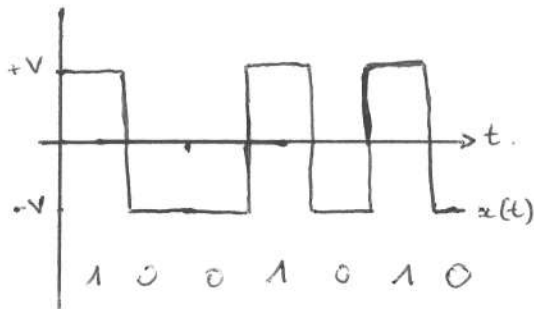


# 1 Codage numérique en bande de base.

## 1.1 Codage NRZ.

1.

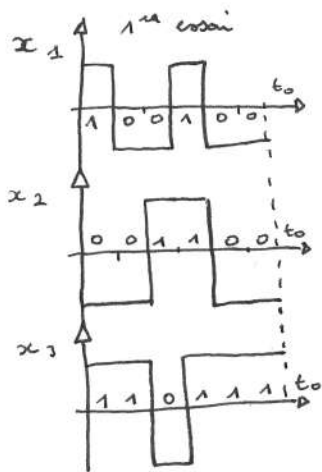


La fonction est aléatoire, quantifiée

→ 2 valeurs possibles.

Le signal est stationnaire.

$$\bar{x}(t) = \lim_{T \rightarrow \infty} \left\{ \frac{1}{T} \int_{-T/2}^{T/2} x(t) dt \right\} : \text{moyenne temporelle.}$$



$$E(x(t_0)) = p_0(-V) + p_1(+V) = 0$$

↑ Espérance ou moyenne statistique  
 $p_0 = 1/2$   
 $p_1 = 1/2$

2.

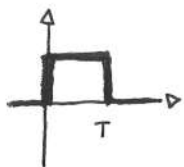
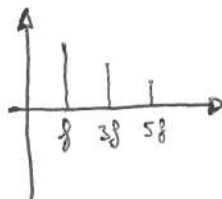
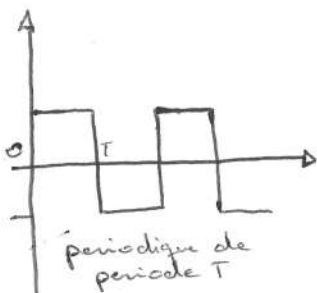


Table de Codage.

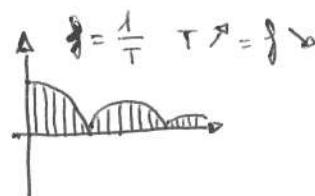
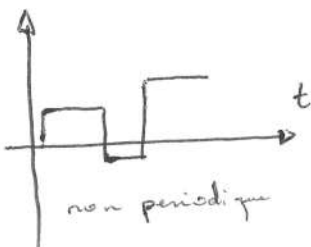
| $\alpha k$ | $a_k$ | $a_k x_g \leftarrow "t=kT"$ |
|------------|-------|-----------------------------|
| 0          | -1    | -V                          |
| 1          | +1    | +V                          |

3.



$$G(f) = \int_{-\infty}^{+\infty} g(t) e^{-j2\pi f t} dt$$

paramètre d'intégration



$$\begin{aligned}
 G(f) &= \int_0^T V e^{-j2\pi f t} dt \\
 &= \frac{-V}{2\pi j f} \left[ e^{-j2\pi f t} \right]_0^T \\
 &= \frac{-V}{2\pi j f} \left[ e^{-j2\pi f T} - 1 \right] \\
 &= \frac{-V}{2\pi j f} \left[ e^{-j\pi f T} (e^{-j\pi f T} - e^{+j\pi f T}) \right]
 \end{aligned}$$

$$\text{sinc}(x) = \frac{\sin x}{x}$$

$$e^{j\theta} = \cos \theta + j \sin \theta \quad (1)$$

$$e^{-j\theta} = \cos \theta - j \sin \theta \quad (2)$$

~~(1) (2)~~

$$G(f) = \frac{-V}{\pi f} e^{-j\pi f T} \left[ \frac{e^{-j\pi f T} - e^{+j\pi f T}}{2j} \right]$$

$$= \frac{V}{\pi f} e^{-j\pi f T} \sin(\pi f T)$$

$$G(f) = T V e^{-j\pi f T} \times \frac{\sin \pi f T}{\pi f T}$$

$$= V e^{-j\pi f T} \text{sinc}(\pi f T)$$

$$|G(f)| = VT \times 1 \times |\text{sinc}(\pi f T)|$$

$$S_{gg}(f) = |G(f)|^2$$

$$S_{gg}(f) = V^2 T^2 \text{sinc}^2(\pi f T)$$

1.1.4.

$$S_{xx}(f) = S_{gg}(f) * \left[ \frac{G_a^2}{T} + \frac{m_a^2}{T^2} \times \Delta_{\frac{1}{T}}(f) \right]$$

← formule de benett simplifiée.

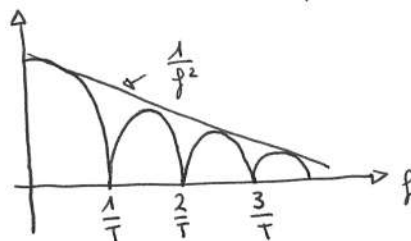
$$m_a = 0$$

$$G_a^2 = E(a k^2 - m_a^2)$$

$$= 1$$

$$S_{xx}(f) = V^2 T^2 \text{sinc}^2(\pi f T) \times \frac{1}{T} = V^2 T \text{sinc}^2(\pi f T) \Big|_{p_0 = \frac{1}{2}}^{p_1 = \frac{1}{2}}$$

$$P_{\text{moy}} = \int_{-\infty}^{+\infty} S_{xx}(f) \cdot df$$



1.1.5.

le spectre s'étend jusqu'à l'infini  $\Rightarrow$  filtrage nécessaire.

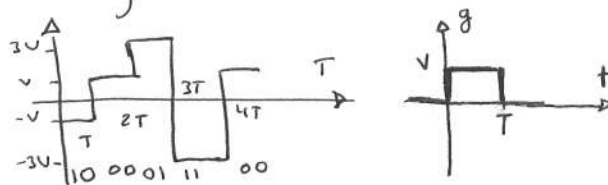
## 1.2 Codage 2 Binaire 1 quaternaire - NRZ

## Table de codage

|              | mot binaire | $b_k$ |
|--------------|-------------|-------|
| Code de Gray | 11          | -3    |
|              | 10          | -1    |
|              | 00          | +1    |
|              | 01          | +3    |

Le code de Gray permet de minimiser la probabilité d'erreur à la détection.

Deux symboles binaires ( $b_k$ ) voisins ne sont séparés que par 1 bit.



$$S_{xx}(f) = |G(f)|^2 \times \left[ \frac{6a^2}{T} + \frac{ma^2}{T^2} \times \sum \delta\left(f - \frac{k}{T}\right) \right]$$

Formule de Bennett simplifiée utilisée dans le cas où les symboles binaires ( $b_k$ ) sont équivalents.

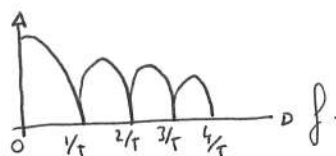
$$ma = \frac{-3 + (-1) + 1 + 3}{4} = 0$$

$$6a^2 = \frac{E(b_k^2) - E(ma^2)}{4} = \frac{(-3)^2 + (-1)^2 + 1^2 + 3^2}{4} = 5$$

$$S_{xx}(f) = |G(f)|^2 = v^2 T^2 \times \text{sinc}^2(\pi f T)$$

$$S_{xx}(f) = v^2 T^2 \text{sinc}^2(\pi f T) \times \frac{5}{T} = 5v^2 T \text{sinc}^2(\pi f T)$$

d'allure de  $S_{xx}(f)$  est inchangée



NRZ : 1 bit sur 1 période

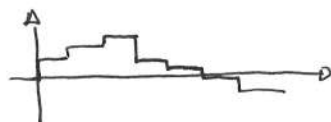
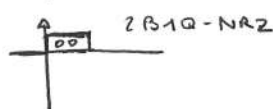
2B 1Q-NRZ : 2 bits sur 1 période

-> Le débit binaire est doublé mais le spectre de  $S_{xx}(f)$  est inchangé.

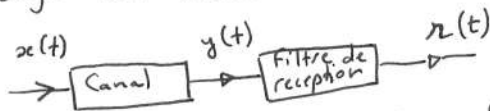
4. Le code 2B 1Q-NRZ est un code de type M-vaient (M: nombre de symboles) avec  $M=4$ .

Rappel :  $M=2^n$  -> nombre de bits par symbole.

$$M \Rightarrow \begin{matrix} D \\ P \text{ et } b \end{matrix}$$



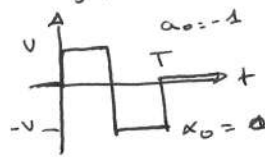
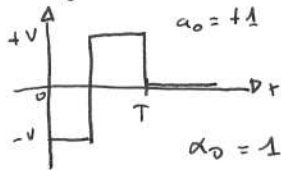
## Sujet 2: Transmission sur canal bruité



1. Energie d'un signal réel  $s(t)$  est:

$$E = \int_{-\infty}^{+\infty} s^2(t) dt \quad y(t) = \sum_k a_k \underbrace{g(t-kT)}_{\substack{\text{signal reçu} \\ \text{pour 1 bit} \\ \text{à } t=kT}} + \underbrace{n(t)}_{\text{bruit}}$$

Pour  $t=0$  le signal reçu est  $a_0 g(t)$  pour 1 bit.



$$E = \int_{-\infty}^{+\infty} s^2(t) dt \quad E_b = \int_0^T (a_0 g(t))^2 dt = \int_0^T V^2 dt$$

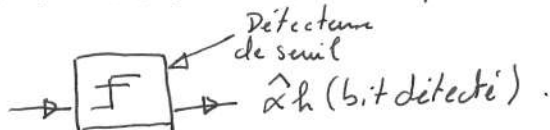
$$E_b = V^2 T$$

$g_r(t)$  (réponse impulsionnelle)

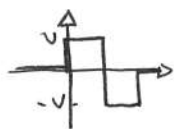
$$\boxed{\begin{aligned} z(t) &= y(t) * g_r(t) \Leftrightarrow \overbrace{R(f)}^{TF \text{ de}} = \underbrace{\gamma(f)}_{TF \text{ de } y(t)} \times \underbrace{G_r(f)}_{TF \text{ de } g_r(t)} \\ z(t) &= \int_{-\infty}^{\infty} y(\tau) \times g(t-\tau) d\tau \end{aligned}}$$

Théorème de Plancherel.

$g_r(t) = A \cdot g(t_0 - t)$  Réponse impulsionnelle d'un filtre minimisant la probabilité d'erreur binaire  $P_{eb}$  à la décision.  $g_r(t) = 0$  pour  $t < 0$ .



$$g(t_0 - t) = g(-(t - t_0)) = g(t_0 - t)$$



$$g_r(t) = A \cdot g(t_0 - t)$$

$$g(-t) = \begin{cases} -V & \text{pour } 0 < -t < T/2 \\ V & \text{pour } T/2 < -t < T \end{cases}$$

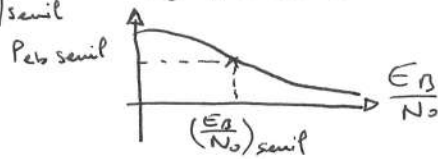
$$g(-t) = \begin{cases} -V & \text{pour } -T/2 < t < 0 \\ V & \text{pour } -T < t < -T/2 \end{cases}$$

$$2.2.4) \cdot P_{\text{émission}} = \frac{E_B}{T} = D \cdot E_B$$

$$= D N_0 \cdot \left( \frac{E_B}{N_0} \right)$$

$$P_{eb} < (P_{eb})_{\text{seuil}}$$

$$\Rightarrow \left( \frac{E_B}{N_0} \right) > \left( \frac{E_B}{N_0} \right)_{\text{seuil}} \text{ car } P_{eb} \text{ est décroissante}$$





2.2.4.

$$N_0 = 4 \cdot 10^{-21} \text{ W/Hz}$$

$$D = 34 \text{ Mbit/s}$$

$$P_{\max} = 10^{-4}$$

$$P_e \approx \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{E_b}{N_0}} \right)$$

$$P_e < P_{\max} \Rightarrow \frac{E_b}{N_0} > \left( \frac{E_b}{N_0} \right)_{\min}$$

$$\Rightarrow \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{E_b}{N_0}} \right)_{\min} = 10^{-4}$$

$$\operatorname{erfc} \left( \sqrt{\frac{E_b}{N_0}} \right)_{\min} = 2 \cdot 10^{-4}$$

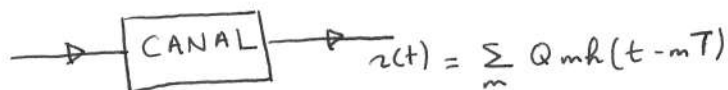
$$D' \text{ après le tableau } \Rightarrow \left( \sqrt{\frac{E_b}{N_0}} \right)_{\min} = 2,63$$

$$P = E_b \times D = E_b \times D \times \frac{N_0}{N_0} = D N_0 \times \left( \frac{E_b}{N_0} \right)$$

$$P_{\min} = D N_0 \times \left( \frac{E_b}{N_0} \right) = 34 \cdot 10^6 \times 4 \cdot 10^{-21} \times (2,63)^2 = 0,94 \text{ pW}$$

TD n° 3:

Canal à bande limitée en bande de base.



$$x(t) = \sum_m a_m g(t-mT)$$


 $t = t_1 + nT$  (instant de décision)

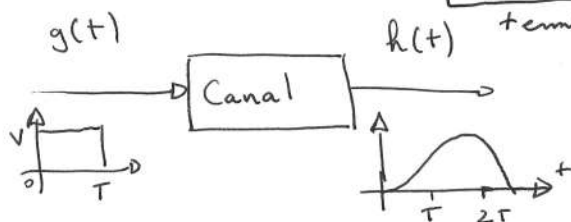
$$z(t_1 + nT) = \sum_m a_m h(t_1 + nT - mT)$$

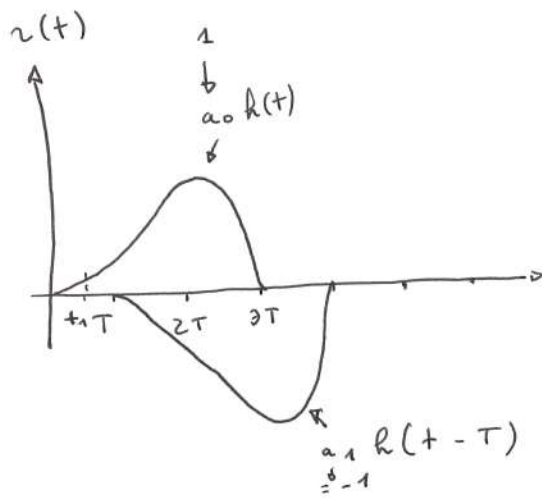
$$= \sum_m a_m h(t_1 + \underbrace{(n-m)}_k T)$$

$$\begin{aligned} k &= n-m \\ m &= n-k \end{aligned}$$

$$= a_n h(t_1) + \sum_{\substack{k \\ k \geq 1}} a_{n-k} h(t_1 + kT)$$

terme d'IES.

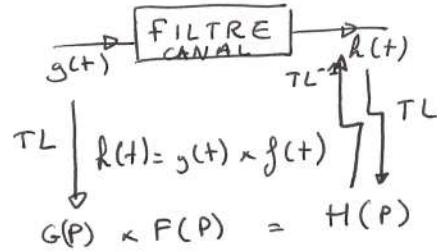
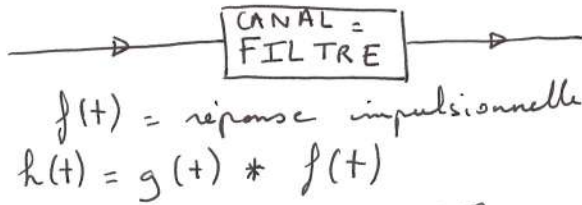




$$z(t_1) = a_0 h(t_1)$$

$$z(t_1 + T) = a_0 h(t_1 + T) + a_1 h(t_1 + T - T) \\ = \underbrace{a_0 h(t_1 + T)}_{\text{IES.}} + a_1 h(t_1)$$

3.1.



$$f(t) \xrightarrow{\text{canale}} F(p) = \int_0^{+\infty} e^{-pt} f(t) dt.$$

$$p \in \mathbb{C}$$

$$f(t) = 0 \text{ pour } t < 0$$

Table de transformée.

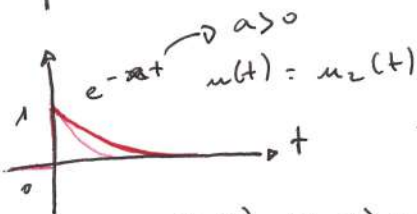
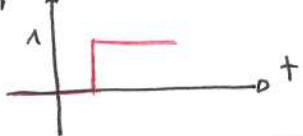
\*  $u(t) = \text{fonction échelon-unité}$

$$\xrightarrow{TL} U(p) = \frac{1}{p}$$

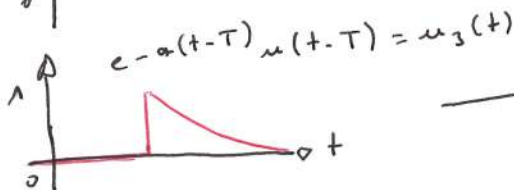


\*  $u(t-T) = u_1(t)$

$$\xrightarrow{TL} u_1(p) = \frac{e^{-Tp}}{p}$$



$$\xrightarrow{TL} u_2(p) = \frac{1}{p+a}$$

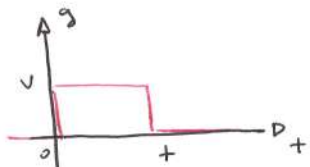


$$\xrightarrow{TL} u_3(p) = \frac{e^{-Tp}}{p+a}$$

$$\xrightarrow{\text{FILTRE P.B. 1 ordre}} F(p) = \frac{1}{1+\tau p}$$

3.1.1.

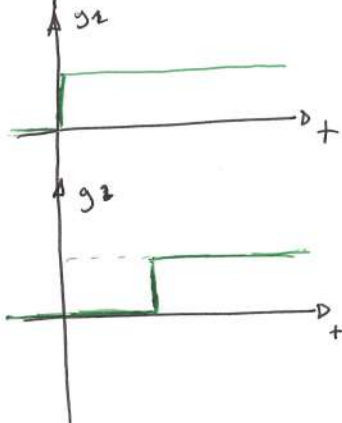
$$H(p) = F(p) * G(p)$$



$$g(t) = g_1(t) - g_2(t)$$

$$G(P) = G_1(P) - G_2(P)$$

$$= \frac{V}{P} - \frac{V e^{-TP}}{P}$$



$$H(P) = \left( \frac{1}{1 + \tau P} \right) \left( \frac{V}{P} - \frac{V e^{-TP}}{P} \right)$$

$$= \left( \frac{V}{P(1 + \tau P)} \right) (H_1(P) - H_2(P))$$

$$\Rightarrow h(t) = h_1(t) - h_2(t)$$

$$H_1(P) = \frac{V}{P(1 + \tau P)} = \frac{A}{P} + \frac{B}{1 + \tau P} = \frac{A(1 + \tau P) + B(P)}{P(1 + \tau P)}$$

$$\Rightarrow \begin{cases} A = V \\ A\tau + B = 0 \\ \Rightarrow B = -V\tau \end{cases}$$

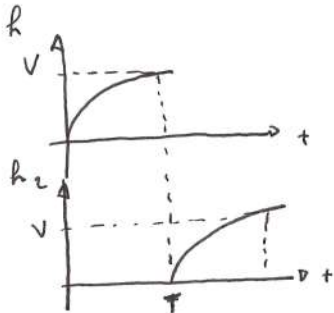
$$H_1(P) = \frac{V}{P} - \frac{\tau V}{1 + \tau P} = \frac{V}{P} - \frac{\tau}{\tau} \times \frac{V}{P + 1/\tau} = \frac{V}{P} - \frac{V}{P + 1/\tau}$$

$$\Rightarrow h_1(t) = V u(t) - V e^{-t/\tau} u(t)$$

$$h_1(t) = V(1 - e^{-t/\tau}) u(t)$$

De même on obtient :

$$h_2(t) = V(1 - e^{-(t-T)/\tau}) \times u(t-T)$$



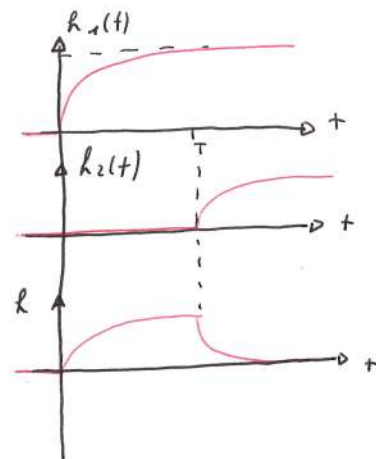
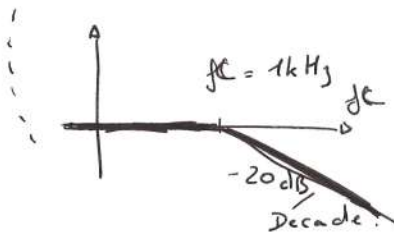
$$h_1(t) = \mathcal{TL}^{-1}(H_1(P))$$

$$h_2(t) = \mathcal{TL}^{-1}(H_2(P))$$

$$\omega_c = \frac{1}{\tau}$$

$$\omega_c = 2\pi f_c$$

$$a: \tau \ll T$$

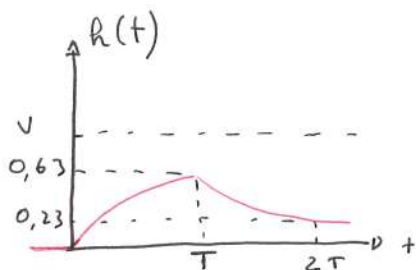
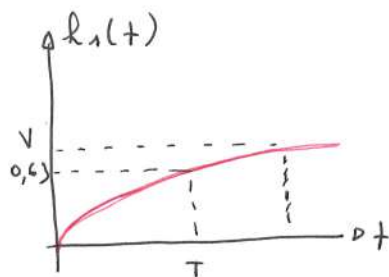


b.  $\tau = T$

$$h_1(T) = V(1 - e^{-T/\tau})$$

$$= V(1 - e^{-1})$$

$\underbrace{\hspace{1.5cm}}_{0,63}$



c.  $\tau \gg T$

$$\frac{\tau}{T} \gg 1$$

$$\frac{T}{\tau} \ll 1$$

D L (développement Limité).

$$e^x \approx 1 + x$$

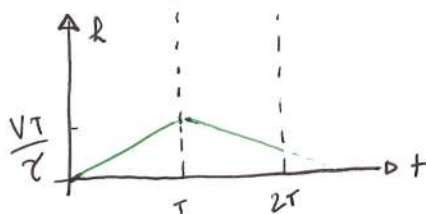
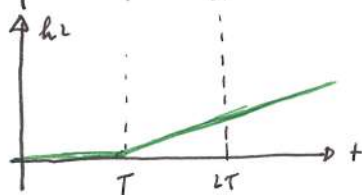
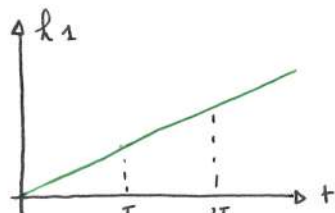
$$e^{-x} \approx 1 - x$$

$$h_1(t) = V(1 - e^{-t/\tau}) u(t)$$

$$h_1(t) \approx V(1 - (1 - \frac{t}{\tau})) u(t)$$

$$\approx \frac{Vt}{\tau} u(t)$$

$$h_1(T) = \frac{VT}{\tau}$$

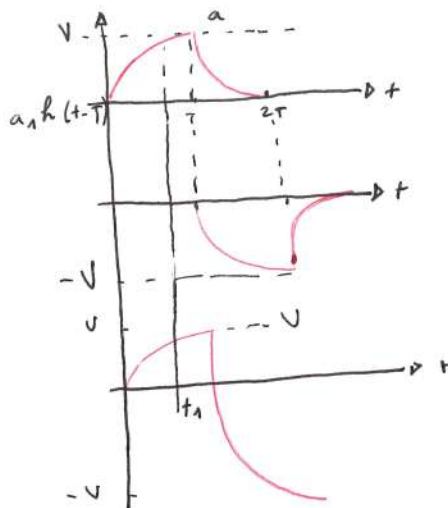


3.1.2. Représenter  $z(t)$  sur deux périodes avec la séquence

binnaire  $\alpha_0 = 1$   $\alpha_1 = 0$

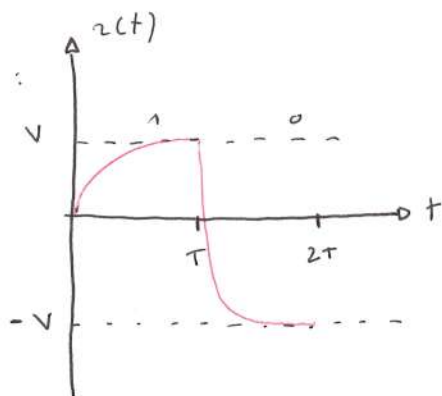
(codage NRZ  $a_0 = 1$ ,  $a_1 = -1$ )

a.  $\tau \ll T$ .



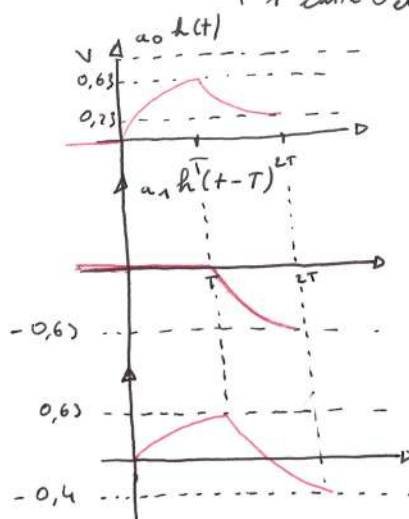
3.1.2.

a.  $\tau \ll T$ :



$\tau = T$   $z(t) = \underbrace{a_0}_{=1} h(t) + \underbrace{a_1}_{=-1} h(t-T)$  entre 0 et 2T

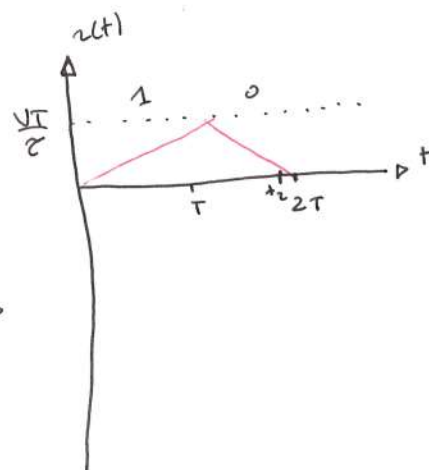
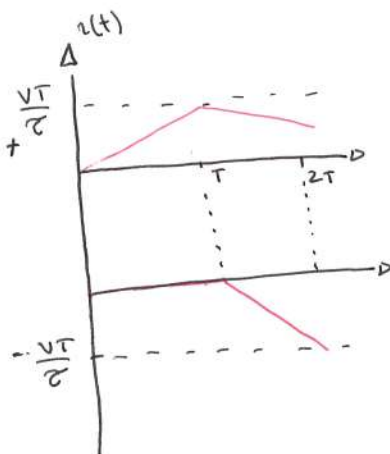
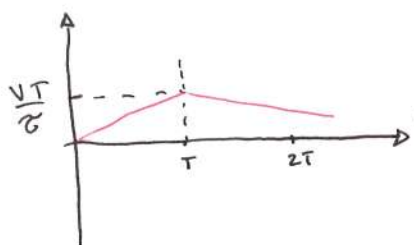
("1" entre 0 et T) ("0" entre T et 2T)



Si:  $T < t_1 + T < t_2$   
erreur de détection  
décision

Si:  $t_2 < t_1 + T < 2T$   
détection correcte  
décision.

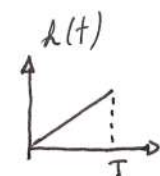
c.  $\tau \gg T$



3.  $y(t)$

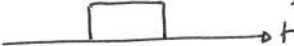


CANAL

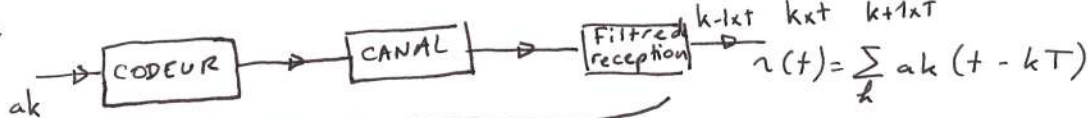


de canal se comporte comme un intégrateur.

IES car  $h(t-kT) \neq 0$   
pour  $t > (k+1)T$



3.2

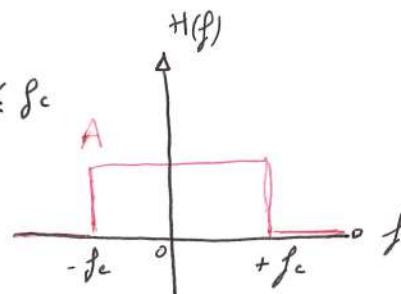


$H(f)$  (TF de  $h(t)$ )  
 $H(f) = A \cdot \Pi(f/2f_c)$

constante.

$H(f) = \begin{cases} A \text{ pour } -\frac{1}{2} \leq \frac{f}{2f_c} \leq \frac{1}{2} \\ 0 \text{ ailleurs.} \end{cases}$

$= \begin{cases} A \text{ pour } -f_c \leq f \leq f_c \\ 0 \text{ ailleurs} \end{cases}$



TF de  $h(t)$  :

$$H(f) = \int_{-\infty}^{+\infty} h(t) e^{-j2\pi f t} dt$$

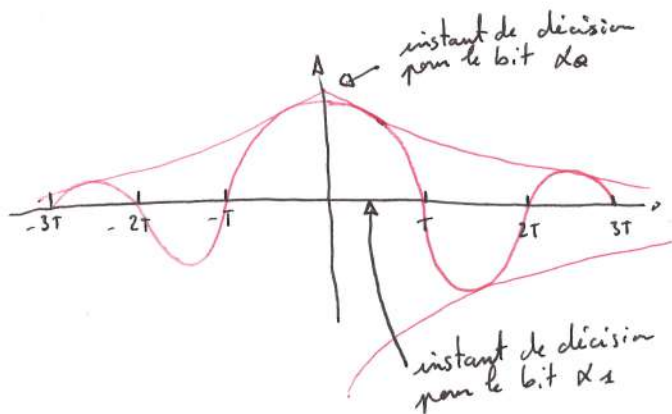
TF<sup>-1</sup> de  $H(f)$

$$h(t) = \int_{-\infty}^{+\infty} H(f) e^{+j2\pi f t} df$$

$$h(t) = \int_{-f_c}^{f_c} A e^{j2\pi f t} df = A \left[ \frac{e^{j2\pi f t}}{j2\pi t} \right]_{-f_c}^{f_c} = A \left[ \frac{e^{j2\pi f_c t} - e^{-j2\pi f_c t}}{j2\pi t} \right]$$

$$\sin \theta = \frac{e^{j\theta} - e^{-j\theta}}{2j}$$

$$h(t) = \frac{A}{\pi t} \sin(2\pi f_c t) = \frac{2f_c}{2f_c} \times \frac{A}{\pi t} \sin(2\pi f_c t) \quad h(t) = 2A f_c \operatorname{sinc}(2\pi f_c t)$$



3.2.2.

$$r(t) = \sum_k a_k h(t - kT)$$

instants de décision :  $t = t_1 + nT = nT$

$\hat{a}_m = r(nT) = \sum_k a_k h(t - kT)$  avec  $t = nT$   
 symbole détecté  $= \sum_k a_k h(nT - kT)$

Critère de Nyquist :

$$\boxed{k=0} \quad h(t) \neq 0 \quad \text{pour } n=0 \quad t=0$$

$$= 0 \quad \text{pour } n \neq 0 \quad n=1, 2, \dots \quad (t=nT)$$

Généralisation :

$$h(t - kT) \neq 0 \quad \text{pour } n=k \quad (t=kT)$$

$$\boxed{k \text{ quelconque}} \quad = 0 \quad \text{pour } n \neq k \quad (t=nT \text{ et } n \neq k)$$

$$h(t) = 2A f_c \frac{\sin(2\pi f_c t)}{2\pi f_c t}$$

$$\Rightarrow 2\pi f_c T = l\pi$$

$$f_c = \frac{l}{2T}$$

Plus petite fréquence

$$f_{c \min} = \frac{1}{2T}$$

$$h(nT - kT) = 0 \Rightarrow 2\pi f_c ((n-k)T)$$

3.2.4

Premier critère de Nyquist. Pas d'IES si le signal  $r(t)$  est contenu dans une bande de fréquence  $[0, f_c \dots]$  bande de Nyquist avec  $f_c \geq f_{c \min} = \frac{1}{2T}$

## 4.1.1

$$s(t) = A_0 \cos(2\pi f_0 t + \varphi_0) \quad (\text{porteuse})$$

$$s(t) = x(t) \cos(2\pi f_0 t + \varphi_0) \quad (\text{porteuse modulée en amplitude})$$

$$s(t) = A_0 \cos(2\pi f_0 t + y(t)) \quad (\text{phase}).$$

## 4.1.2.

$$\cos(a+b) = \cos a \cos b - \sin a \sin b$$

$$s(t) = x(t) \cos(2\pi f_0 t + y(t))$$

$$s(t) = x(t) \left( \cos(2\pi f_0 t) \cos(y(t)) - \sin(2\pi f_0 t) \sin(y(t)) \right)$$

$$s(t) = \underbrace{x(t) \cos(y(t))}_{I(t)} \cos(2\pi f_0 t) - \underbrace{x(t) \sin(y(t))}_{Q(t)} \underbrace{\sin(2\pi f_0 t)}_{\cos(2\pi f_0 t - \frac{\pi}{2})}$$



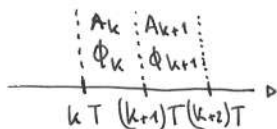
# Sujet 4: Modulation numérique

4.1.3

$$s(t) = I(t) \cos 2\pi f_0 t - Q(t) \sin 2\pi f_0 t$$

Initialement,  $s(t) = x(t) \cos(2\pi f_0 t + y(t))$  (signal modulé en amplitude)

$$s(t) = \sum_k A_k y(t - kT) \cos(2\pi f_0 t + \phi_k)$$



Entre  $t = kT$  et  $t = (k+1)T$ :

$$s(t) = A_k \cos(2\pi f_0 t + \phi_k)$$

$$\text{ou } s(t) = a_k \cos 2\pi f_0 t + b_k \sin 2\pi f_0 t$$

$$I(t) = x(t) \cos y(t) \rightarrow a_k = A_k \cos \phi_k$$

$$Q(t) = x(t) \sin y(t) \rightarrow b_k = A_k \sin \phi_k$$

$$\begin{cases} a_k^2 = A_k^2 \cos^2 \phi_k \\ b_k^2 = A_k^2 \sin^2 \phi_k \end{cases}$$

$$\Rightarrow A_k^2 = a_k^2 + b_k^2$$

$$\Rightarrow A_k = \sqrt{a_k^2 + b_k^2}$$

$$\begin{cases} a_k = A_k \cos \phi_k \\ b_k = A_k \sin \phi_k \end{cases}$$

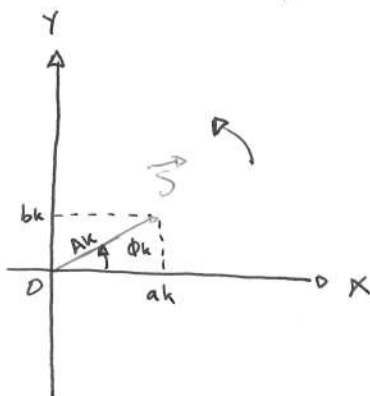
$$\Rightarrow \tan \phi_k = \frac{b_k}{a_k}$$

Représentation de Fresnel:

On associe à une fonction sinusoïdale  $s(t) = A_k \cos(2\pi f_0 t + \phi_k)$  un vecteur  $\vec{S}$ :

- module =  $A_k$

- angle / axe des abscisses =  $\phi_k$



Exemple: modulation QAM-16 (cas général QAM-M)

16 états

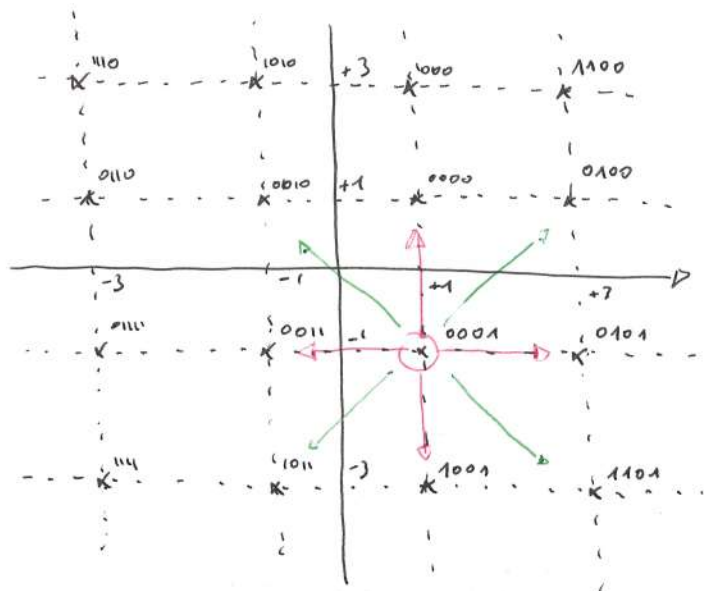
16 états

$M = 2^n$  n = nombre de bits du mot à moduler

$2^4 = 16$  (on code des mots de 4 bits)

$$a_k \in \{-3, -1, +1, +3\}$$

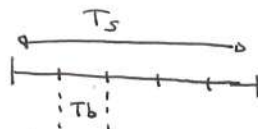
$$b_k \in \{-3, -1, +1, +3\}$$



Constellation QAM-16  
avec code de gray.

(5)

(4)



$$T_s = n T_b$$

$$\frac{1}{T_s} = \frac{1}{n} \times \frac{1}{T_b} \Rightarrow R = \frac{D}{n}$$

$$\Rightarrow D = n R$$

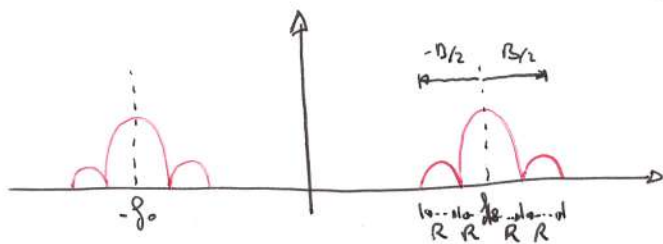
$$M = 2^n$$

$$\Rightarrow n = \log_2 M$$

$$\Rightarrow D = (\log_2 M) R$$

(6)

$$S_{ss}(f) = \frac{T_s}{4} \text{sinc}^2(\pi(f-f_0)T_s) + \frac{T_s}{4} \text{sinc}^2(\pi(f+f_0)T_s)$$



$S_{ss}(f)$  = Densité spectrale de puissance de  $s(t)$

$B$  : Largeur de la bande disponible pour le signal

Premier critère de Nyquist :  $\frac{B}{2} > \frac{R}{2}$  (condition pour éviter l'IES).

$$B > R$$

$$R < B$$

$$\frac{D}{\log_2 M} < B$$

$$D < (\log_2 M) B$$

Débit max ( $D_{max}$ )

$$n \Rightarrow n+1$$

$$M \Rightarrow 2M$$

$$2^{n+1} = 2^n \times 2$$

$$D_{max} \Rightarrow D_{max} + B$$

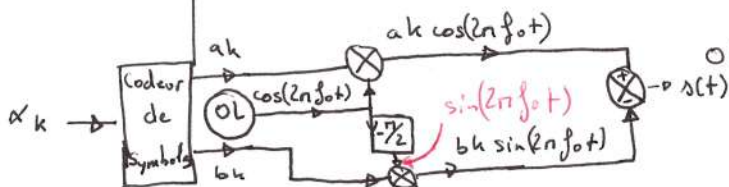
$$D'_{max} = (\log_2 2M) B$$

$$= (\log_2 M + 1) B$$

nouvelle valeur

$$= D_{max} + B$$

(7)



OL : Oscillateur Local  
 $\sin(2\pi f_0 t)$   
 $= \cos(2\pi f_0 t - \frac{\pi}{2})$

(8)

$$s(t) \propto \cos(2\pi f_0 t)$$

$$s(t) \propto \sin(2\pi f_0 t)$$

$$s(t) \propto \cos(2\pi f_0 t)$$

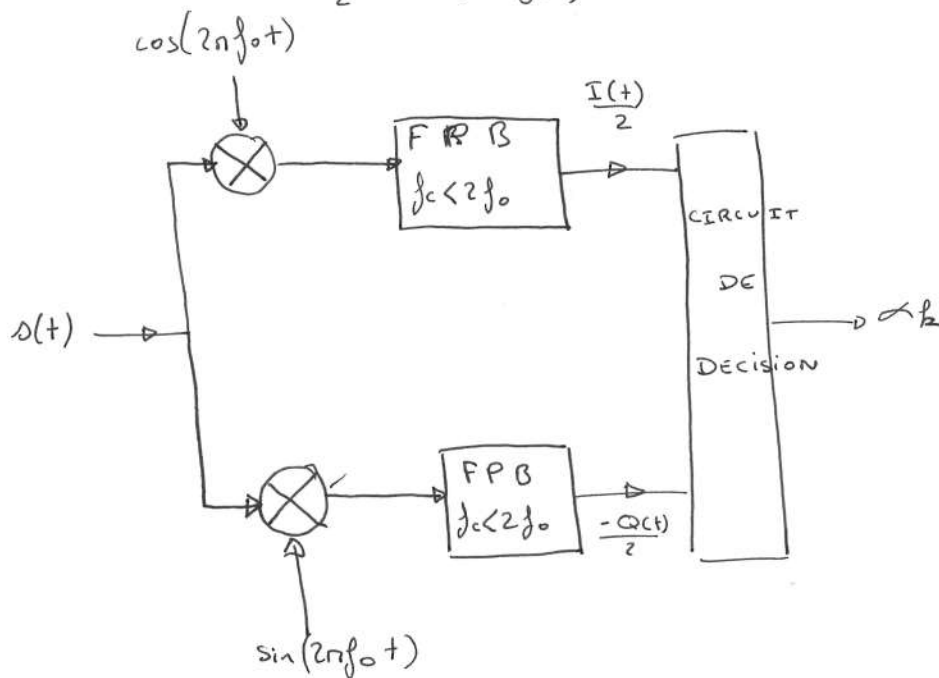
$$= (I(t) \cos(2\pi f_0 t) - Q(t) \sin(2\pi f_0 t)) \cos(2\pi f_0 t)$$

$$= I(t) \cos^2(2\pi f_0 t) - Q(t) \sin(2\pi f_0 t) \cos(2\pi f_0 t)$$

$$= I(t) \left( \frac{1}{2} (1 + \cos(4\pi f_0 t)) \right) - Q(t) \times \frac{1}{2} \sin(4\pi f_0 t)$$

$$= \frac{I(t)}{2} + \frac{I(t)}{2} \cos(4\pi f_0 t) - \frac{Q(t)}{2} \sin(4\pi f_0 t)$$

$$\begin{aligned}
 s(t) &\propto \sin(2\pi f_0 t) \\
 &= (I(t) \cos(2\pi f_0 t) - Q(t) \sin(2\pi f_0 t)) \sin(2\pi f_0 t) \\
 &= I(t) \cos(2\pi f_0 t) \sin(2\pi f_0 t) - Q(t) \sin^2(2\pi f_0 t) \\
 &= I(t) \times \frac{1}{2} \sin(4\pi f_0 t) - Q(t) [1 - \cos^2(2\pi f_0 t)] \\
 &= \frac{I(t)}{2} \sin(4\pi f_0 t) - Q(t) \left[ 1 - \frac{1}{2}(1 + \cos(4\pi f_0 t)) \right] \\
 &= -\frac{Q(t)}{2} + \frac{Q(t)}{2} \cos(4\pi f_0 t) + \frac{I(t)}{2} \sin(4\pi f_0 t).
 \end{aligned}$$



4.2 :

$$\begin{array}{l}
 \text{MAQ} \\
 \text{QAM}
 \end{array} \Big|^{-2} : n=1 \Rightarrow D = nB = B = 4,3 \text{ kb/s} \quad (1 \text{ canal})$$

$$\begin{array}{l}
 \text{MAQ} \\
 \text{QAM}
 \end{array} \Big|^{-512} : n=9 \Rightarrow D = nB = 9 \times B = 9 \times 4,3 = 38,7 \text{ kb/s} \quad (1 \text{ canal}).$$

On a 225 canaux pour les données descendant.

$$D_t = D \times \text{Nb canaux.}$$

$$\text{MAQ} - 2 \quad D_t = 4,3 \times 225 = 967,5 \text{ kb/s} \quad (D_{\min})$$

$$\text{MAQ} - 512 \quad D_t = 38,7 \times 225 = 8,707 \text{ Mb/s} \quad (D_{\max})$$

