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## Fourier transform identities and properties

Time domain $x(t)$	Frequency domain $X(f)$
$\text{rect}\left(\frac{t}{T}\right) \quad \Pi\left(\frac{t}{T}\right)$	$T \text{sinc}(fT)$
$\text{sinc}(2Wt)$	$\frac{1}{2W} \text{rect}\left(\frac{f}{2W}\right) \quad \frac{1}{2W} \Pi\left(\frac{f}{2W}\right)$
$\exp(-at)u(t), \quad a > 0$	$\frac{1}{a+j2\pi f}$
$\exp(-a t ), \quad a > 0$	$\frac{2a}{a^2+(2\pi f)^2}$
$\exp(-\pi t^2)$	$\exp(-\pi f^2)$
$1 - \frac{ t }{T}, \quad  t  < T$	$T \text{sinc}^2(fT)$
$\delta(t)$	1
1	$\delta(f)$
$\delta(t - t_0)$	$\exp(-j2\pi f t_0)$
$\exp(j2\pi f_c t)$	$\delta(f - f_c)$
$\cos(2\pi f_c t)$	$\frac{1}{2}[\delta(f - f_c) + \delta(f + f_c)]$
$\cos(2\pi f_c t + \theta)$	$\frac{1}{2}[\delta(f - f_c) \exp(j\theta) + \delta(f + f_c) \exp(-j\theta)]$ Use for coherent recv.
$\sin(2\pi f_c t)$	$\frac{1}{2j}[\delta(f - f_c) - \delta(f + f_c)]$
$\sin(2\pi f_c t + \theta)$	$\frac{1}{2j}[\delta(f - f_c) \exp(j\theta) - \delta(f + f_c) \exp(-j\theta)]$
$\text{sgn}(t)$	$\frac{1}{j\pi f}$
$\frac{1}{\pi t}$	$-j \text{sgn}(f)$
$u(t)$	$\frac{1}{2} \delta(f) + \frac{1}{j2\pi f}$
$\sum_{n=-\infty}^{\infty} \delta(t - nT_0)$	$\frac{1}{T_0} \sum_{n=-\infty}^{\infty} \delta\left(f - \frac{n}{T_0}\right) = f_0 \sum_{n=-\infty}^{\infty} \delta(f - n f_0)$

Time domain $x(t)$	Frequency domain $X(f)$	Property
$g(t - a)$	$\exp(-j2\pi f a)G(f)$	Time shifting
$\exp(-j2\pi f_c t)g(t)$	$G(f - f_c)$	Frequency shifting
$g(bt)$	$\frac{G(f/b)}{ b }$	Time scaling
$g(bt - a)$	$\frac{1}{ b } \exp(-j2\pi a(f/b)) \cdot G(f/b)$	Time scaling and shifting
$\frac{d}{dt}g(t)$	$j2\pi f G(f)$	Differentiation wrt time
$tg(t)$	$\frac{1}{2\pi} \frac{d}{df} G(f)$	Differentiation wrt frequency
$g^*(t)$	$G^*(-f)$	Conjugate functions
$G(t)$	$g(-f)$	Duality
$\int_{-\infty}^t g(\tau) d\tau$	$\frac{1}{j2\pi f} G(f) + \frac{G(0)}{2} \delta(f)$	Integration wrt time
$g(t)h(t)$	$G(f) * H(f)$	Time multiplication
$g(t) * h(t)$	$G(f)H(f)$	Time convolution
$ag(t) + bh(t)$	$aG(f) + bH(f)$	Linearity $a, b$ constants
$\int_{-\infty}^{\infty} x(t)y^*(t)dt$	$\int_{-\infty}^{\infty} X(f)Y^*(f)df$	Parseval's theorem
$E_x = \int_{-\infty}^{\infty}  x(t) ^2 dt$	$E_x = \int_{-\infty}^{\infty}  X(f) ^2 df$	Parseval's theorem

Description	Property
$g(0) = \int_{-\infty}^{\infty} G(f)df$	Area under $G(f)$
$G(0) = \int_{-\infty}^{\infty} G(t)dt$	Area under $g(t)$

$$u(t) = \begin{cases} 1, & t > 0 \\ \frac{1}{2}, & t = 0 \\ 0, & t < 0 \end{cases} \quad \text{Unit Step Function}$$

$$\text{sgn}(t) = \begin{cases} +1, & t > 0 \\ 0, & t = 0 \\ -1, & t < 0 \end{cases} \quad \text{Signum Function}$$

$$\text{sinc}(2Wt) = \frac{\sin(2\pi Wt)}{2\pi Wt} \quad \text{sinc Function}$$

$$\text{rect}(t) = \Pi(t) = \begin{cases} 1, & -0.5 < t < 0.5 \\ 0, & |t| > 0.5 \end{cases} \quad \text{Rectangular/Gate Function}$$

$$g(t) * h(t) = (g * h)(t) = \int_{-\infty}^{\infty} g(\tau)h(t - \tau)d\tau \quad \text{Convolution}$$

## Fourier transform of continuous time periodic signal

Required for some questions on **sampling**:

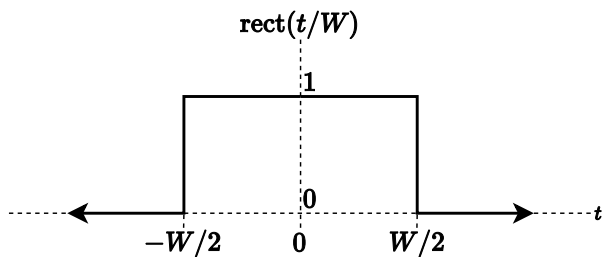
Transform a continuous time-periodic signal  $x_p(t) = \sum_{n=-\infty}^{\infty} x(t - nT_s)$  with period  $T_s$ :

$$X_p(f) = \sum_{n=-\infty}^{\infty} C_n \delta(f - nf_s) \quad f_s = \frac{1}{T_s}$$

Calculate  $C_n$  coefficient as follows from  $x_p(t)$ :

$$\begin{aligned} C_n &= \frac{1}{T_s} \int_{T_s} x_p(t) \exp(-j2\pi f_s t) dt \\ &= \frac{1}{T_s} X(nf_s) \quad (\text{TODO: Check}) \quad x(t - nT_s) \text{ is contained in the interval } T_s \end{aligned}$$

## rect function



## Bessel function

$$\begin{aligned} \sum_{n \in \mathbb{Z}} J_n^2(\beta) &= 1 \\ J_n(\beta) &= (-1)^n J_{-n}(\beta) \end{aligned}$$

## White noise

$$\begin{aligned} R_W(\tau) &= \frac{N_0}{2} \delta(\tau) = \frac{kT}{2} \delta(\tau) = \sigma^2 \delta(\tau) \\ G_w(f) &= \frac{N_0}{2} \\ N_0 &= kT \\ G_y(f) &= |H(f)|^2 G_w(f) \\ G_y(f) &= G(f) G_w(f) \end{aligned}$$

## WSS

$$\begin{aligned} \mu_X(t) &= \mu_X \text{ Constant} \\ R_{XX}(t_1, t_2) &= R_X(t_1 - t_2) = R_X(\tau) \\ E[X(t_1)X(t_2)] &= E[X(t)X(t + \tau)] \end{aligned}$$

## Ergodicity

$$\begin{aligned}\langle X(t) \rangle_T &= \frac{1}{2T} \int_{-T}^T x(t) dt \\ \langle X(t+\tau)X(t) \rangle_T &= \frac{1}{2T} \int_{-T}^T x(t+\tau)x(t) dt \\ E[\langle X(t) \rangle_T] &= \frac{1}{2T} \int_{-T}^T x(t) dt = \frac{1}{2T} \int_{-T}^T m_X dt = m_X\end{aligned}$$

Type	Normal	Mean square sense
ergodic in mean	$\lim_{T \rightarrow \infty} \langle X(t) \rangle_T = m_X(t) = m_X$	$\lim_{T \rightarrow \infty} \text{VAR}[\langle X(t) \rangle_T] = 0$
ergodic in autocorrelation function	$\lim_{T \rightarrow \infty} \langle X(t+\tau)X(t) \rangle_T = R_X(\tau)$	$\lim_{T \rightarrow \infty} \text{VAR}[\langle X(t+\tau)X(t) \rangle_T] = 0$

Note: **A WSS random process needs to be both ergodic in mean and autocorrelation to be considered an ergodic process**

## Other identities

$$f * (g * h) = (f * g) * h \quad \text{Convolution associative}$$

$$a(f * g) = (af) * g \quad \text{Convolution associative}$$

$$\sum_{x=-\infty}^{\infty} (f(xa)\delta(\omega - xb)) = f\left(\frac{\omega a}{b}\right)$$

## Other trig

$$\cos 2\theta = 2 \cos^2 \theta - 1 \Leftrightarrow \frac{\cos 2\theta + 1}{2} = \cos^2 \theta$$

$$e^{-j\alpha} - e^{j\alpha} = -2j \sin(\alpha)$$

$$e^{-j\alpha} + e^{j\alpha} = 2 \cos(\alpha)$$

$$\cos(-A) = \cos(A)$$

$$\sin(-A) = -\sin(A)$$

$$\sin(A + \pi/2) = \cos(A)$$

$$\sin(A - \pi/2) = -\cos(A)$$

$$\cos(A - \pi/2) = \sin(A)$$

$$\cos(A + \pi/2) = -\sin(A)$$

$$\int_{x \in \mathbb{R}} \text{sinc}(Ax) = \frac{1}{|A|}$$

$$\cos(A + B) = \cos(A)\cos(B) - \sin(A)\sin(B)$$

$$\sin(A + B) = \sin(A)\cos(B) + \cos(A)\sin(B)$$

$$\cos(A)\cos(B) = \frac{1}{2}(\cos(A - B) + \cos(A + B))$$

$$\cos(A)\sin(B) = \frac{1}{2}(\sin(A + B) - \sin(A - B))$$

$$\sin(A)\sin(B) = \frac{1}{2}(\cos(A - B) - \cos(A + B))$$

$$\cos(A) + \cos(B) = 2 \cos\left(\frac{A}{2} - \frac{B}{2}\right) \cos\left(\frac{A}{2} + \frac{B}{2}\right)$$

$$\cos(A) - \cos(B) = -2 \sin\left(\frac{A}{2} - \frac{B}{2}\right) \sin\left(\frac{A}{2} + \frac{B}{2}\right)$$

$$\sin(A) + \sin(B) = 2 \sin\left(\frac{A}{2} + \frac{B}{2}\right) \cos\left(\frac{A}{2} - \frac{B}{2}\right)$$

$$\sin(A) - \sin(B) = 2 \sin\left(\frac{A}{2} - \frac{B}{2}\right) \cos\left(\frac{A}{2} + \frac{B}{2}\right)$$

$$\cos(A) + \sin(B) = -2 \sin\left(\frac{A}{2} - \frac{B}{2} - \frac{\pi}{4}\right) \sin\left(\frac{A}{2} + \frac{B}{2} + \frac{\pi}{4}\right)$$

$$\cos(A) - \sin(B) = -2 \sin\left(\frac{A}{2} + \frac{B}{2} - \frac{\pi}{4}\right) \sin\left(\frac{A}{2} - \frac{B}{2} + \frac{\pi}{4}\right)$$

## IQ/Complex envelope

Def.  $\tilde{g}(t) = g_I(t) + jg_Q(t)$  as the complex envelope. Best to convert to  $e^{j\theta}$  form.

### Convert complex envelope representation to time-domain representation of signal

$$\begin{aligned}g(t) &= g_I(t) \cos(2\pi f_c t) - g_Q(t) \sin(2\pi f_c t) \\&= \operatorname{Re}[\tilde{g}(t) \exp(j2\pi f_c t)] \\&= A(t) \cos(2\pi f_c t + \phi(t)) \\A(t) &= |g(t)| = \sqrt{g_I^2(t) + g_Q^2(t)} \quad \text{Amplitude} \\ \phi(t) & \quad \text{Phase} \\g_I(t) &= A(t) \cos(\phi(t)) \quad \text{In-phase component} \\g_Q(t) &= A(t) \sin(\phi(t)) \quad \text{Quadrature-phase component}\end{aligned}$$

### For transfer function

$$\begin{aligned}h(t) &= h_I(t) \cos(2\pi f_c t) - h_Q(t) \sin(2\pi f_c t) \\&= 2\operatorname{Re}[\tilde{h}(t) \exp(j2\pi f_c t)] \\ \Rightarrow \tilde{h}(t) &= h_I(t)/2 + jh_Q(t)/2 = A(t)/2 \exp(j\phi(t))\end{aligned}$$

## AM

### CAM

$$\begin{aligned}m_a &= \frac{\min_t |k_a m(t)|}{A_c} \quad k_a \text{ is the amplitude sensitivity (volt}^{-1}\text{), } m_a \text{ is the modulation index.} \\m_a &= \frac{A_{\max} - A_{\min}}{A_{\max} + A_{\min}} \quad (\text{Symmetrical } m(t)) \\m_a &= k_a A_m \quad (\text{Symmetrical } m(t)) \\x(t) &= A_c \cos(2\pi f_c t) [1 + k_a m(t)] = A_c \cos(2\pi f_c t) [1 + m_a m(t)/A_c], \\& \quad \text{where } m(t) = A_m \hat{m}(t) \text{ and } \hat{m}(t) \text{ is the normalized modulating signal} \\P_c &= \frac{A_c^2}{2} \quad \text{Carrier power} \\P_x &= \frac{1}{4} m_a^2 A_c^2 \\ \eta &= \frac{\text{Signal Power}}{\text{Total Power}} = \frac{P_x}{P_x + P_c} \\B_T &= 2f_m = 2B\end{aligned}$$

$B_T$ : Signal bandwidth  $B$ : Bandwidth of modulating wave

Overmodulation (resulting in phase reversals at crossing points):  $m_a > 1$

### DSB-SC

$$\begin{aligned}x_{\text{DSB}}(t) &= A_c \cos(2\pi f_c t) m(t) \\B_T &= 2f_m = 2B\end{aligned}$$

## FM/PM

$$\begin{aligned}s(t) &= A_c \cos[2\pi f_c t + k_p m(t)] \quad \text{Phase modulated (PM)} \\s(t) &= A_c \cos(\theta_i(t)) = A_c \cos\left[2\pi f_c t + 2\pi k_f \int_{-\infty}^t m(\tau) d\tau\right] \quad \text{Frequency modulated (FM)} \\s(t) &= A_c \cos[2\pi f_c t + \beta \sin(2\pi f_m t)] \quad \text{FM single tone} \\f_i(t) &= \frac{1}{2\pi} \frac{d}{dt} \theta_i(t) \quad \text{Instantaneous frequency from instantaneous phase} \\ \Delta f &= \beta f_m = k_f A_m f_m = \max_t(k_f m(t)) - \min_t(k_f m(t)) \quad \text{Maximum frequency deviation} \\ \Delta f &= \max_t(f_i(t)) - \min_t(f_i(t)) \quad \text{Maximum frequency deviation} \\ \beta &= \frac{\Delta f}{f_m} = k_f A_m \quad \text{Modulation index} \\ D &= \frac{\Delta f}{W_m} \quad \text{Deviation ratio, where } W_m \text{ is bandwidth of } m(t) \text{ (Use FT)}\end{aligned}$$

## Bessel form and magnitude spectrum (single tone)

$$s(t) = A_c \cos[2\pi f_c t + \beta \sin(2\pi f_m t)] \Leftrightarrow s(t) = A_c \sum_{n=-\infty}^{\infty} J_n(\beta) \cos[2\pi(f_c + n f_m)t]$$

## FM signal power

$$P_{\text{av}} = \frac{A_c^2}{2}$$

$$P_{\text{band\_index}} = \frac{A_c^2 J_{\text{band\_index}}^2(\beta)}{2}$$

$$\text{band\_index} = 0 \implies f_c + 0f_m$$

$$\text{band\_index} = 1 \implies f_c + 1f_m, \dots$$

## Carson's rule to find $B$ (98% power bandwidth rule)

$$B = 2M f_m = 2(\beta + 1)f_m$$

$$= 2(\Delta f + f_m)$$

$$= 2(k_f A_m + f_m)$$

$$= 2(D + 1)W_m$$

$$B = \begin{cases} 2(\Delta f + f_m) & \text{FM, sinusoidal message} \\ 2(\Delta\phi + 1)f_m & \text{PM, sinusoidal message} \end{cases}$$

## Complex envelope

$$s(t) = A_c \cos(2\pi f_c t + \beta \sin(2\pi f_m t)) \Leftrightarrow \tilde{s}(t) = A_c \exp(j\beta \sin(2\pi f_m t))$$

$$s(t) = \text{Re}[\tilde{s}(t) \exp(j2\pi f_c t)]$$

$$\tilde{s}(t) = A_c \sum_{n=-\infty}^{\infty} J_n(\beta) \exp(j2\pi f_m t)$$

## Band

**Narrowband**      **Wideband**

$$D < 1, \beta < 1 \quad D > 1, \beta > 1$$

## Power, energy and autocorrelation

$$G_{\text{WGN}}(f) = \frac{N_0}{2}$$

$$G_x(f) = |H(f)|^2 G_w(f) \text{ (PSD)}$$

$$G_x(f) = G(f) G_w(f) \text{ (PSD)}$$

$$G_x(f) = \lim_{T \rightarrow \infty} \frac{|X_T(f)|^2}{T} \text{ (PSD)}$$

$$G_x(f) = \mathfrak{F}[R_x(\tau)] \text{ (WSS)}$$

$$P_x = \sigma_x^2 = \int_{\mathbb{R}} G_x(f) df \quad \text{For zero mean}$$

$$P_x = \sigma_x^2 = \lim_{t \rightarrow \infty} \frac{1}{T} \int_{-T/2}^{T/2} |x(t)|^2 dt \quad \text{For zero mean}$$

$$P[A \cos(2\pi ft + \phi)] = \frac{A^2}{2} \quad \text{Power of sinusoid}$$

$$E_x = \int_{-\infty}^{\infty} |x(t)|^2 dt = \int_{-\infty}^{\infty} |X(f)|^2 df \quad \text{Parseval's theorem}$$

$$R_x(\tau) = \mathfrak{F}(G_x(f)) \quad \text{PSD to Autocorrelation}$$

## Noise performance

Coherent detection system.

$$\begin{aligned}y(t) &= m(t) \cos(2\pi f_c t + \theta) = m(t) \cos^2(2\pi f_c t + \theta) \text{ After IF mixing.} \\ &= m(t) \frac{1}{2} (1 + \cos(4f_c t + 2\theta)) \\ &= \frac{1}{2} m(t) + \frac{1}{2} \cos(4f_c t + 2\theta) \\ \implies S_u(f) &= \left(\frac{1}{2}\right)^2 S_u(f) \text{ After LPF.}\end{aligned}$$

Use formulas from previous section, [Power, energy and autocorrelation](#).

Use these formulas in particular:

$$\begin{aligned}G_{\text{WGN}}(f) &= \frac{N_0}{2} \\ G_x(f) &= |H(f)|^2 G_w(f) \quad \text{Note the square in } |H(f)|^2 \\ P_x &= \sigma_x^2 = \int_{\mathbb{R}} G_x(f) df \quad \text{Often perform graphical integration} \\ \text{CNR}_{\text{in}} &= \frac{P_{\text{in}}}{P_{\text{noise}}} \\ \text{CNR}_{\text{in,FM}} &= \frac{A^2}{2WN_0} \\ \text{SNR}_{\text{FM}} &= \frac{3A^2 k_f^2 P}{2N_0 W^3} \\ \text{SNR(dB)} &= 10 \log_{10}(\text{SNR}) \quad \text{Decibels from ratio}\end{aligned}$$

## Sampling

$$\begin{aligned}t &= nT_s \\ T_s &= \frac{1}{f_s} \\ x_s(t) &= x(t) \delta_s(t) = x(t) \sum_{n \in \mathbb{Z}} \delta(t - nT_s) = \sum_{n \in \mathbb{Z}} x(nT_s) \delta(t - nT_s) \\ X_s(f) &= X(f) * \sum_{n \in \mathbb{Z}} \delta\left(f - \frac{n}{T_s}\right) = X(f) * \sum_{n \in \mathbb{Z}} \delta(f - nf_s) \\ B &> \frac{1}{2} f_s, 2B > f_s \rightarrow \text{Aliasing}\end{aligned}$$

### Procedure to reconstruct sampled signal

Analog signal  $x'(t)$  which can be reconstructed from a sampled signal  $x_s(t)$ : Put  $x_s(t)$  through LPF with maximum frequency of  $f_s/2$  and minimum frequency of  $-f_s/2$ . Anything outside of the BPF will be attenuated, therefore  $n$  which results in frequencies outside the BPF will evaluate to 0 and can be ignored.

Example:  $f_s = 5000 \implies \text{LPF} \in [-2500, 2500]$

Then iterate for  $n = 0, 1, -1, 2, -2, \dots$  until the first iteration where the result is 0 since all terms are eliminated by the LPF.

TODO: Add example

Then add all terms and transform  $\bar{X}_s(f)$  back to time domain to get  $x_s(t)$

### Fourier transform of continuous time periodic signal (1)

Required for some questions on **sampling**:

Transform a continuous time-periodic signal  $x_p(t) = \sum_{n=-\infty}^{\infty} x(t - nT_s)$  with period  $T_s$ :

$$X_p(f) = \sum_{n=-\infty}^{\infty} C_n \delta(f - nf_s) \quad f_s = \frac{1}{T_s}$$

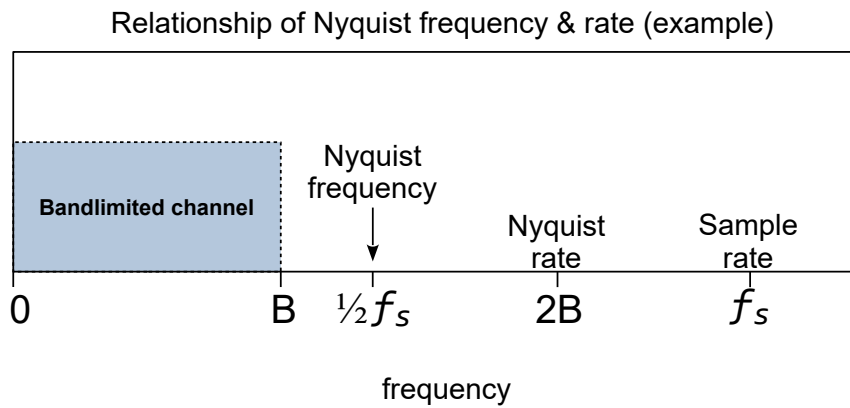
Calculate  $C_n$  coefficient as follows from  $x_p(t)$ :

$$C_n = \frac{1}{T_s} \int_{T_s} x_p(t) \exp(-j2\pi f_s t) dt$$

$$= \frac{1}{T_s} X(nf_s) \quad (\text{TODO: Check}) \quad x(t - nT_s) \text{ is contained in the interval } T_s$$

### Nyquist criterion for zero-ISI

Do not transmit more than  $2B$  samples per second over a channel of  $B$  bandwidth.



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sampling

### Quantizer

$$\Delta = \frac{x_{\text{Max}} - x_{\text{Min}}}{2^k} \quad \text{for } k\text{-bit quantizer (V/lsb)}$$

### Quantization noise

$$e := y - x \quad \text{Quantization error}$$

$$\mu_E = E[E] = 0 \quad \text{Zero mean}$$

$$\sigma_E^2 = E[E^2] - 0^2 = \int_{-\Delta/2}^{\Delta/2} e^2 \times \left(\frac{1}{\Delta}\right) de \quad \text{Where } E \sim 1/\Delta \text{ uniform over } (-\Delta/2, \Delta/2)$$

$$\text{SQNR} = \frac{\text{Signal power}}{\text{Quantization noise}}$$

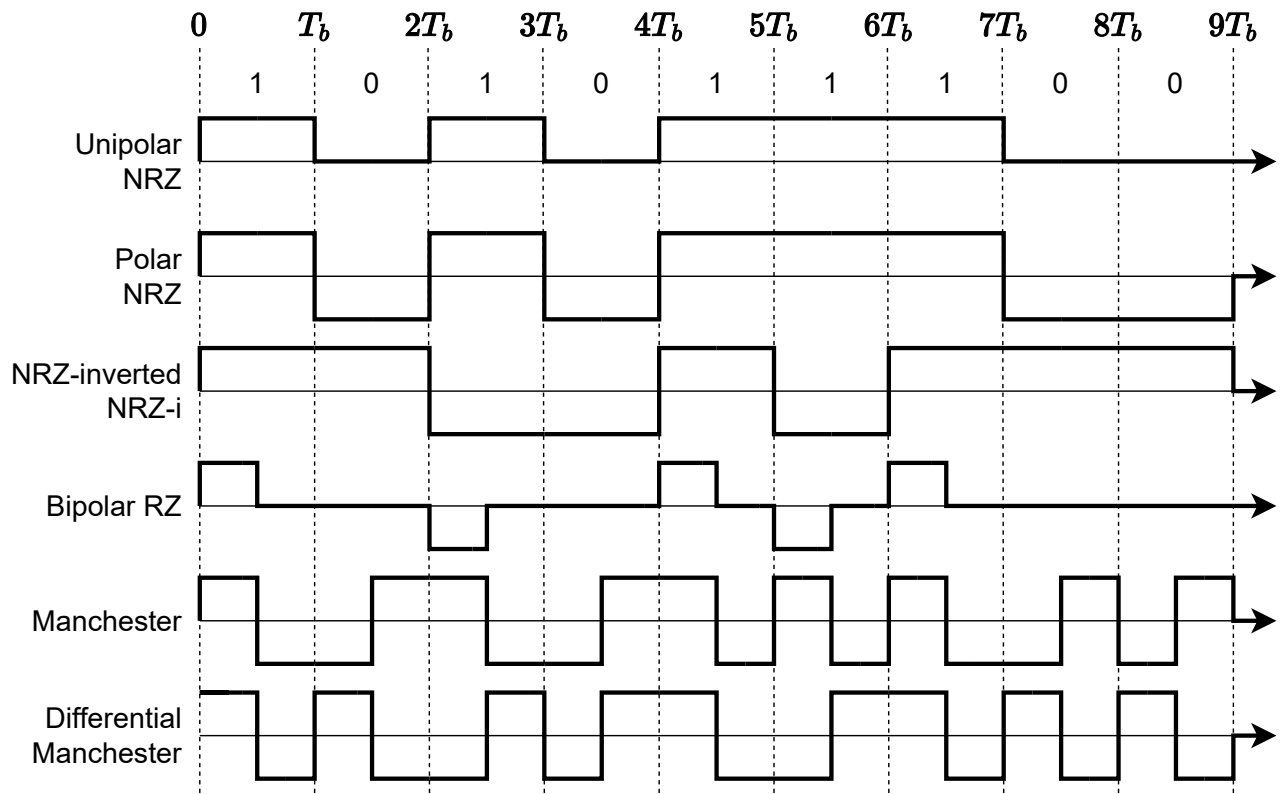
$$\text{SQNR(dB)} = 10 \log_{10}(\text{SQNR})$$

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quantizer

### Line codes



$R_b \rightarrow$  Bit rate

$D \rightarrow$  Symbol rate  $|R_d| 1/T_b$

$A \rightarrow m_a$

$V(f) \rightarrow$  Pulse shape

$$V_{\text{rectangle}}(f) = T \text{sinc}(fT \times \text{DutyCycle})$$

$$G_{\text{MunipolarNRZ}}(f) = \frac{(M^2 - 1)A^2D}{12} |V(f)|^2 + \frac{(M - 1)^2}{4} (DA)^2 \sum_{l=-\infty}^{\infty} |V(lD)|^2 \delta(f - lD)$$

$$G_{\text{MpolarNRZ}}(f) = \frac{(M^2 - 1)A^2D}{3} |V(f)|^2$$

$$G_{\text{unipolarNRZ}}(f) = \frac{A^2}{4R_b} \left( \text{sinc}^2 \left( \frac{f}{R_b} \right) + R_b \delta(f) \right), \text{NB}_0 = R_b$$

$$G_{\text{polarNRZ}}(f) = \frac{A^2}{R_b} \text{sinc}^2 \left( \frac{f}{R_b} \right)$$

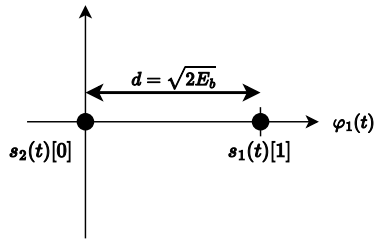
$$G_{\text{unipolarNRZ}}(f) = \frac{A^2}{4R_b} \left( \text{sinc}^2 \left( \frac{f}{R_b} \right) + R_b \delta(f) \right)$$

$$G_{\text{unipolarRZ}}(f) = \frac{A^2}{16} \left( \sum_{l=-\infty}^{\infty} \delta \left( f - \frac{l}{T_b} \right) |\text{sinc}(\text{duty} \times l)|^2 + T_b |\text{sinc}(\text{duty} \times fT_b)|^2 \right), \text{NB}_0 = 2R_b$$

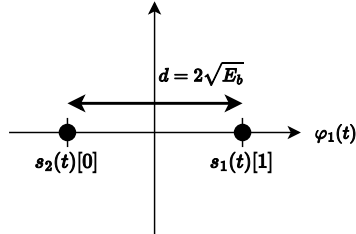
## Modulation and basis functions



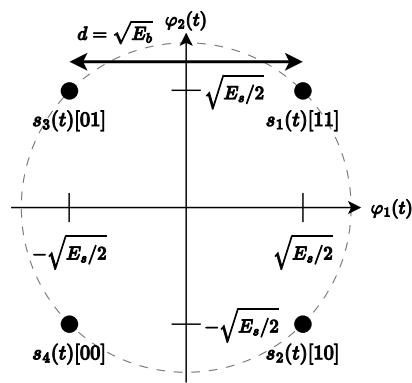
## BASK constellation



## BPSK constellation



## QPSK constellation



## BASK

### Basis functions

$$\varphi_1(t) = \sqrt{\frac{2}{T_b}} \cos(2\pi f_c t) \quad 0 \leq t \leq T_b$$

### Symbol mapping

$$b_n : \{1, 0\} \rightarrow a_n : \{1, 0\}$$

### 2 possible waveforms

$$s_1(t) = A_c \sqrt{\frac{T_b}{2}} \varphi_1(t) = \sqrt{2E_b} \varphi_1(t)$$

$$s_2(t) = 0$$

$$\text{Since } E_b = E_{\text{average}} = \frac{1}{2} \left( \frac{A_c^2}{2} \times T_b + 0 \right) = \frac{A_c^2}{4} T_b$$

Distance is  $d = \sqrt{2E_b}$

## BPSK

### Basis functions

$$\varphi_1(t) = \sqrt{\frac{2}{T_b}} \cos(2\pi f_c t) \quad 0 \leq t \leq T_b$$

### Symbol mapping

$$b_n : \{1, 0\} \rightarrow a_n : \{1, -1\}$$

### 2 possible waveforms

$$s_1(t) = A_c \sqrt{\frac{T_b}{2}} \varphi_1(t) = \sqrt{E_b} \varphi_1(t)$$

$$s_2(t) = -A_c \sqrt{\frac{T_b}{2}} \varphi_1(t) = -\sqrt{E_b} \varphi_1(t)$$

$$\text{Since } E_b = E_{\text{average}} = \frac{1}{2} \left( \frac{A_c^2}{2} \times T_b + \frac{A_c^2}{2} \times T_b \right) = \frac{A_c^2}{2} T_b$$

Distance is  $d = 2\sqrt{E_b}$

## QPSK ( $M = 4$ PSK)

### Basis functions

$T = 2T_b$  Time per symbol for two bits  $T_b$

$$\varphi_1(t) = \sqrt{\frac{2}{T}} \cos(2\pi f_c t) \quad 0 \leq t \leq T$$

$$\varphi_2(t) = \sqrt{\frac{2}{T}} \sin(2\pi f_c t) \quad 0 \leq t \leq T$$

#### 4 possible waveforms

$$s_1(t) = \sqrt{E_s/2} [\varphi_1(t) + \varphi_2(t)]$$

$$s_2(t) = \sqrt{E_s/2} [\varphi_1(t) - \varphi_2(t)]$$

$$s_3(t) = \sqrt{E_s/2} [-\varphi_1(t) + \varphi_2(t)]$$

$$s_4(t) = \sqrt{E_s/2} [-\varphi_1(t) - \varphi_2(t)]$$

Note on energy per symbol: Since  $|s_i(t)| = A_c$ , have to normalize distance as follows:

$$\begin{aligned} s_i(t) &= A_c \sqrt{T/2} / \sqrt{2} \times [\alpha_{1i} \varphi_1(t) + \alpha_{2i} \varphi_2(t)] \\ &= \sqrt{T A_c^2 / 4} [\alpha_{1i} \varphi_1(t) + \alpha_{2i} \varphi_2(t)] \\ &= \sqrt{E_s/2} [\alpha_{1i} \varphi_1(t) + \alpha_{2i} \varphi_2(t)] \end{aligned}$$

#### Signal

Symbol mapping:  $\{1, 0\} \rightarrow \{1, -1\}$

$$I(t) = b_{2n} \varphi_1(t) \quad \text{Even bits}$$

$$Q(t) = b_{2n+1} \varphi_2(t) \quad \text{Odd bits}$$

$$x(t) = A_c [I(t) \cos(2\pi f_c t) - Q(t) \sin(2\pi f_c t)]$$

#### Example of waveform

##### ► Code

Remember that  $T = 2T_b$

$b_n$	QPSK bits
$I(t)$ (Odd, 1st bits)	QPSK bits
$Q(t)$ (Even, 2nd bits)	QPSK bits

# Matched filter

## 1. Filter function

Find transfer function  $h(t)$  of matched filter and apply to an input:

Note that  $x(T-t)$  is equivalent to horizontally flipping  $x(t)$  around  $x = T/2$ .

$$h(t) = s_1(T-t) - s_2(T-t)$$

$$h(t) = s^*(T-t) \quad (.)^* \text{ is the conjugate}$$

$$s_{on}(t) = h(t) * s_n(t) = \int_{-\infty}^{\infty} h(\tau) s_n(t-\tau) d\tau \quad \text{Filter output}$$

$$n_o(t) = h(t) * n(t) \quad \text{Noise at filter output}$$

## 2. Bit error rate of matched filter

Bit error rate (BER) from matched filter outputs and filter output noise

$$Q(x) = \frac{1}{2} - \frac{1}{2} \operatorname{erf} \left( \frac{x}{\sqrt{2}} \right) \Leftrightarrow \operatorname{erf} \left( \frac{x}{\sqrt{2}} \right) = 1 - 2Q(x)$$

$$E_b = d^2 = \int_{-\infty}^{\infty} |s_1(t) - s_2(t)|^2 dt \quad \text{Energy per bit/Distance}$$

$$T = 1/R_b \quad R_b: \text{Bitrate}$$

$$E_b = P_{av} T = P_{av} / R_b \quad \text{Energy per bit}$$

$$P_{av} = E_b / T = E_b R_b \quad \text{Average power}$$

$$P(W) = 10^{\frac{P(\text{dB})}{10}}$$

$$P_{RX}(W) = P_{TX}(W) \cdot 10^{\frac{P_{\text{loss}}(\text{dB})}{10}} \quad P_{\text{loss}} \text{ is expressed with negative sign e.g. } "-130 \text{ dB}"$$

$$\text{BER}_{\text{MatchedFilter}} = Q \left( \sqrt{\frac{d^2}{2N_0}} \right) = Q \left( \sqrt{\frac{E_b}{2N_0}} \right)$$

$$\text{BER}_{\text{unipolarNRZ|BASK}} = Q \left( \sqrt{\frac{d^2}{N_0}} \right) = Q \left( \sqrt{\frac{E_b}{N_0}} \right)$$

$$\text{BER}_{\text{polarNRZ|BPSK}} = Q \left( \sqrt{\frac{2d^2}{N_0}} \right) = Q \left( \sqrt{\frac{2E_b}{N_0}} \right)$$

# Value tables for erf( $x$ ) and $Q(x)$

## $Q(x)$ function

$x$	$Q(x)$	$x$	$Q(x)$	$x$	$Q(x)$	$x$	$Q(x)$
0.00	0.5	2.30	0.010724	4.55	$2.6823 \times 10^{-6}$	6.80	$5.231 \times 10^{-12}$
0.05	0.48006	2.35	0.0093867	4.60	$2.1125 \times 10^{-6}$	6.85	$3.6925 \times 10^{-12}$
0.10	0.46017	2.40	0.0081975	4.65	$1.6597 \times 10^{-6}$	6.90	$2.6001 \times 10^{-12}$
0.15	0.44038	2.45	0.0071428	4.70	$1.3008 \times 10^{-6}$	6.95	$1.8264 \times 10^{-12}$
0.20	0.42074	2.50	0.0062097	4.75	$1.0171 \times 10^{-6}$	7.00	$1.2798 \times 10^{-12}$
0.25	0.40129	2.55	0.0053861	4.80	$7.9333 \times 10^{-7}$	7.05	$8.9459 \times 10^{-13}$
0.30	0.38209	2.60	0.0046612	4.85	$6.1731 \times 10^{-7}$	7.10	$6.2378 \times 10^{-13}$
0.35	0.36317	2.65	0.0040246	4.90	$4.7918 \times 10^{-7}$	7.15	$4.3389 \times 10^{-13}$
0.40	0.34458	2.70	0.003467	4.95	$3.7107 \times 10^{-7}$	7.20	$3.0106 \times 10^{-13}$
0.45	0.32636	2.75	0.0029798	5.00	$2.8665 \times 10^{-7}$	7.25	$2.0839 \times 10^{-13}$
0.50	0.30854	2.80	0.0025551	5.05	$2.2091 \times 10^{-7}$	7.30	$1.4388 \times 10^{-13}$
0.55	0.29116	2.85	0.002186	5.10	$1.6983 \times 10^{-7}$	7.35	$9.9103 \times 10^{-14}$
0.60	0.27425	2.90	0.0018658	5.15	$1.3024 \times 10^{-7}$	7.40	$6.8092 \times 10^{-14}$
0.65	0.25785	2.95	0.0015889	5.20	$9.9644 \times 10^{-8}$	7.45	$4.667 \times 10^{-14}$
0.70	0.24196	3.00	0.0013499	5.25	$7.605 \times 10^{-8}$	7.50	$3.1909 \times 10^{-14}$
0.75	0.22663	3.05	0.0011442	5.30	$5.7901 \times 10^{-8}$	7.55	$2.1763 \times 10^{-14}$
0.80	0.21186	3.10	0.0009676	5.35	$4.3977 \times 10^{-8}$	7.60	$1.4807 \times 10^{-14}$
0.85	0.19766	3.15	0.00081635	5.40	$3.332 \times 10^{-8}$	7.65	$1.0049 \times 10^{-14}$
0.90	0.18406	3.20	0.00068714	5.45	$2.5185 \times 10^{-8}$	7.70	$6.8033 \times 10^{-15}$
0.95	0.17106	3.25	0.00057703	5.50	$1.899 \times 10^{-8}$	7.75	$4.5946 \times 10^{-15}$
1.00	0.15866	3.30	0.00048342	5.55	$1.4283 \times 10^{-8}$	7.80	$3.0954 \times 10^{-15}$
1.05	0.14686	3.35	0.00040406	5.60	$1.0718 \times 10^{-8}$	7.85	$2.0802 \times 10^{-15}$
1.10	0.13567	3.40	0.00033693	5.65	$8.0224 \times 10^{-9}$	7.90	$1.3945 \times 10^{-15}$
1.15	0.12507	3.45	0.00028029	5.70	$5.9904 \times 10^{-9}$	7.95	$9.3256 \times 10^{-16}$
1.20	0.11507	3.50	0.00023263	5.75	$4.4622 \times 10^{-9}$	8.00	$6.221 \times 10^{-16}$
1.25	0.10565	3.55	0.00019262	5.80	$3.3157 \times 10^{-9}$	8.05	$4.1397 \times 10^{-16}$
1.30	0.0968	3.60	0.00015911	5.85	$2.4579 \times 10^{-9}$	8.10	$2.748 \times 10^{-16}$
1.35	0.088508	3.65	0.00013112	5.90	$1.8175 \times 10^{-9}$	8.15	$1.8196 \times 10^{-16}$
1.40	0.080757	3.70	0.0001078	5.95	$1.3407 \times 10^{-9}$	8.20	$1.2019 \times 10^{-16}$
1.45	0.073529	3.75	$8.8417 \times 10^{-5}$	6.00	$9.8659 \times 10^{-10}$	8.25	$7.9197 \times 10^{-17}$
1.50	0.066807	3.80	$7.2348 \times 10^{-5}$	6.05	$7.2423 \times 10^{-10}$	8.30	$5.2056 \times 10^{-17}$
1.55	0.060571	3.85	$5.9059 \times 10^{-5}$	6.10	$5.3034 \times 10^{-10}$	8.35	$3.4131 \times 10^{-17}$
1.60	0.054799	3.90	$4.8096 \times 10^{-5}$	6.15	$3.8741 \times 10^{-10}$	8.40	$2.2324 \times 10^{-17}$
1.65	0.049471	3.95	$3.9076 \times 10^{-5}$	6.20	$2.8232 \times 10^{-10}$	8.45	$1.4565 \times 10^{-17}$
1.70	0.044565	4.00	$3.1671 \times 10^{-5}$	6.25	$2.0523 \times 10^{-10}$	8.50	$9.4795 \times 10^{-18}$
1.75	0.040059	4.05	$2.5609 \times 10^{-5}$	6.30	$1.4882 \times 10^{-10}$	8.55	$6.1544 \times 10^{-18}$
1.80	0.03593	4.10	$2.0658 \times 10^{-5}$	6.35	$1.0766 \times 10^{-10}$	8.60	$3.9858 \times 10^{-18}$
1.85	0.032157	4.15	$1.6624 \times 10^{-5}$	6.40	$7.7688 \times 10^{-11}$	8.65	$2.575 \times 10^{-18}$
1.90	0.028717	4.20	$1.3346 \times 10^{-5}$	6.45	$5.5925 \times 10^{-11}$	8.70	$1.6594 \times 10^{-18}$
1.95	0.025588	4.25	$1.0689 \times 10^{-5}$	6.50	$4.016 \times 10^{-11}$	8.75	$1.0668 \times 10^{-18}$

$x$	$Q(x)$	$x$	$Q(x)$	$x$	$Q(x)$	$x$	$Q(x)$
2.00	0.02275	4.30	$8.5399 \times 10^{-6}$	6.55	$2.8769 \times 10^{-11}$	8.80	$6.8408 \times 10^{-19}$
2.05	0.020182	4.35	$6.8069 \times 10^{-6}$	6.60	$2.0558 \times 10^{-11}$	8.85	$4.376 \times 10^{-19}$
2.10	0.017864	4.40	$5.4125 \times 10^{-6}$	6.65	$1.4655 \times 10^{-11}$	8.90	$2.7923 \times 10^{-19}$
2.15	0.015778	4.45	$4.2935 \times 10^{-6}$	6.70	$1.0421 \times 10^{-11}$	8.95	$1.7774 \times 10^{-19}$
2.20	0.013903	4.50	$3.3977 \times 10^{-6}$	6.75	$7.3923 \times 10^{-12}$	9.00	$1.1286 \times 10^{-19}$
2.25	0.012224						

Adapted from table 6.1 M F Mesiya - Contemporary Communication Systems

### erf( $x$ ) function

$x$	erf( $x$ )	$x$	erf( $x$ )	$x$	erf( $x$ )
0.00	0.00000	0.75	0.71116	1.50	0.96611
0.05	0.05637	0.80	0.74210	1.55	0.97162
0.10	0.11246	0.85	0.77067	1.60	0.97635
0.15	0.16800	0.90	0.79691	1.65	0.98038
0.20	0.22270	0.95	0.82089	1.70	0.98379
0.25	0.27633	1.00	0.84270	1.75	0.98667
0.30	0.32863	1.05	0.86244	1.80	0.98909
0.35	0.37938	1.10	0.88021	1.85	0.99111
0.40	0.42839	1.15	0.89612	1.90	0.99279
0.45	0.47548	1.20	0.91031	1.95	0.99418
0.50	0.52050	1.25	0.92290	2.00	0.99532
0.55	0.56332	1.30	0.93401	2.50	0.99959
0.60	0.60386	1.35	0.94376	3.00	0.99998
0.65	0.64203	1.40	0.95229	3.30	0.999998**
0.70	0.67780	1.45	0.95970		

\*\*The value of erf(3.30) should be  $\approx 0.999997$  instead, but this value is quoted in the formula table.

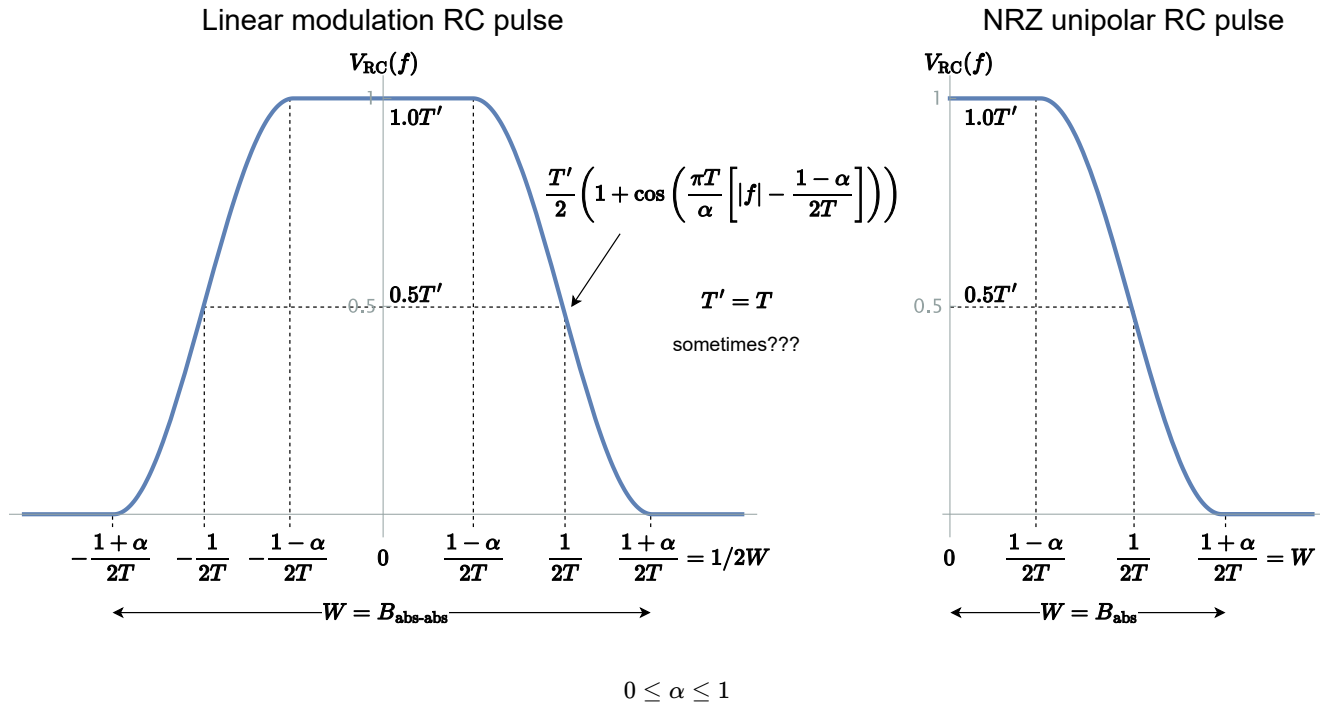
## Receiver output shift

$$r_o(t) = \begin{cases} s_{o1}(t) + n_o(t) & \text{code 1} \\ s_{o2}(t) + n_o(t) & \text{code 0} \end{cases}$$

$n$  : AWGN with  $\sigma_o^2$

## ISI, channel model

### Raised cosine (RC) pulse



△ NOTE might not be safe to assume  $T' = T$ , if you can solve the question without  $T$  then use that method.

### Nyquist criterion for zero ISI

$D > 2W$  Use  $W$  from table below depending on modulation scheme.

$$B_{Nyquist} = \frac{W}{1+\alpha}$$

$$\alpha = \frac{\text{Excess BW}}{B_{Nyquist}} = \frac{B_{abs} - B_{Nyquist}}{B_{Nyquist}}$$

### Nomenclature

$D$  → Symbol Rate, Max. Signalling Rate  
 $T$  → Symbol Duration  
 $M$  → Symbol set size  
 $W$  → Bandwidth

### Bandwidth $W$ and bit error rate of modulation schemes

To solve this type of question:

1. Use the formula for  $D$  below
2. Consult the BER table below to get the BER which relates the noise of the channel  $N_0$  to  $E_b$  and to  $R_b$ .

Linear modulation	Half
BPSK, QPSK, $M$ -PSK, $M$ -QAM, ASK, FSK	$M$ -PAM, PAM
RZ unipolar, Manchester	NRZ Unipolar, NRZ Polar, Bipolar RZ
$W = B_{abs-abs}$	$W = B_{abs}$
$W = B_{abs-abs} = \frac{1+\alpha}{T} = (1+\alpha)D$	$W = B_{abs} = \frac{1+\alpha}{2T} = (1+\alpha)D/2$
$D = \frac{W \text{ symbol/s}}{1+\alpha}$	$D = \frac{2W \text{ symbol/s}}{1+\alpha}$

$$R_b \text{ bit/s} = (D \text{ symbol/s}) \times (k \text{ bit/symbol})$$

$$M \text{ symbol/set} = 2^k$$

$$T \text{ s/symbol} = 1/(D \text{ symbol/s})$$

$$E_b = PT = P_{av}/R_b \quad \text{Energy per bit}$$

Table of bandpass signalling and BER

Binary Bandpass Signaling	$B_{\text{null-null}}$ (Hz)	$B_{\text{abs-abs}} = 2B_{\text{abs}}$ (Hz)	BER with Coherent Detection	BER with Noncoherent Detection
ASK, unipolar NRZ	$2R_b$	$R_b(1 + \alpha)$	$Q\left(\sqrt{E_b/N_0}\right)$	$0.5 \exp(-E_b/(2N_0))$
BPSK	$2R_b$	$R_b(1 + \alpha)$	$Q\left(\sqrt{2E_b/N_0}\right)$	Requires coherent detection
Sunde's FSK	$3R_b$		$Q\left(\sqrt{E_b/N_0}\right)$	$0.5 \exp(-E_b/(2N_0))$
DBPSK, $M$ -ary Bandpass Signaling	$2R_b$	$R_b(1 + \alpha)$		$0.5 \exp(-E_b/N_0)$
QPSK/ OQPSK ( $M = 4$ , PSK)	$R_b$	$\frac{R_b(1+\alpha)}{2}$	$Q\left(\sqrt{2E_b/N_0}\right)$	Requires coherent detection
MSK	$1.5R_b$	$\frac{3R_b(1+\alpha)}{4}$	$Q\left(\sqrt{2E_b/N_0}\right)$	Requires coherent detection
$M$ -PSK ( $M > 4$ )	$2R_b/\log_2 M$	$\frac{R_b(1+\alpha)}{\log_2 M}$	$\frac{2}{\log_2 M} Q\left(\sqrt{2 \log_2 M \sin^2(\pi/M) E_b/N_0}\right)$	Requires coherent detection
$M$ -DPSK ( $M > 4$ )	$2R_b/\log_2 M$	$\frac{R_b(1+\alpha)}{2 \log_2 M}$		$\frac{2}{\log_2 M} Q\left(\sqrt{4 \log_2 M \sin^2(\pi/(2M)) E_b/N_0}\right)$
$M$ -QAM (Square constellation)	$2R_b/\log_2 M$	$\frac{R_b(1+\alpha)}{\log_2 M}$	$\frac{4}{\log_2 M} \left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3 \log_2 M}{M-1} E_b/N_0}\right)$	Requires coherent detection
$M$ -FSK Coherent	$\frac{(M+3)R_b}{2 \log_2 M}$		$\frac{M-1}{\log_2 M} Q\left(\sqrt{(\log_2 M) E_b/N_0}\right)$	
Noncoherent	$2MR_b/\log_2 M$			$\frac{M-1}{2 \log_2 M} 0.5 \exp(-(\log_2 M) E_b/2N_0)$

Adapted from table 11.4 M F Mesiya - Contemporary Communication Systems

### PSD of modulated signals

Modulation	$G_x(f)$
Quadrature	$\frac{A_c^2}{4} [G_I(f - f_c) + G_I(f + f_c) + G_Q(f - f_c) + G_Q(f + f_c)]$
Linear	$\frac{ V(f) ^2}{2} \sum_{l=-\infty}^{\infty} R(l) \exp(-j2\pi l f T)$ What??

### Symbol error probability

- Minimum distance between any two point
- Different from bit error since a symbol can contain multiple bits

# Information theory

## Entropy for discrete random variables

$$\begin{aligned}
 H(x) &\geq 0 \\
 H(x) &= - \sum_{x_i \in A_x} p_X(x_i) \log_2(p_X(x_i)) \\
 H(x, y) &= - \sum_{x_i \in A_x} \sum_{y_j \in A_y} p_{XY}(x_i, y_j) \log_2(p_{XY}(x_i, y_j)) \quad \text{Joint entropy} \\
 H(x, y) &= H(x) + H(y) \quad \text{Joint entropy if } x \text{ and } y \text{ independent} \\
 H(x|y = y_j) &= - \sum_{x_i \in A_x} p_X(x_i|y = y_j) \log_2(p_X(x_i|y = y_j)) \quad \text{Conditional entropy} \\
 H(x|y) &= - \sum_{y_j \in A_y} p_Y(y_j) H(x|y = y_j) \quad \text{Average conditional entropy, equivocation} \\
 H(x|y) &= - \sum_{x_i \in A_x} \sum_{y_j \in A_y} p_X(x_i, y_j) \log_2(p_X(x_i|y = y_j)) \\
 H(x|y) &= H(x, y) - H(y) \\
 H(x, y) &= H(x) + H(y|x) = H(y) + H(x|y)
 \end{aligned}$$

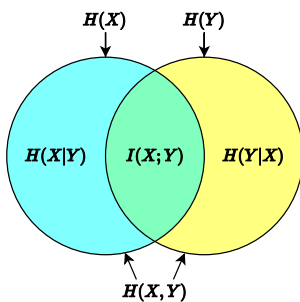
Entropy is **maximized** when all have an equal probability.

## Differential entropy for continuous random variables

TODO: Cut out if not required

$$h(x) = - \int_{\mathbb{R}} f_X(x) \log_2(f_X(x)) dx$$

## Mutual information



Amount of entropy decrease of  $x$  after observation by  $y$ .

$$I(x; y) = H(x) - H(x|y) = H(y) - H(y|x)$$

## Channel model

Vertical,  $x$ : input

Horizontal,  $y$ : output

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1N} \\ p_{21} & p_{22} & \dots & p_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ p_{M1} & p_{M2} & \dots & p_{MN} \end{bmatrix}$$

$P(y_j x_i)$	$y_1$	$y_2$	$\dots$	$y_N$
$x_1$	$p_{11}$	$p_{12}$	$\dots$	$p_{1N}$
$x_2$	$p_{21}$	$p_{22}$	$\dots$	$p_{2N}$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$x_M$	$p_{M1}$	$p_{M2}$	$\dots$	$p_{MN}$

Input has probability distribution  $p_X(a_i) = P(X = a_i)$

Channel maps alphabet ' $\{a_1, \dots, a_M\} \rightarrow \{b_1, \dots, b_N\}$ '

Output has probability distribution  $p_Y(b_j) = P(y = b_j)$



$$\begin{aligned}
p_Y(b_j) &= \sum_{i=1}^M P[x = a_i, y = b_j] \quad 1 \leq j \leq N \\
&= \sum_{i=1}^M P[X = a_i]P[Y = b_j|X = a_i] \\
[p_Y(b_0) \quad p_Y(b_1) \quad \dots \quad p_Y(b_j)] &= [p_X(a_0) \quad p_X(a_1) \quad \dots \quad p_X(a_i)] \times \mathbf{P}
\end{aligned}$$

Fast procedure to calculate  $I(y; x)$

1. Find  $H(x)$
2. Find  $[p_Y(b_0) \quad p_Y(b_1) \quad \dots \quad p_Y(b_j)] = [p_X(a_0) \quad p_X(a_1) \quad \dots \quad p_X(a_i)] \times \mathbf{P}$
3. Multiply each row in  $\mathbf{P}$  by  $p_X(a_i)$  since  $p_{XY}(x_i, y_i) = P(y_i|x_i)P(x_i)$
4. Find  $H(x, y)$  using each element from (3.)
5. Find  $H(x|y) = H(x, y) - H(y)$
6. Find  $I(y; x) = H(x) - H(x|y)$

## Channel types

Type	Definition
Symmetric channel	Every row is a permutation of every other row, Every column is a permutation of every other column. Symmetric $\implies$ Weakly symmetric
Weakly symmetric	Every row is a permutation of every other row, Every column has the same sum

### Channel capacity of weakly symmetric channel

- $C \rightarrow$  Channel capacity (bits/channels used)
- $N \rightarrow$  Output alphabet size
- $\mathbf{p} \rightarrow$  Probability vector, any row of the transition matrix
- $C = \log_2(N) - H(\mathbf{p})$  Capacity for weakly symmetric and symmetric channels
- $R_b < C$  for error-free transmission

### Channel capacity of an AWGN channel

$$y_i = x_i + n_i \quad n_i \sim N(0, N_0/2)$$

$$C = \frac{1}{2} \log_2 \left( 1 + \frac{P_{av}}{N_0/2} \right)$$

### Channel capacity of a bandwidth limited AWGN channel

$$\begin{aligned}
P_s &\rightarrow \text{Bandwidth limited average power} \\
y_i &= \text{bandpass}_W(x_i) + n_i \quad n_i \sim N(0, N_0/2) \\
C &= W \log_2 \left( 1 + \frac{P_s}{N_0 W} \right) \\
C &= W \log_2(1 + \text{SNR}) \\
\text{SNR} &= P_s / (N_0 W)
\end{aligned}$$

### Shannon limit

$$\begin{aligned}
R_b &< C \\
\implies R_b &< W \log_2 \left( 1 + \frac{P_s}{N_0 W} \right) \quad \text{For bandwidth limited AWGN channel} \\
\frac{E_b}{N_0} &> \frac{2^\eta - 1}{\eta} \quad \text{SNR per bit required for error-free transmission} \\
\eta &= \frac{R_b}{W} \quad \text{Spectral efficiency (bit/(s-Hz))} \\
\eta &\gg 1 \quad \text{Bandwidth limited} \\
\eta &\ll 1 \quad \text{Power limited}
\end{aligned}$$

## Channel code

Note: Define XOR ( $\oplus$ ) as exclusive OR, or modulo-2 addition.

Hamming weight	$w_H(x)$	Number of '1' in codeword $x$
Hamming distance	$d_H(x_1, x_2) = w_H(x_1 \oplus x_2)$	Number of different bits between codewords $x_1$ and $x_2$ which is the hamming weight of the XOR of the two codes.
Minimum distance	$d_{\min}$	<b>IMPORTANT:</b> $x \neq \mathbf{0}$ , excludes weight of all-zero codeword. For a linear block code, $d_{\min} = w_{\min}$

## Linear block code

Code is  $(n, k)$

$n$  is the width of a codeword

$2^k$  codewords

A linear block code must be a subspace and satisfy both:

1. Zero vector must be present at least once
2. The XOR of any codeword pair in the code must result in a codeword that is already present in the code table.
3.  $d_{\min} = w_{\min}$  (Implied by (1) and (2).)

## Code generation

Each generator vector is a binary string of size  $n$ . There are  $k$  generator vectors in  $\mathbf{G}$ .

$$\mathbf{g}_i = [g_{i,0} \ \dots \ g_{i,n-2} \ g_{i,n-1}]$$

$$\mathbf{g}_0 = [1010] \quad \text{Example for } n = 4$$

$$\mathbf{G} = \begin{bmatrix} \mathbf{g}_0 \\ \mathbf{g}_1 \\ \vdots \\ \mathbf{g}_{k-1} \end{bmatrix} = \begin{bmatrix} g_{0,0} & \dots & g_{0,n-2} & g_{0,n-1} \\ g_{1,0} & \dots & g_{1,n-2} & g_{1,n-1} \\ \vdots & \ddots & \vdots & \vdots \\ g_{k-1,0} & \dots & g_{k-1,n-2} & g_{k-1,n-1} \end{bmatrix}$$

A message block  $\mathbf{m}$  is coded as  $\mathbf{x}$  using the generation codewords in  $\mathbf{G}$ :

$$\mathbf{m} = [m_0 \ \dots \ m_{n-2} \ m_{k-1}]$$

$$\mathbf{m} = [101001] \quad \text{Example for } k = 6$$

$$\mathbf{x} = \mathbf{mG} = m_0\mathbf{g}_0 + m_1\mathbf{g}_1 + \dots + m_{k-1}\mathbf{g}_{k-1}$$

## Systemic linear block code

Contains  $k$  message bits (Copy  $\mathbf{m}$  as-is) and  $(n - k)$  parity bits after the message bits.

$$\mathbf{G} = [\mathbf{I}_k \mid \mathbf{P}] = \left[ \begin{array}{cccc|cccc} 1 & 0 & \dots & 0 & p_{0,0} & \dots & p_{0,n-2} & p_{0,n-1} \\ 0 & 1 & \dots & 0 & p_{1,0} & \dots & p_{1,n-2} & p_{1,n-1} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & 1 & p_{k-1,0} & \dots & p_{k-1,n-2} & p_{k-1,n-1} \end{array} \right]$$

$$\mathbf{m} = [m_0 \ \dots \ m_{n-2} \ m_{k-1}]$$

$$\mathbf{x} = \mathbf{mG} = \mathbf{m} [\mathbf{I}_k \mid \mathbf{P}] = [\mathbf{mI}_k \mid \mathbf{mP}] = [\mathbf{m} \mid \mathbf{b}]$$

$$\mathbf{b} = \mathbf{mP} \quad \text{Parity bits of } \mathbf{x}$$

## Parity check matrix $\mathbf{H}$

Transpose  $\mathbf{P}$  for the parity check matrix

$$\mathbf{H} = [\mathbf{P}^T \mid \mathbf{I}_{n-k}]$$

$$= \left[ \begin{array}{cccc|cccc} \mathbf{p}_0^T & \mathbf{p}_1^T & \dots & \mathbf{p}_{k-1}^T & \vdots & \vdots & \vdots & \vdots \end{array} \right]$$

$$= \left[ \begin{array}{cccc|cccc} p_{0,0} & \dots & p_{0,k-2} & p_{0,k-1} & 1 & 0 & \dots & 0 \\ p_{1,0} & \dots & p_{1,k-2} & p_{1,k-1} & 0 & 1 & \dots & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{n-1,0} & \dots & p_{n-1,k-2} & p_{n-1,k-1} & 0 & 0 & \dots & 1 \end{array} \right]$$

$$\mathbf{xH}^T = \mathbf{0} \implies \text{Codeword is valid}$$

### Procedure to find parity check matrix from list of codewords

1. From the number of codewords, find  $k = \log_2(N)$
2. Partition codewords into  $k$  information bits and remaining bits into  $n - k$  parity bits. The information bits should be a simple counter (?).
3. Express parity bits as a linear combination of information bits
4. Put coefficients into  $\mathbf{P}$  matrix and find  $\mathbf{H}$

Example:

$x_1$	$x_2$	$x_3$	$x_4$	$x_5$
1	0	1	1	0
0	1	1	1	1
0	0	0	0	0
1	1	0	0	1

Set  $x_1, x_2$  as information bits. Express  $x_3, x_4, x_5$  in terms of  $x_1, x_2$ .

$$\begin{aligned} x_3 &= x_1 \oplus x_2 \\ x_4 &= x_1 \oplus x_2 \implies \mathbf{P} = \begin{array}{c|cc} & x_1 & x_2 \\ \hline x_3 & 1 & 1 \\ x_4 & 1 & 1 \\ x_5 & 0 & 1 \end{array} \\ x_5 &= x_2 \end{aligned}$$
$$\mathbf{H} = \left[ \begin{array}{cc|ccc} 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 \end{array} \right]$$

### Error detection and correction

**Detection** of  $s$  errors:  $d_{\min} \geq s + 1$

**Correction** of  $u$  errors:  $d_{\min} \geq 2u + 1$

### CHECKLIST

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- Transfer function in complex envelope form  $\tilde{h}(t)$  should be divided by two.
- Convolutions: do not forget width when using graphical method
- todo: add more items to check