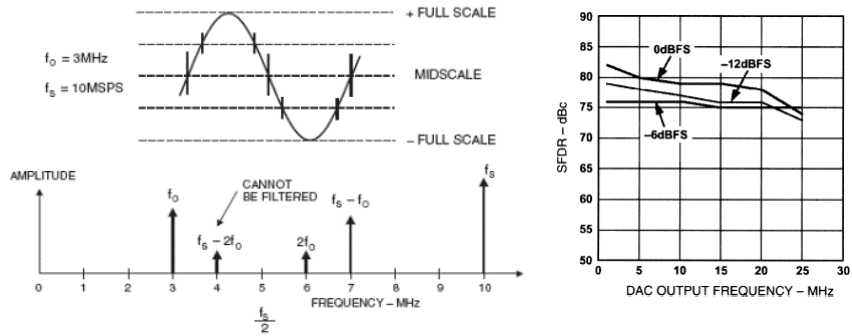
- Error Band = $\pm 1/2$ ou 1 LSB
- Slew time \ll autres temps

Glitch de commutation



- Couplage capacitif \rightarrow bipolaire
- Dispersion temporelle \rightarrow unipolaire
- Unité (u/p) Volt*s ; surface.
- Pire cas (souvent) 0111...111 \rightarrow 1000...000
- Dépend du code
- Réduire les temps d'établissement dépendant du code.

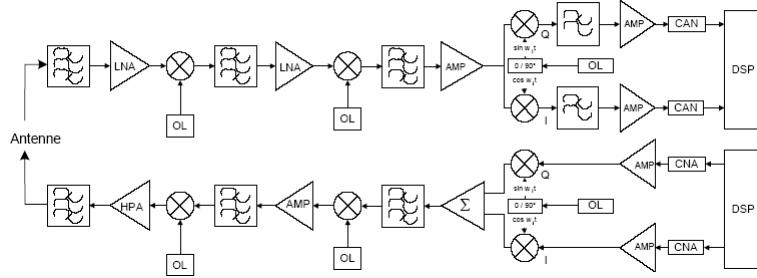
Distorsion - SFDR



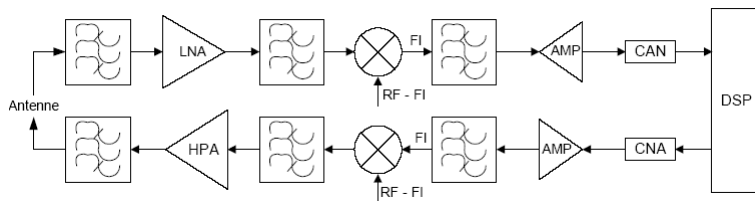
Radio logicielle

introduction

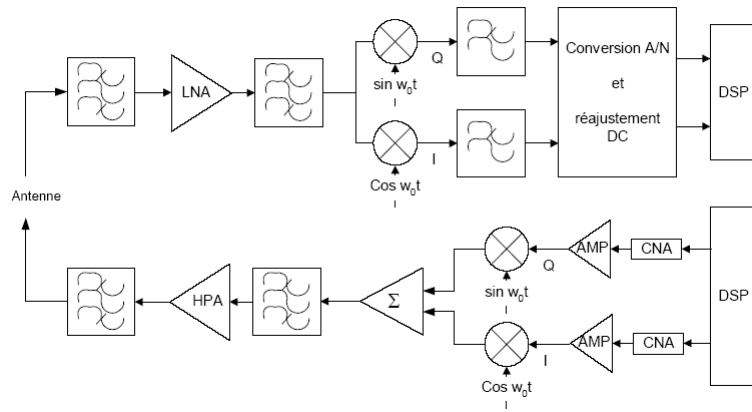
Superheterodyne



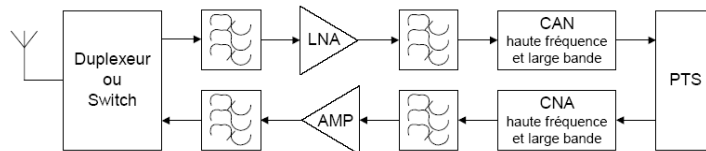
Emission/Réception FI basse fréquence



Conversion directe

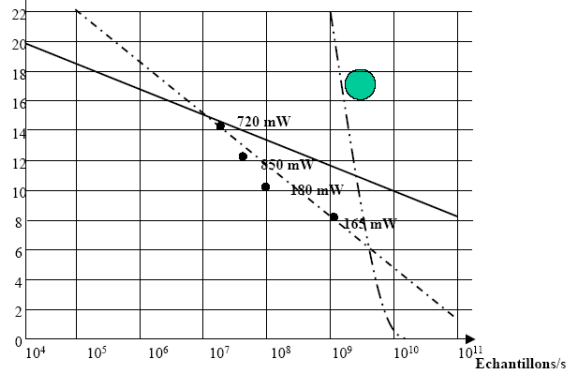


Radio logicielle idéale



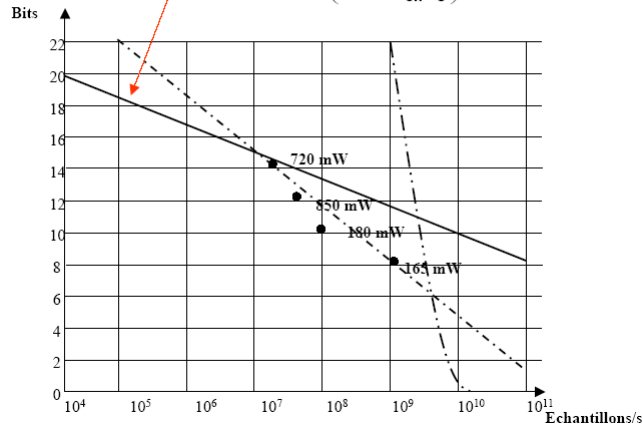
$F_e > 2\text{GHz}$ et $ENOB > 16$ bits

- Fe élevée
- SFDR
- Linéarité
- Nb de bits
- Fe 5 GHz



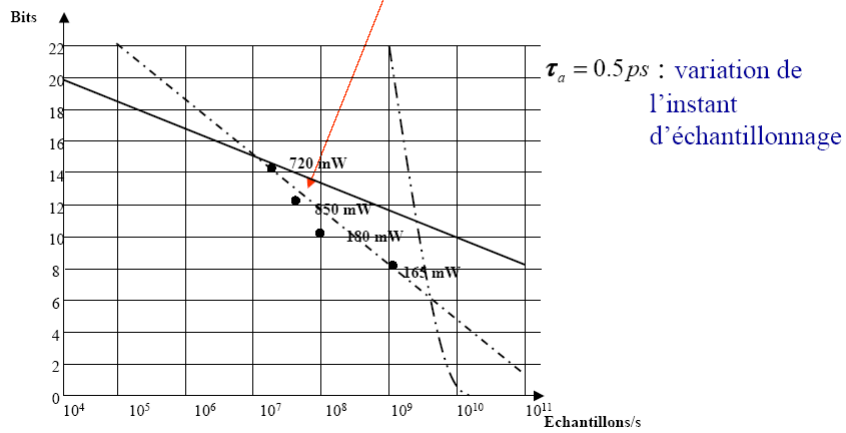
Les limites des CAN

Bruit thermique : $\log_2 \left(\frac{V_{FS}^2}{6kTR_{eff}F_s} \right)^{1/2} - 1.$



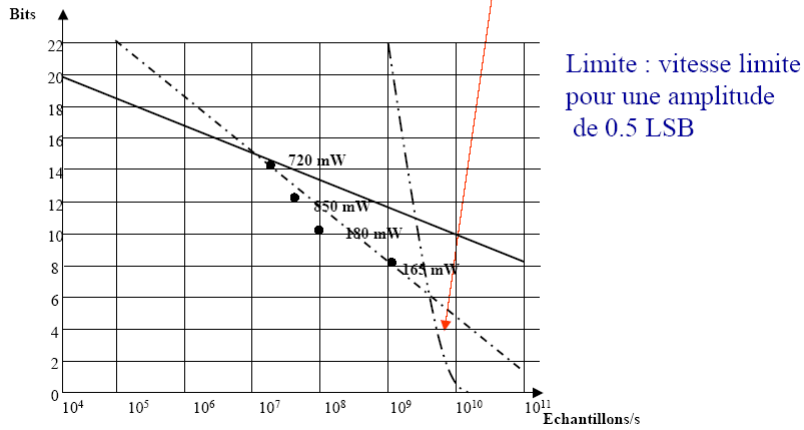
Les limites des CAN

Erreur sur l'instant d'échantillonnage : $\log_2 \left(\frac{2}{\sqrt{3\pi}F_s\tau_a} \right) - 1.$

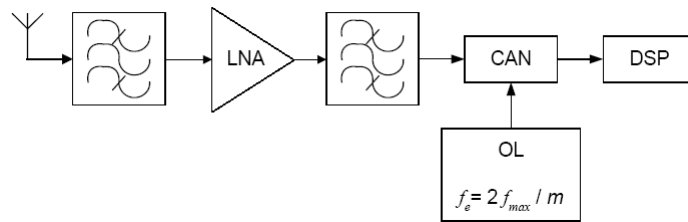


Les limites des CAN

Effet du comparateur : $\frac{\pi f_T}{7F_s} - 1.1.$

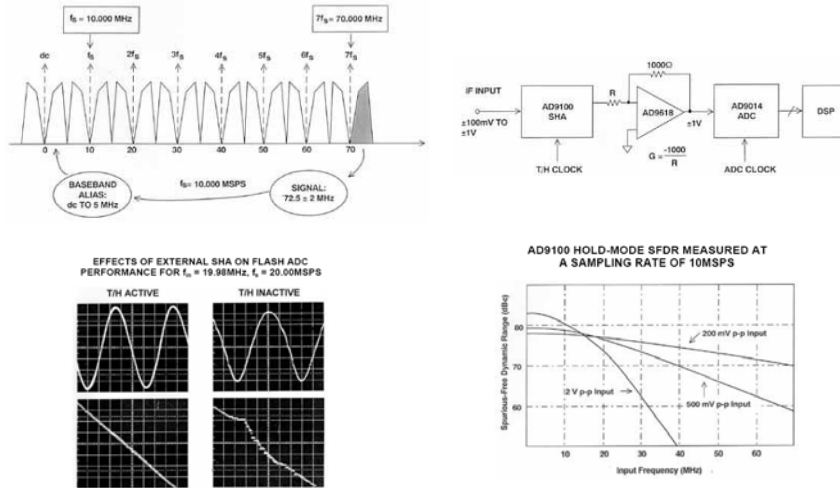


Réception Sous échantillonnage

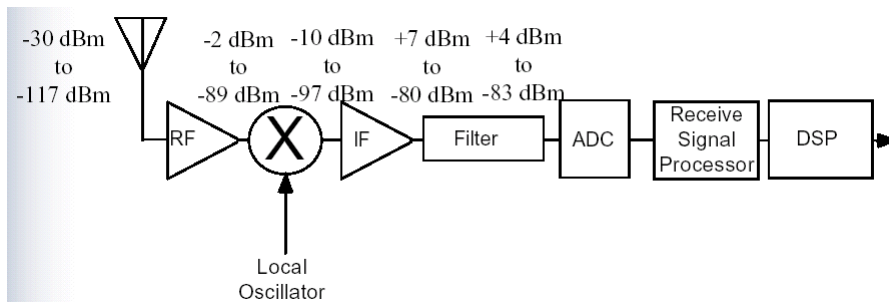


Difficile en RF, possible en FI
 Fe 5 GHz

Sous échantillonnage



Chaîne de réception

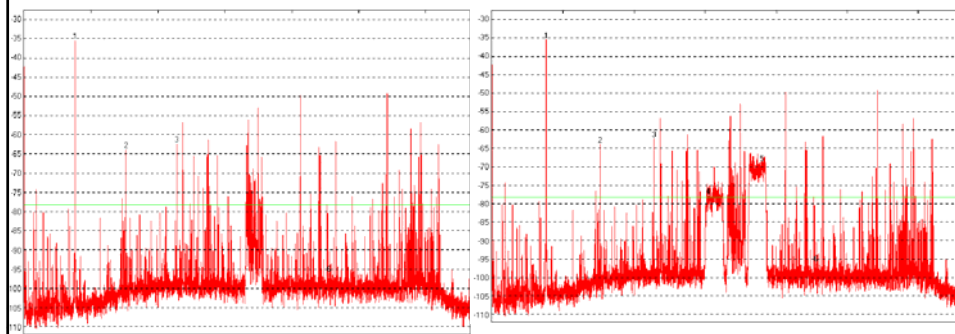


Dynamique ~90dB + marge de garde

Applications	f_{RF}	f_{IF}
GSM	900 MHz	71 MHz
PCS	1900 MHz	100 MHz
NADC	900 MHz	100 MHz
WLAN	2500 MHz	350 MHz
DECT	1900 MHz	240 MHz
GPS	1570 MHz	170 MHz

- GSM450
- GSM900
- DCS1800/PCS1900
- UMTS bands I – VII (ranging from 869MHz to 2690MHz for BTS Tx)
- WiMAX bands from 2.3-2.7GHz and 3.3-3.8GHz.

Le spectre radio



Radio analogique

+Radio numérique

Références & Sources

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- *Mesures temporelles et conversion analogique-numérique - P. Nayman - CNRS-IN2P3*
- *Digital Audio Signal Processing – Udo Zolzer - Wiley*
- *Cascaded Noise-Shaping Modulators for Oversampled Data Conversion – B. Wooley – standford*
- *Pipeline Analog-to-Digital Converters for Wide-Band Wireless Communications - Lauri Sumanen*
- *Numérisation du signal radio - Patrick Loumeau – ENST Comelec*
- *Architecture Emission- Réception – J.Palicot – FT R&D*
- *Analog devices – Brad Brannon - <http://www.converter-radio.com/index.htm>*
- *Notes d'application : Analog devices, Maxim, Microchip, ...*