CIRF
Circuit Intégré Radio Fréquence

Lecture I

- Introduction
- Baseband Pulse Transmission
- Digital Passband Transmission
- Circuit Non-idealities Effect

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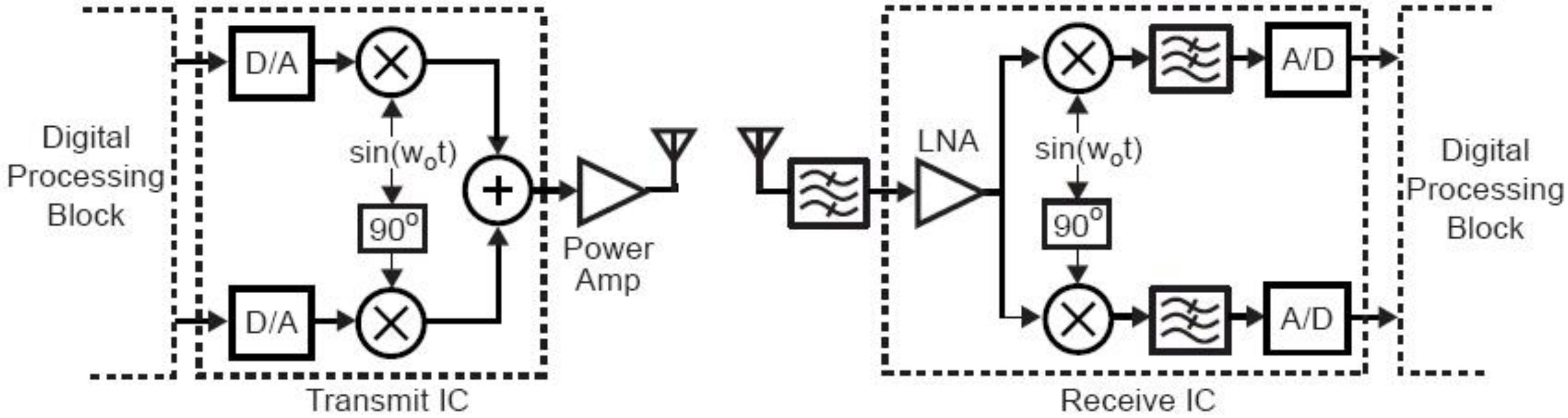
Wireless Systems

- Direct conversion architecture



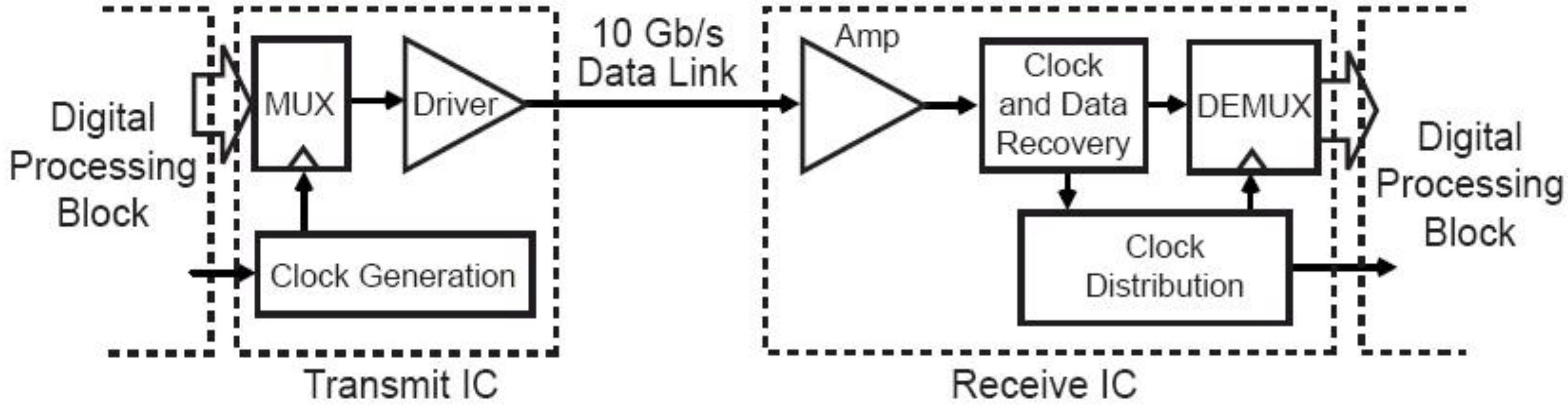
- Transmitter issues
  - Meeting the spectral mask (LO phase noise & feedthrough, quadrature accuracy), D/A accuracy, power amp linearity
- Receiver Issues
  - Meeting SNR (Noise figure, blocking performance, channel selectivity, LO phase noise, A/D nonlinearity and noise), selectivity (filtering), and emission requirements

Future Goals

- Low cost, low power, and small area solutions
  - New architectures and circuits!
- Increased spectral efficiency
  - Example: GSM cellphones (GMSK) to 8-PSK (Edge)
    - Requires a linear power amplifier!
- Increased data rates
  - Example: 802.11b (11 Mb/s) to 802.11a (> 50 Mb/s)
    - GFSK modulation changes to OFDM modulation
- Higher carrier frequencies
  - 802.11b (2.5 GHz) to 802.11a (5 GHz) to ? (60 GHz)
- New modulation formats
  - GMSK, CDMA, OFDM, pulse position modulation
- New application areas

High Speed Data Links

- A common architecture



- Transmitter Issues
  - Intersymbol interference (limited bandwidth of IC amplifiers, packaging), clock jitter, power, area
- Receiver Issue
  - Intersymbol interference (same as above), jitter from clock and data recovery, power, area

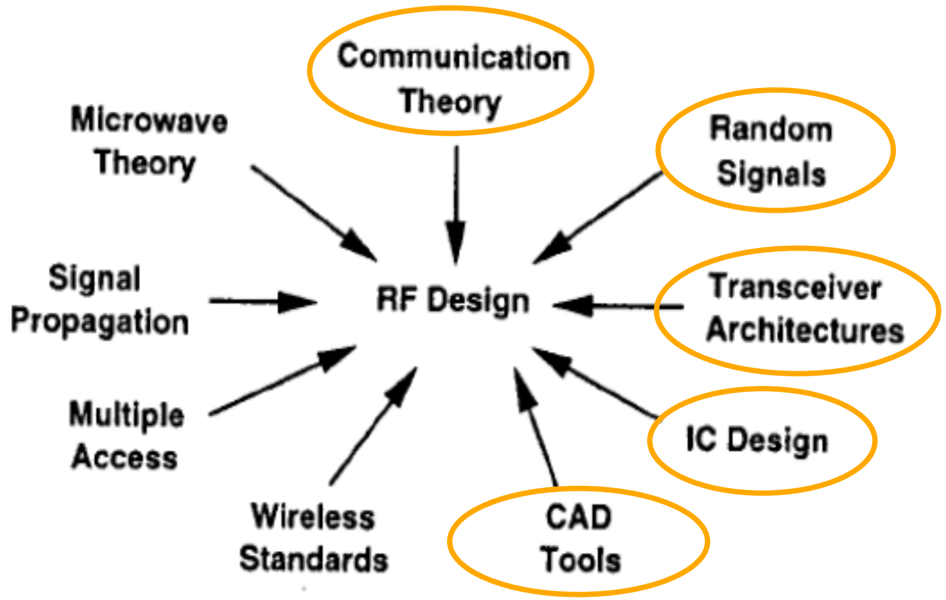
Future Goals

- Low cost, low power, small area solutions
  - New architectures and circuits!
- Increased data rates
  - 40 Gb/s for optical (moving to 120 Gb/s!)
    - Electronics is a limitation (optical issues getting significant)
  - > 5 Gb/s for backplane applications
    - The channel (i.e., the PC board trace) is the limitation
- High frequency compensation/equalization
  - Higher data rates, lower bit error rates (BER), improved robustness in the face of varying conditions
  - How do you do this at GHz speeds?
- Multi-level modulation
  - Better spectral efficiency (more bits in given bandwidth)

What are the Issues with Wireless Systems?

- Noise
  - Need to extract the radio signal with sufficient SNR
- Selectivity (filtering, processing gain)
  - Need to remove interferers (which are often much larger!)
- Nonlinearity
  - Degrades transmit spectral mask
  - Degrades selectivity for receiver

Multidisciplinarity of radio design



B. Razavi,
RF Microelectronics, Prentice Hall, 1998

References

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- M. Perrott, "High Speed Communication Circuits and Systems", M.I.T.OpenCourseWare, http://ocw.mit.edu/, Massachusetts Institute of Technology, 2003.
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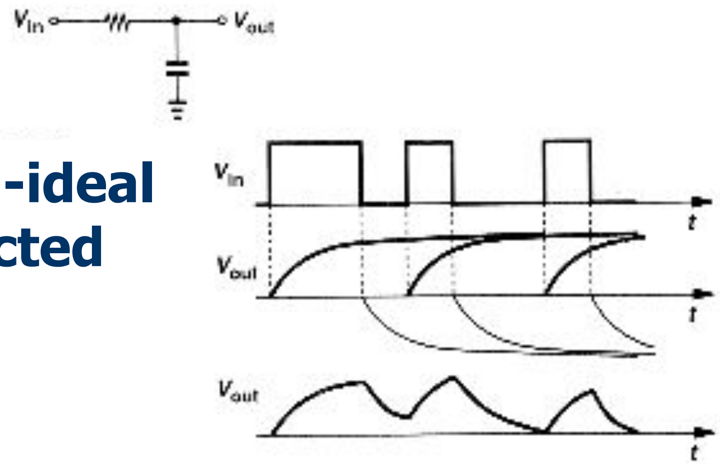
Digital Baseband Transmission

Major sources of errors in the detection of transmitted digital data:

ISI : InterSymbol Interference



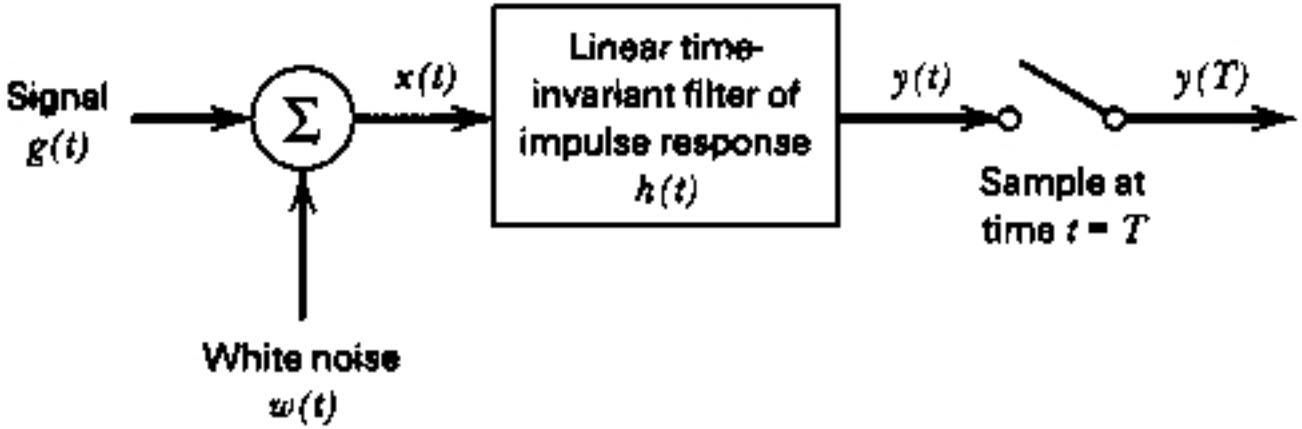
The result of data transmission over a non-ideal channel is that each received pulse is affected by adjacent pulses.

Channel Noise

Detecting a pulse transmitted over a channel that is corrupted by additive noise.

Matched Filter

Linear Receiver Model



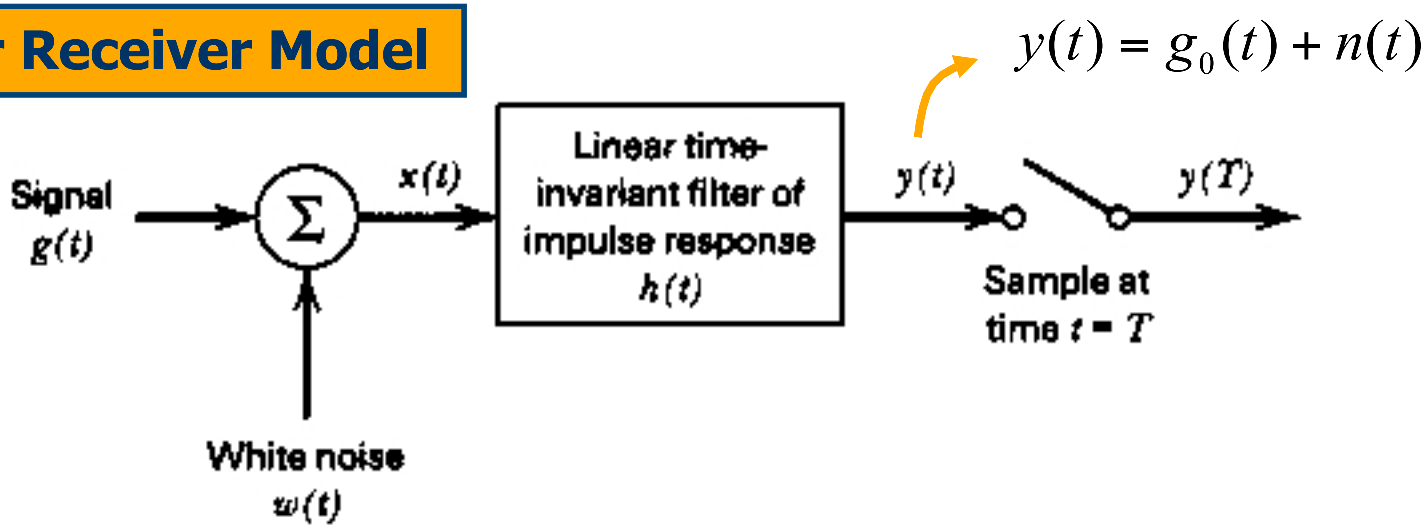
- $g(t)$: transmitted pulse signal, binary symbol '1' or '0'.
- $w(t)$: channel noise, sample function of a white noise process of zero mean and power spectral density $N_0/2$.

$$x(t) = g(t) + w(t) \quad , \quad 0 \le t \le T \;\longrightarrow\; h(t) \;\longrightarrow\; y(t) = g_0(t) + n(t)$$

- Filter Requirements, $h(t)$:
  - Make the instantaneous power in the output signal $g_0(t)$, measured at time $t=T$, as large as possible compared with the average power of the output noise, $n(t)$.

Maximize Signal-to-Noise Ratio

Linear Receiver Model



$$SNR = \frac{\text{instantaneous power in the output signal}}{\text{average output noise power}}$$

$$SNR = \frac{|g_0(T)|^2}{\overline{n^2(t)}}$$

Objective :

Specify the impulse response *h(t)* of the filter such that the output signal-to-noise ratio is maximized.

Math Review

Fourier Transform

$$G(f) = \int_{-\infty}^{\infty} g(t) \quad e^{-j\,2\pi\, f\, t}\, dt$$

Inverse Fourier Transform

$$g(t) = \int_{-\infty}^{\infty} G(f) \quad e^{j\,2\pi\, f\, t}\, df$$

Power Spectral Density of a Random Process $S_X(f)$ applied to a Linear System $H(f)$

$$S_Y(f) = \left|H(f)\right|^2 S_X(f)$$

Compute Signal-to-Noise Ratio

Signal Power

$$g_0(t) = \int_{-\infty}^{\infty} H(f)\, G(f)\, e^{j2\pi f t}\, df$$

$$\left|g_0(T)\right|^2 = \left|\int_{-\infty}^{\infty} H(f)\, G(f)\, e^{j2\pi f T}\, df\right|^2$$

Noise Power

$$S_N(f) = \frac{N_0}{2}\left|H(f)\right|^2$$

$$\overline{n^2(t)} = \int_{-\infty}^{\infty} S_N(f)\, df$$

$$\overline{n^2(t)} = \frac{N_0}{2}\int_{-\infty}^{\infty} \left|H(f)\right|^2\, df$$

Signal-to-Noise Ratio

$$SNR = \frac{\left|\int_{-\infty}^{\infty} H(f)\, G(f)\, e^{j2\pi f T}\, df\right|^2}{\frac{N_0}{2}\int_{-\infty}^{\infty} \left|H(f)\right|^2\, df}$$

Optimization Problem:

⇨ **For a given $G(f)$, find $H(f)$ in order to maximize SNR.**

Schwarz's Inequality

- **If we have 2 complex functions $\phi_1(x)$ and $\phi_2(x)$ in the real variable x, satisfying the conditions:**

$$\int_{-\infty}^{\infty} |\phi_1(x)|^2 \, dx < \infty \qquad \int_{-\infty}^{\infty} |\phi_2(x)|^2 \, dx < \infty$$

then we may write that:

$$\left| \int_{-\infty}^{\infty} \phi_1(x)\, \phi_2(x)\, dx \right|^2 \leq \int_{-\infty}^{\infty} |\phi_1(x)|^2 \, dx \int_{-\infty}^{\infty} |\phi_2(x)|^2 \, dx$$

iff $\phi_1(x) = k\, \phi_2^*(x)$

where k : arbitrary constant

setting: $\phi_1(x) = H(f)$ **and** $\phi_2(x) = G(f)\, e^{\,j\,2\pi f T}$

$$\left| \int_{-\infty}^{\infty} H(f)\, G(f)\, e^{\,j\,2\pi f T} \, df \right|^2 \leq \int_{-\infty}^{\infty} |H(f)|^2 \, df \int_{-\infty}^{\infty} |G(f)|^2 \, df$$

Matched Filter

$$SNR \le \frac{2}{N_0} \int_{-\infty}^{\infty} |G(f)|^2 \, df$$

$$SNR_{max} = \frac{2}{N_0} \int_{-\infty}^{\infty} |G(f)|^2 \, df$$

$$\phi_1(x) = k \, \phi_2^*(x)$$

$$H_{opt}(f) = k \, G^*(f) \, e^{-j 2\pi f T}$$

$$h_{opt}(t) = k \int_{-\infty}^{\infty} G^*(f) \quad e^{-j 2\pi f (T-t)} \, df$$

$$h_{opt}(t) = k \int_{-\infty}^{\infty} G(-f) \quad e^{-j 2\pi f (T-t)} \, df$$

- **for a real signal g(t) we have G*(f)=G(-f)**

$$h_{opt}(t) = k \, g(T-t)$$

- **The impulse response of the optimum filter, except for the scaling factor k, is a time-reversed and delayed version of the input signal g(t)**

Properties of Matched Filters

$$h_{opt}(t) = k\, g(T-t)$$

$$H_{opt}(f) = k\, G^*(f)\, e^{-j2\pi f T}$$

$$\begin{aligned} G_0(f) &= H_{opt}(f)\, G(f) \\ &= k\, G^*(f)\, G(f)\, e^{-j2\pi f T} \\ &= k\left|G(f)\right|^2 e^{-j2\pi f T} \end{aligned}$$

- **Taking the inverse Fourier transform at *t=T*:**

$$g_0(T) = \int_{-\infty}^{\infty} G_0(f)\, e^{\,j2\pi f T}\, df = k \int_{-\infty}^{\infty} \left|G(f)\right|^2 df = k\, E$$

Where E is the energy of the pulse signal *g(t)*

$$\overline{n^2(t)} = \frac{N_0}{2} \int_{-\infty}^{\infty} \left|H(f)\right|^2 df$$

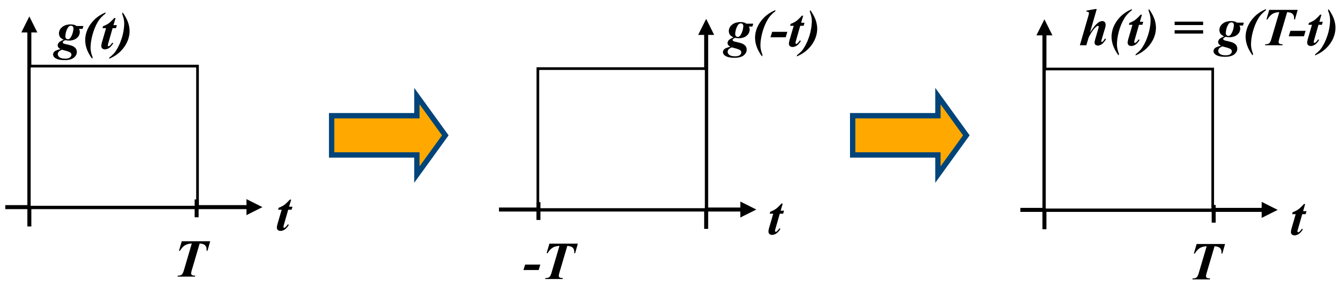
$$\overline{n^2(t)} = \frac{N_0}{2} k^2 \int_{-\infty}^{\infty} \left|G(f)\right|^2 df = k^2 \frac{N_0}{2} E$$

$$SNR_{\max} = \frac{k^2 E^2}{k^2 \frac{N_0}{2} E} = \frac{2\, E}{N_0}$$

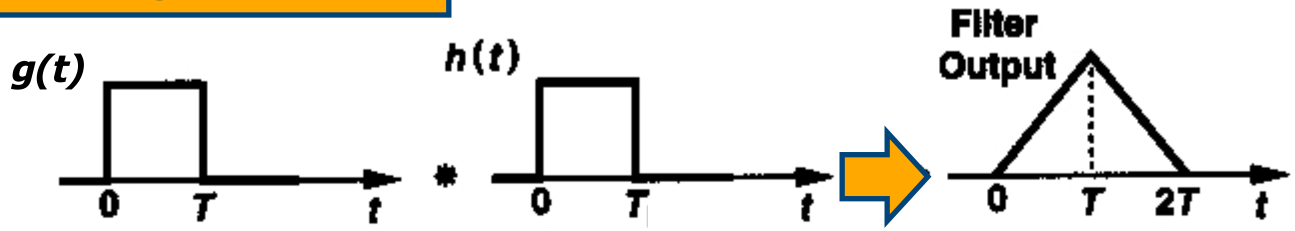
Matched Filter for Rectangular Pulse

h(t) for a rectangular Pulse:

$$h_{opt}(t) = k\ g(T - t)$$

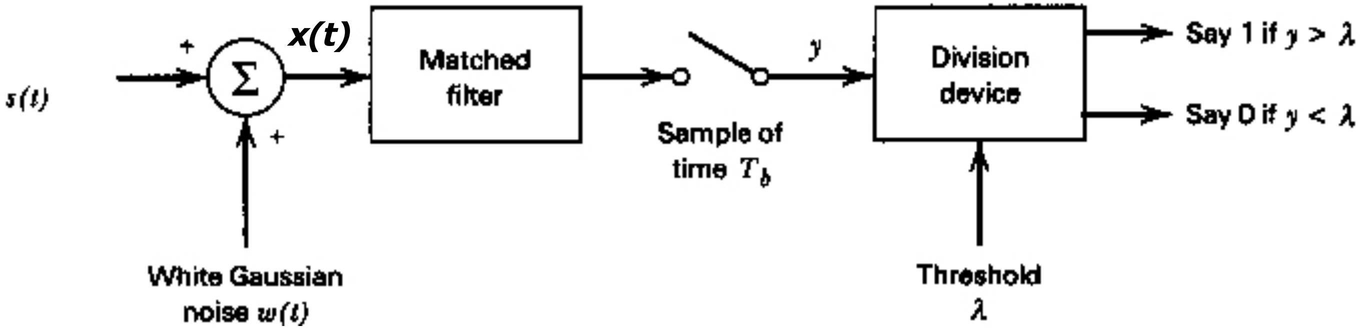


Filter Output g(t)*h(t):



Implementation:

Error Rate due to Noise



In the interval $0 \le t \le T_b$, the received signal:

$$x(t) = \begin{cases} +A + w(t) & , \quad \text{symbol '1' was sent} \\ -A + w(t) & , \quad \text{symbol '0' was sent} \end{cases}$$

T_b is the bit duration, A is the transmitted pulse amplitude

- **The receiver has prior knowledge of the pulse shape but not its polarity.**

- **There are two possible kinds of error to be considered:**
  - **(1) Symbol '1' is chosen when a '0' was transmitted.**
  - **(2) Symbol '0' is chosen when a '1' was transmitted.**

Error Rate due to Noise

Suppose that symbol '0' was sent: $x(t) = -A + w(t) \quad , \quad 0 \le t \le T_b$

The matched filter output is: $Y = \frac{1}{T_b}\int_0^{T_b} x(t)\, dt = -A + \frac{1}{T_b}\int_0^{T_b} w(t)\, dt$

Y is a random variable with Gaussian distribution and a mean of $-A$.

The variance of Y: $\sigma_Y^2 = \overline{(Y + A)^2} = \frac{1}{T_b^2}\int_0^{T_b}\int_0^{T_b} R_W(t,u)\, dt\, du$

Where $R_W(t,u)$ is the autocorrelation function of the white noise $w(t)$.
Since $w(t)$ is white with a PSD of $N_0/2$:

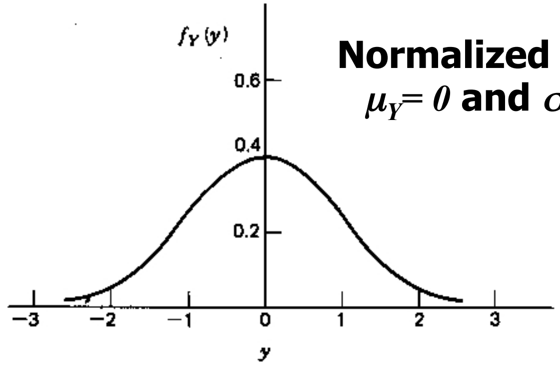
$$R_W(t,u) = \frac{N_0}{2}\delta(t-u)$$

$$\Rightarrow \quad \boxed{\sigma_Y^2 = \frac{N_0}{2\, T_b}}$$

PDF: Probability Density Function

- **Gaussian Distribution:**

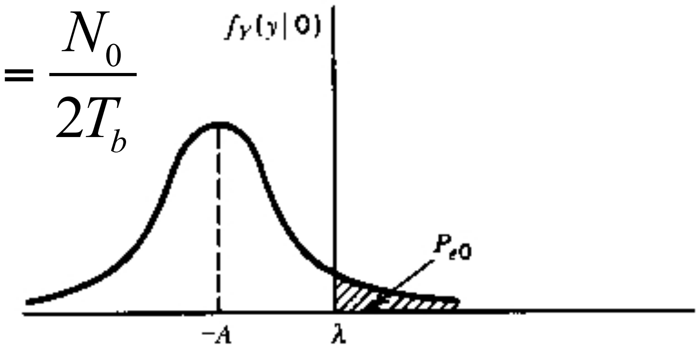
$$f_Y(y) = \frac{1}{\sigma_Y \sqrt{2\pi}} \exp\left[-\frac{(y-\mu_Y)^2}{2\sigma_Y^2}\right]$$



- **Symbol '0' was sent:** $\mu_Y = -A\,,\quad \sigma_Y^2 = \frac{N_0}{2T_b}$

$$P_{e0} = P(y > \lambda | \text{symbol '0' was sent})$$

$$= \int_{\lambda}^{\infty} f_Y(y|0)\, dy$$

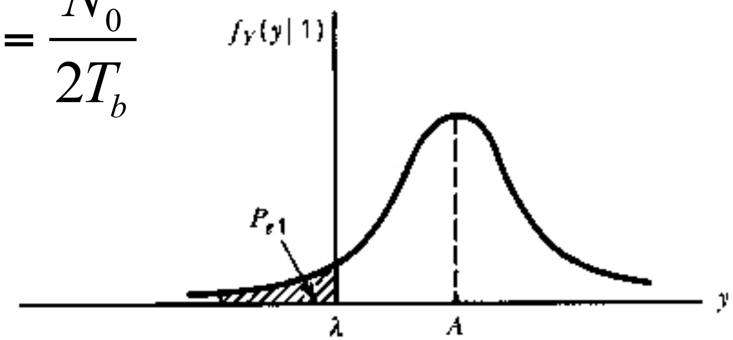


(a)

- **Symbol '1' was sent:** $\mu_Y = +A\,,\quad \sigma_Y^2 = \frac{N_0}{2T_b}$

$$P_{e0} = P(y < \lambda | \text{symbol '1' was sent})$$

$$= \int_{-\infty}^{\lambda} f_Y(y|1)\, dy$$



(b)

BER in a PCM receiver

$$P_{e0} = \frac{1}{\sqrt{\pi N_0 / T_b}} \int_{\lambda}^{\infty} \exp\left[- \frac{(y+A)^2}{N_0 / T_b} \right] dy$$

- **let $\lambda=0$ and the probabilities of binary symbols: $p_0 = p_1 = 1/2$.**

$$z = \frac{y+A}{\sqrt{N_0 / T_b}} \qquad P_{e0} = \frac{1}{\sqrt{\pi}} \int_{\sqrt{E_b / N_0}}^{\infty} \exp\left[-z^2\right] dz$$

- **where $E_b = A^2 T_b$, is the transmitted signal energy per bit.**
- **the complementary error function:** $erfc(u) = \frac{1}{\sqrt{\pi}} \int_{u}^{\infty} \exp\left[-z^2\right] dz$

$$\boxed{P_{e1} = P_{e0} = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}} \right)}$$

BER in a PCM receiver

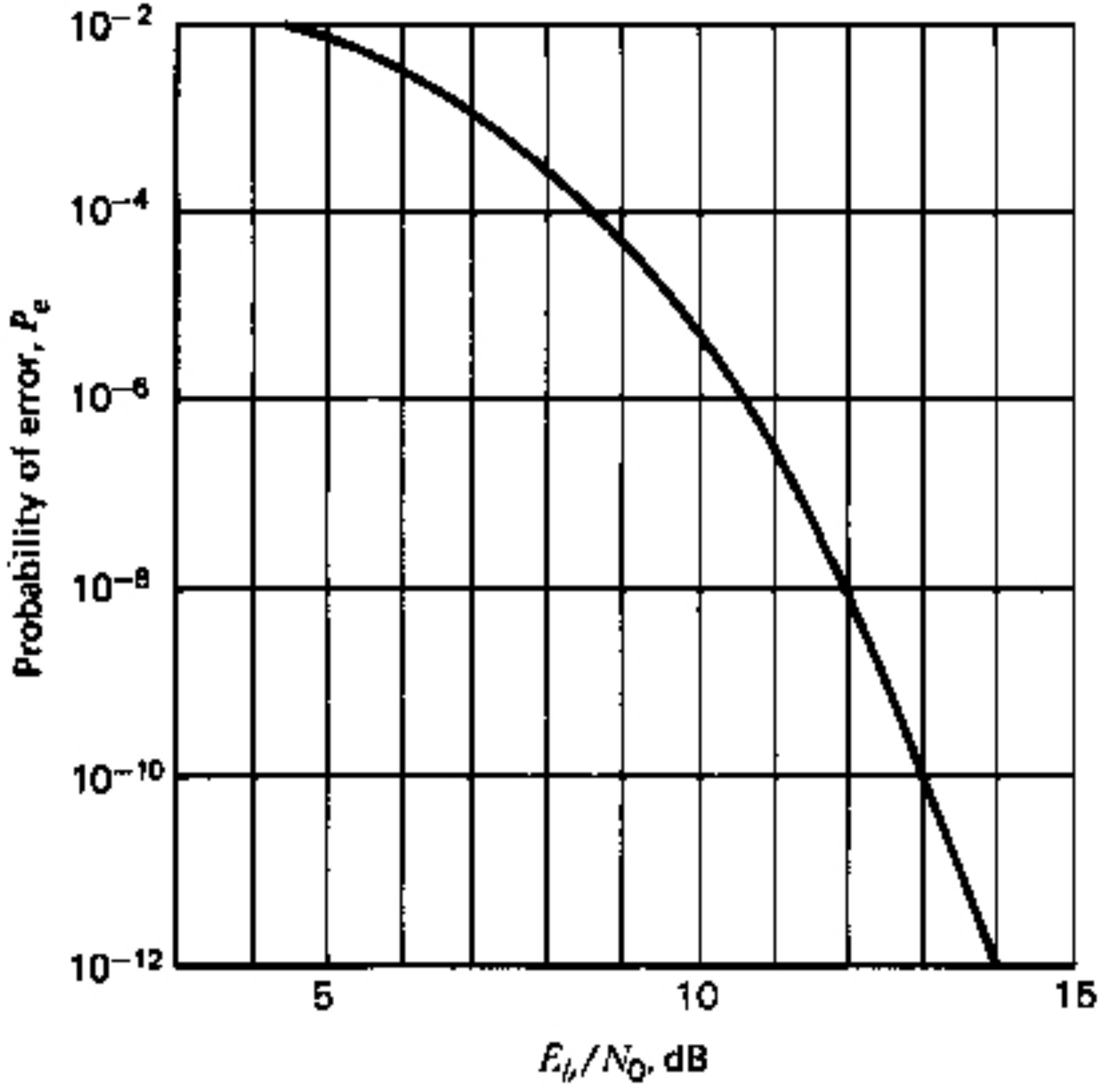
$$P_e = p_0 P_{e0} + p_1 P_{e1}$$

$$P_{e0} = P_{e1}$$

$$p_0 = p_1 = \frac{1}{2}$$

$$P_e = P_{e0} = P_{e1}$$

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



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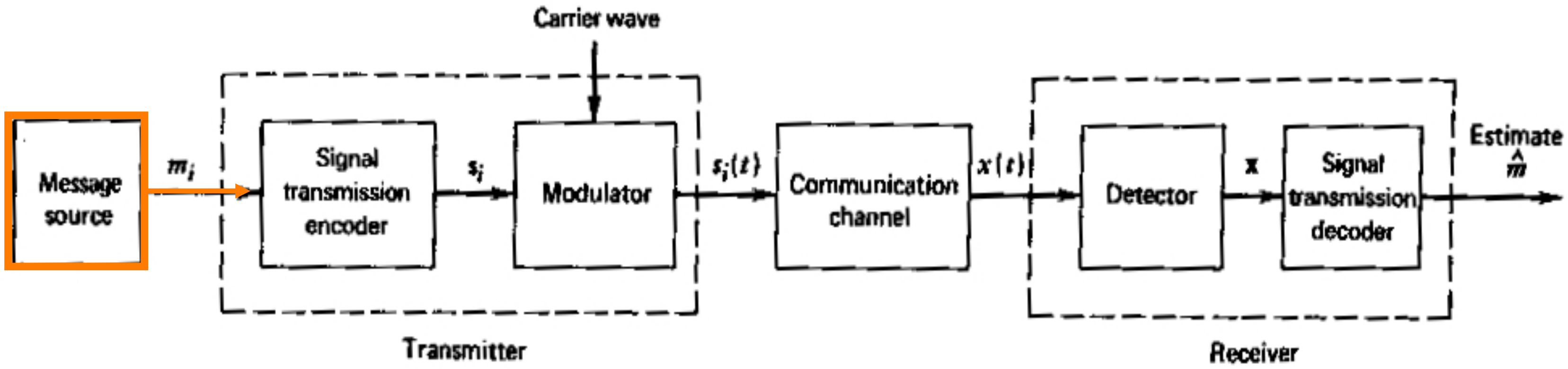
Why Modulation?

- In wired systems, coaxial lines exhibit superior shielding at higher frequencies
- In wireless systems, the antenna size should be a significant fraction of the wavelength to achieve a reasonable gain.
- Communication must occur in a certain part of the spectrum because of FCC regulations.
- Modulation allows simpler detection at the receive end in the presence of non-idealities in the communication channel.

Message Source



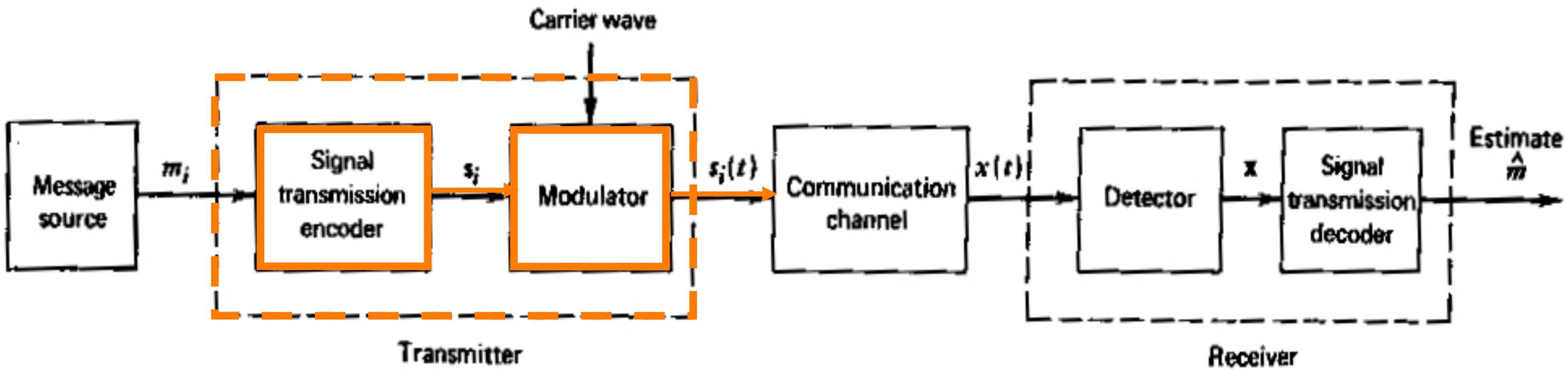
- m_i **: one symbol every** T **seconds**
- **Symbols belong to an alphabet of** M **symbols:** $m_1, m_2, \ldots, m_M$
- **Message output probability:**

$$P(m_1) = P(m_2) = \ldots = P(m_M)$$

$$p_i = P(m_i) = \frac{1}{M}$$

- **Example: Quaternary PCM, 4 symbols:** *00, 01, 10, 11*

Transmitter



- **<u>Signal Transmission Encoder:</u> produces a vector s_i made up of N real elements, where $N \leq M$.**
- **<u>Modulator:</u> constructs a distinct signal $s_i(t)$ representing m_i of duration T .**

- **Energy of $s_i(t)$:**

$$E_i = \int_0^T s_i^2(t) \quad dt, \quad i = 1, 2, \ldots, M$$

- **$s_i(t)$ is real valued and transmitted every T seconds.**

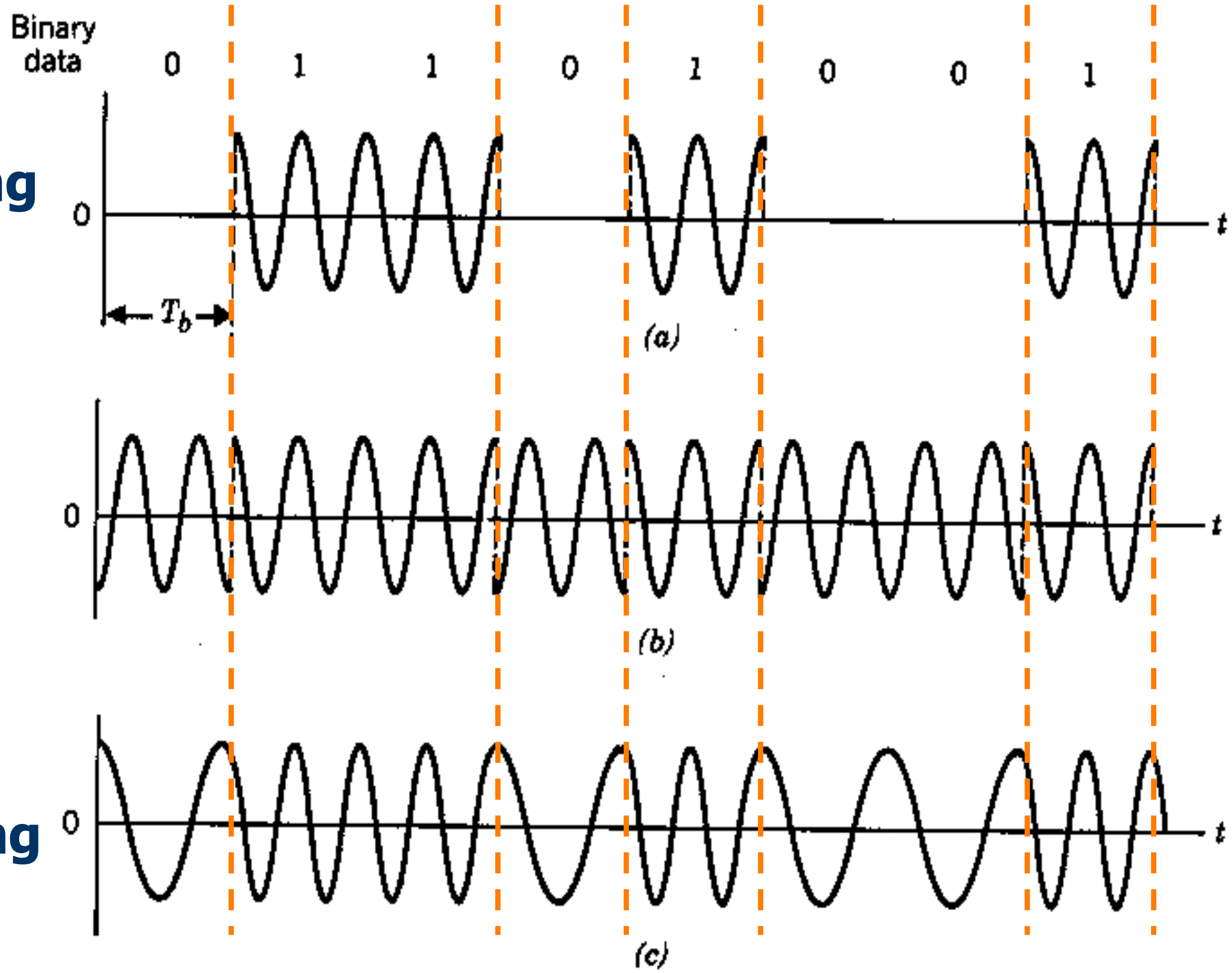
Examples of Transmitted signals: $s_i(t)$

- **The modulator performs a step change in the amplitude, phase or frequency of the sinusoidal carrier**

- **ASK:**
  Amplitude Shift Keying

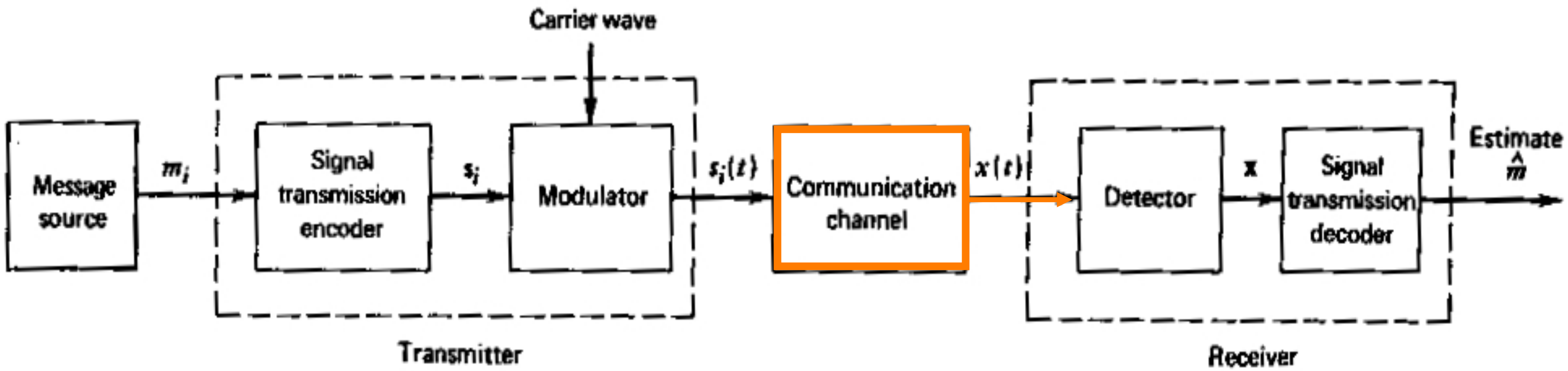
- **PSK:**
  Phase Shift Keying

- **FSK:**
  Frequency Shift Keying



Special case: Symbol Duration T = Bit Duration, T_b

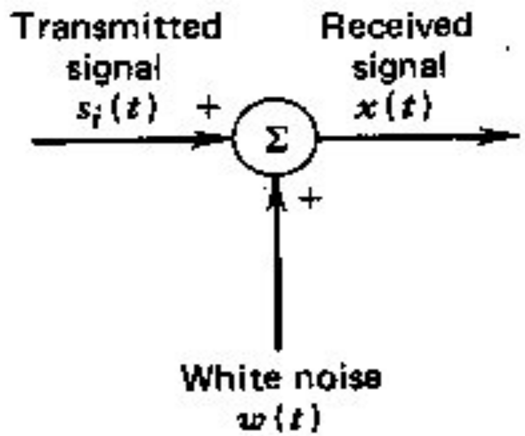
Communication Channel



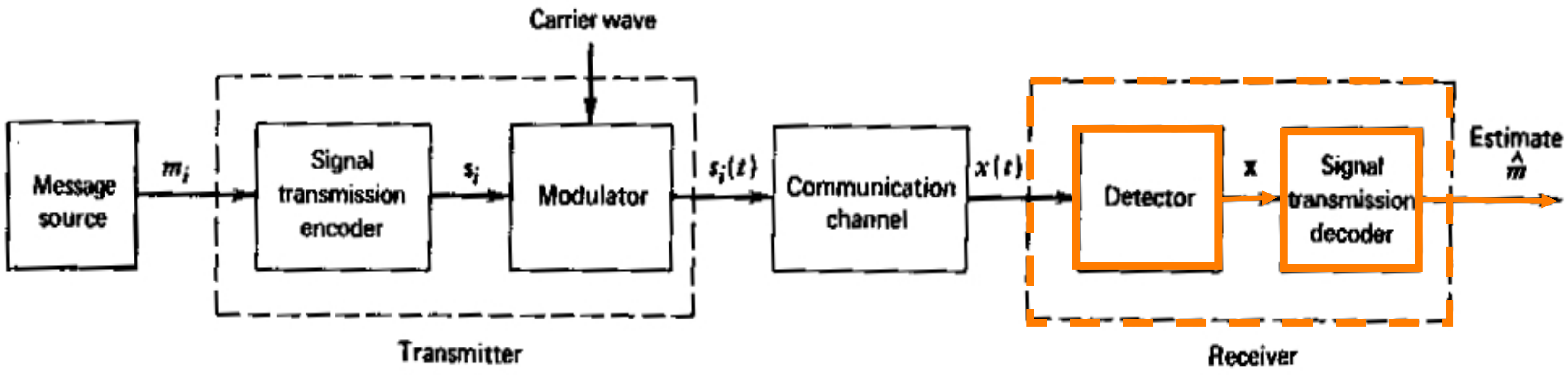
- **Two Assumptions:**
  - **The channel is linear (no distortion).**
  - **$s_i(t)$ is perturbed by an Additive, zero-mean, stationnary, White, Gaussian Noise process (AWGN).**

- **Received signal $x(t)$:**

$$x(t) = s_i(t) + w(t), \quad \begin{cases} 0 \le t \le T \\ i = 1, 2, \ldots, M \end{cases}$$



Receiver

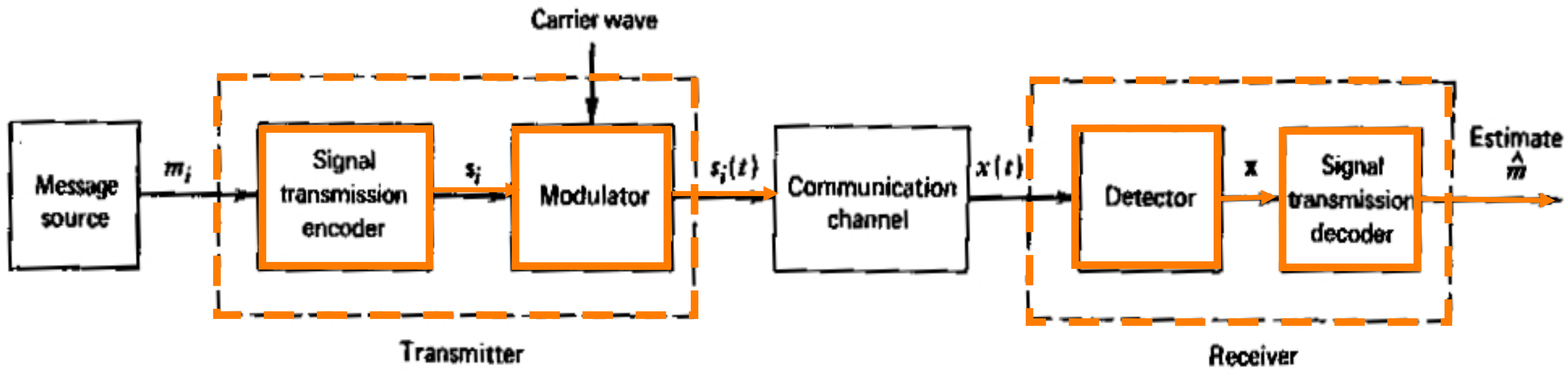


- **TASK: observe received signal, $x(t)$, for a duration T and make a best estimate of transmitted symbol, m_i .**
  - **Detector: produces observation vector x .**
  - **Signal Transmission Decoder: estimates $\hat{m}$ using x, the modulation format and $P(m_i)$.**

- **The requirement is to design a receiver so as to minimize the average probability of symbol error:**

$$P_e = \sum_{i=1}^{M} P(\hat{m} \neq m_i) P(m_i)$$

Coherent and Non-Coherent Detection



- **Coherent Detection:**
  - **The receiver is time synchronized with the transmitter.**
  - **The receiver knows the instants of time when the modulator changes state.**
  - **The receiver is phase-locked to the transmitter.**

- **Non-Coherent Detection:**
  - **No phase synchronism between transmitter and receiver.**

Gram-Schmidt Orthogonalization Procedure

- **we represent the given set of real-valued energy signals** $s_1(t), s_2(t), \ldots, s_M(t)$**, each of duration T:**

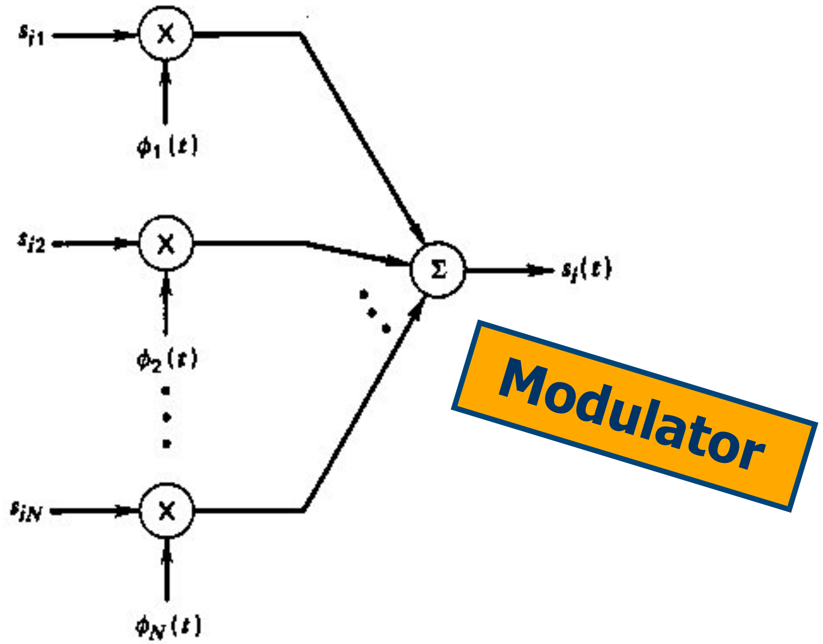
$$s_i(t) = \sum_{j=1}^{N} s_{ij}\,\phi_j(t) \quad , \quad \begin{cases} 0 \le t \le T \\ i = 1, 2, \ldots, M \end{cases}$$

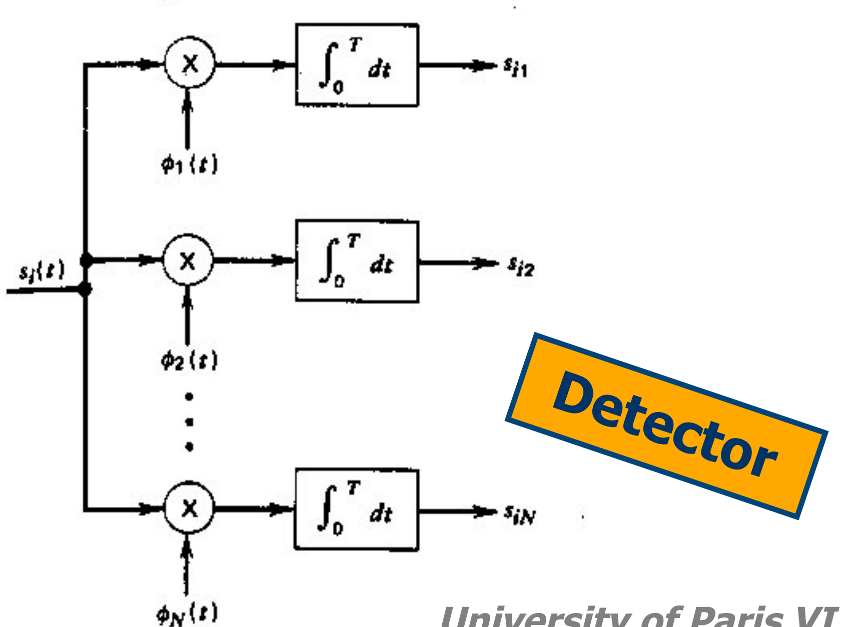
- **where the coefficients of the expansion are defined by:**

$$s_{ij} = \int_0^T s_i(t)\,\phi_j(t)\,dt \quad , \quad \begin{cases} i = 1, 2, \ldots, M \\ j = 1, 2, \ldots, N \end{cases}$$

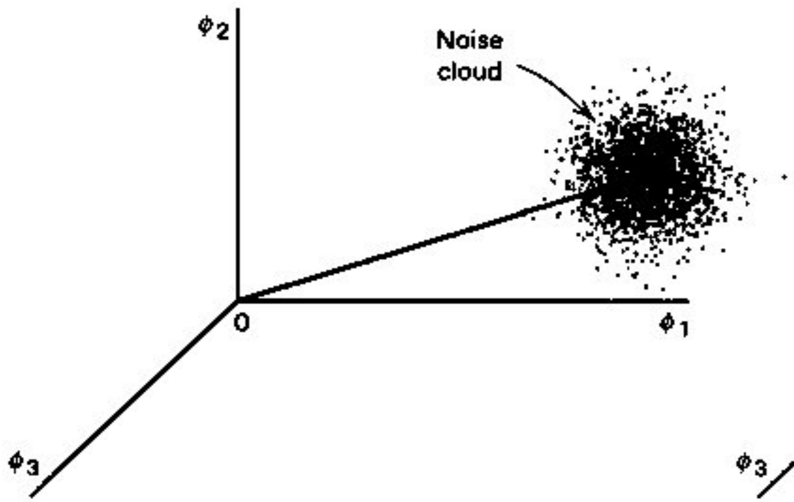
- **the real-valued basis functions** $\phi_1(t), \phi_2(t), \ldots, \phi_N(t)$ **are orthonormal:**

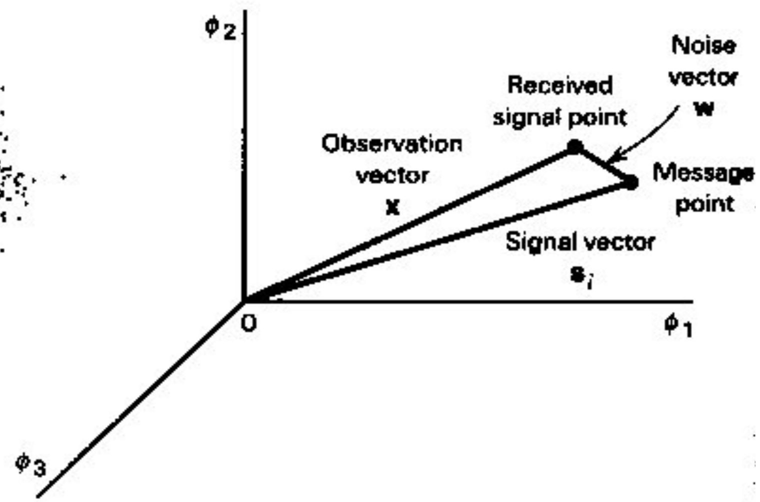
$$\int_0^T \phi_i(t)\,\phi_j(t)\,dt = \begin{cases} 1 & if \quad i = j \\ 0 & if \quad i \ne j \end{cases}$$





Coherent Detection of Signals in Noise





- **Signal Vector s_i :**

$$s_i = \begin{bmatrix} s_{i1} \\ s_{i2} \\ \prec \\ s_{iN} \end{bmatrix} \quad , \quad i = 1,2,\ldots,M$$

- **Observation vector x :**

$$x = s_i + w \quad , \quad i = 1, 2, \ldots, M$$

where w is the noise vector.

$$x(t) = s_i(t) + w(t), \quad \begin{cases} 0 \le t \le T \\ i = 1, 2, \ldots, M \end{cases}$$

- **$w(t)$ is a sample function of an AWGN with power spectral density $N_0/2$.**

Coherent Binary PSK:

- *M=2, N=1*
  $0 \le t \le T_b$

$$s_1(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t)$$

$$s_2(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \pi)$$

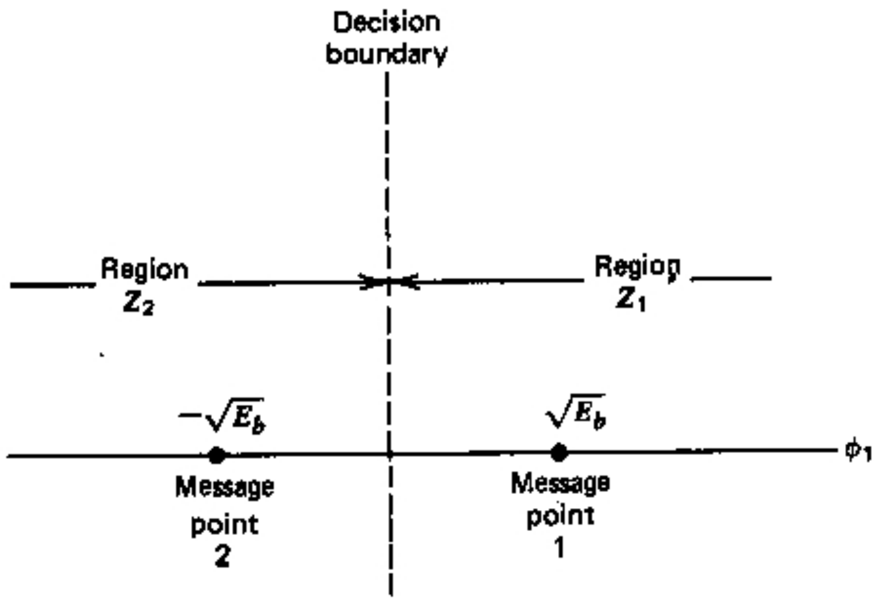
- **To ensure that each transmitted bit contains an integral number of cycles of the carrier wave, fc =nc/Tb, for some fixed integer nc.**

- **One basis function:** $\phi_1(t) = \sqrt{\frac{2}{T_b}}\cos(2\pi f_c t) \quad , \quad 0 \le t \le T_b$

- **Signal constellation consists of two message points:**

$$s_{11} = \int_0^{T_b} s_1(t)\,\phi_1(t)dt = \sqrt{E_b}$$

$$s_{21} = \int_0^{T_b} s_2(t)\,\phi_1(t)dt = -\sqrt{E_b}$$

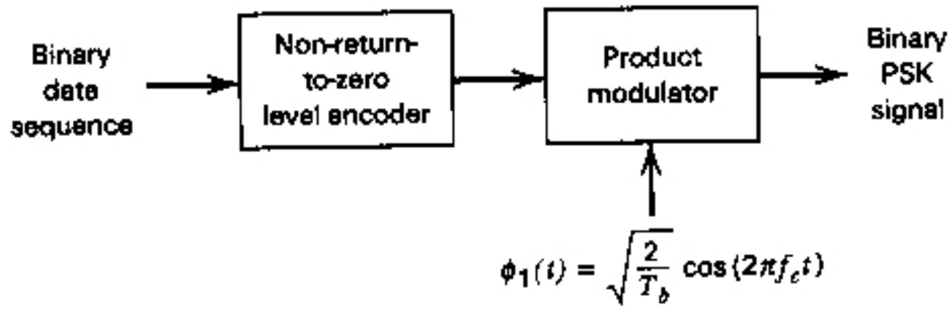


Generation and Detection of Coherent Binary PSK

- **Assuming white Gaussian Noise with** $PSD = N_0/2$ **, The Bit Error Rate for coherent binary PSK is:**

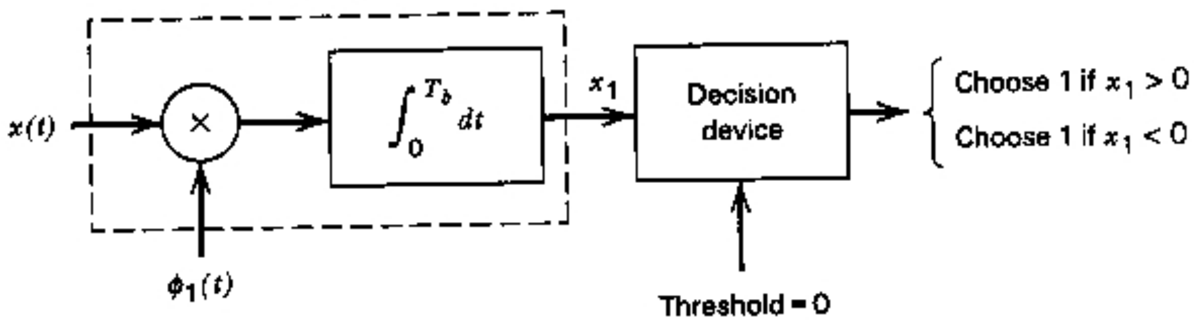
$$P_e = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right)$$

Binary PSK Transmitter



(a)

Coherent Binary PSK Receiver



(b)

Coherent QPSK:

- ***M=4, N=2:***

$$s_i(t) = \begin{cases} \sqrt{\dfrac{2E}{T}} \cos\left[2\pi f_c t + (2i-1)\dfrac{\pi}{4}\right] & , \quad 0 \le t \le T \\ 0 & , \quad \text{elsewhere} \end{cases}$$

$$s_1(t) = \sqrt{\frac{2E}{T}} \cos(2\pi f_c t + \frac{\pi}{4})$$

$$s_2(t) = \sqrt{\frac{2E}{T}} \cos(2\pi f_c t + 3\frac{\pi}{4})$$

$$s_3(t) = \sqrt{\frac{2E}{T}} \cos(2\pi f_c t + 5\frac{\pi}{4})$$

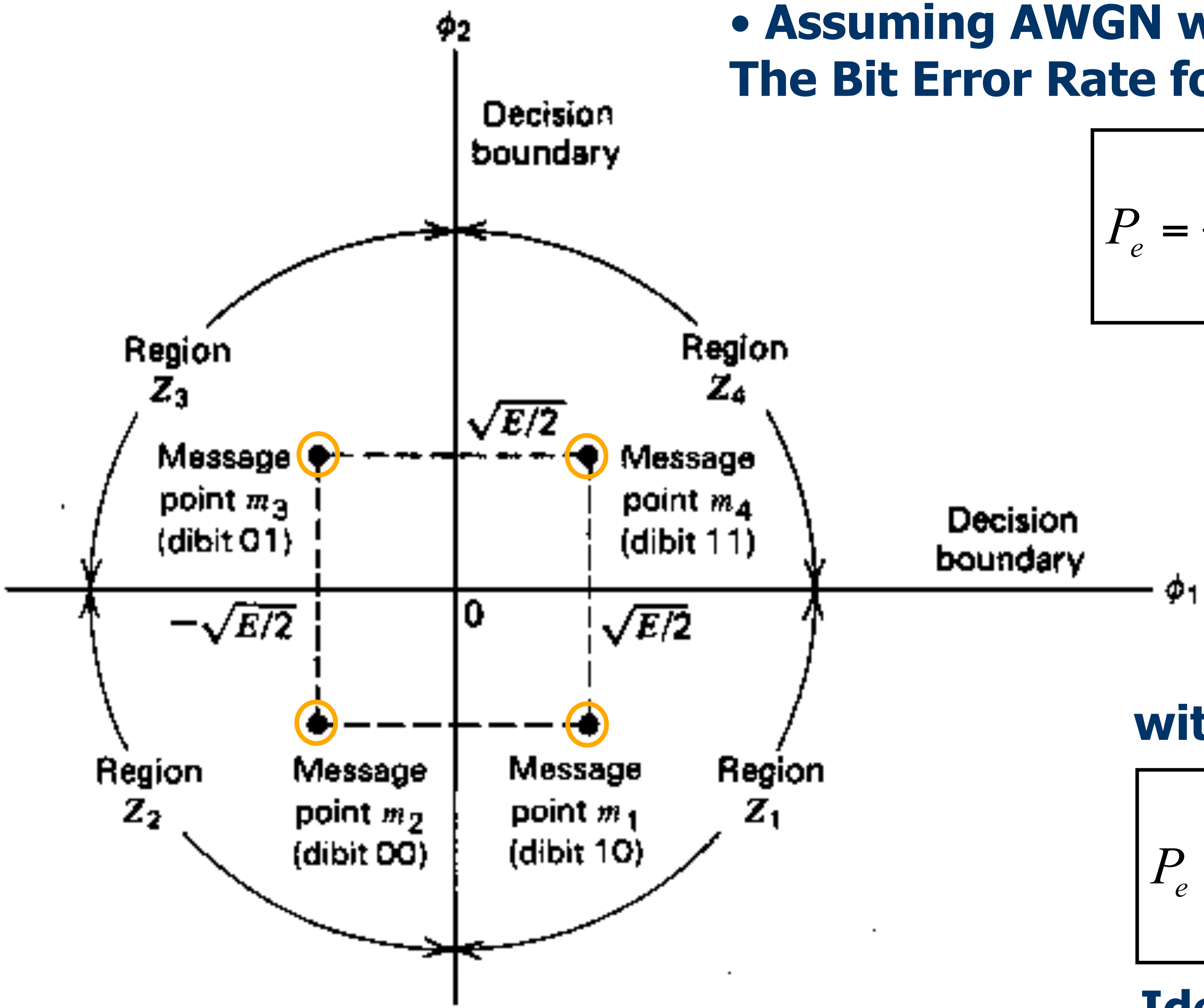
$$s_4(t) = \sqrt{\frac{2E}{T}} \cos(2\pi f_c t + 7\frac{\pi}{4})$$

- **Two basis function:**

$$\phi_1(t) = \sqrt{\frac{2}{T}} \cos(2\pi f_c t) \quad , \quad 0 \le t \le T$$

$$\phi_2(t) = \sqrt{\frac{2}{T}} \sin(2\pi f_c t) \quad , \quad 0 \le t \le T$$

Constellation Diagram of Coherent QPSK System



- **Assuming AWGN with** $PSD = N_0/2$ **,**
The Bit Error Rate for coherent QPSK is:

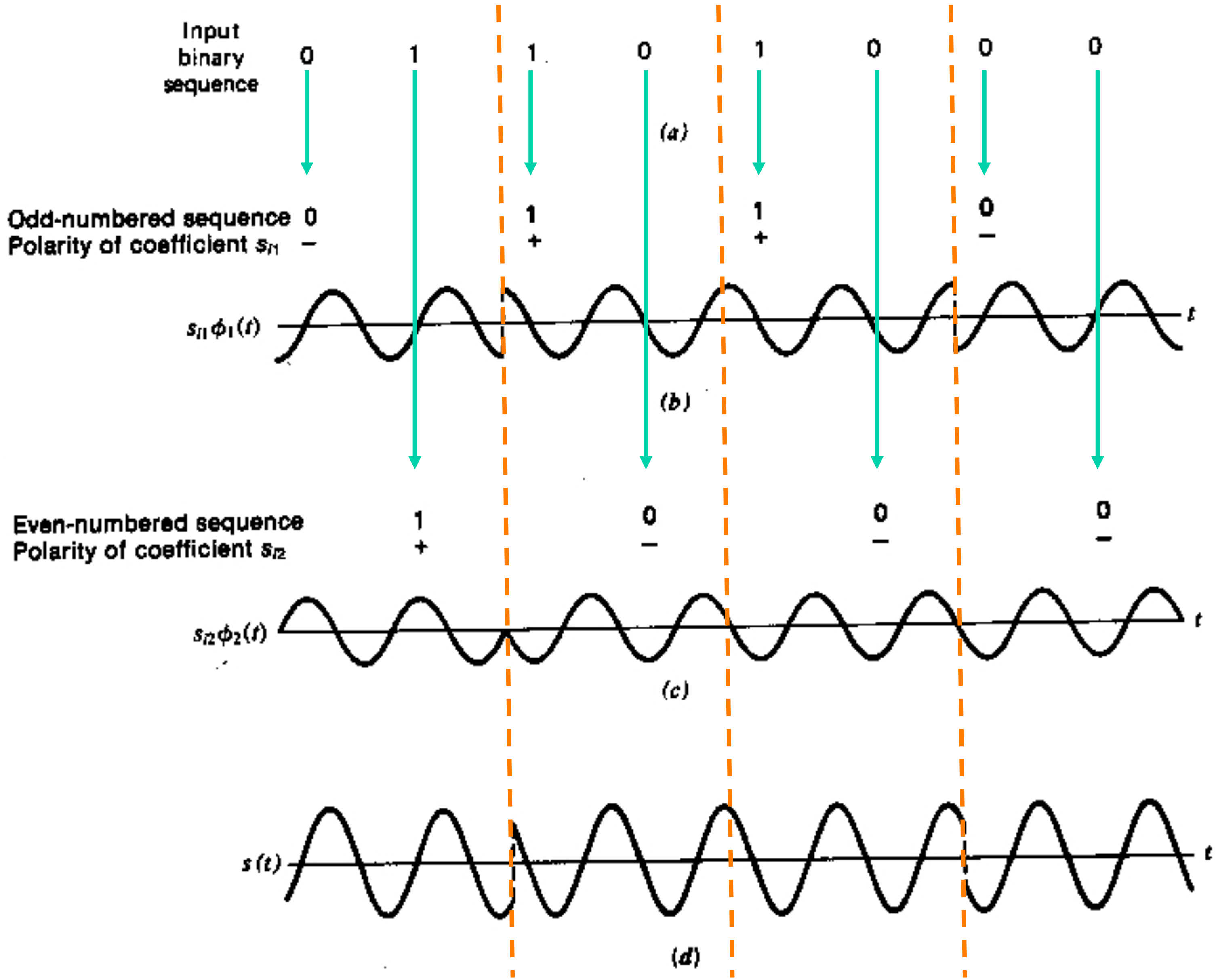
$$P_e = \frac{1}{2} erfc\left(\sqrt{\frac{E/2}{N_0}}\right)$$

with $E = 2\,E_b$

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

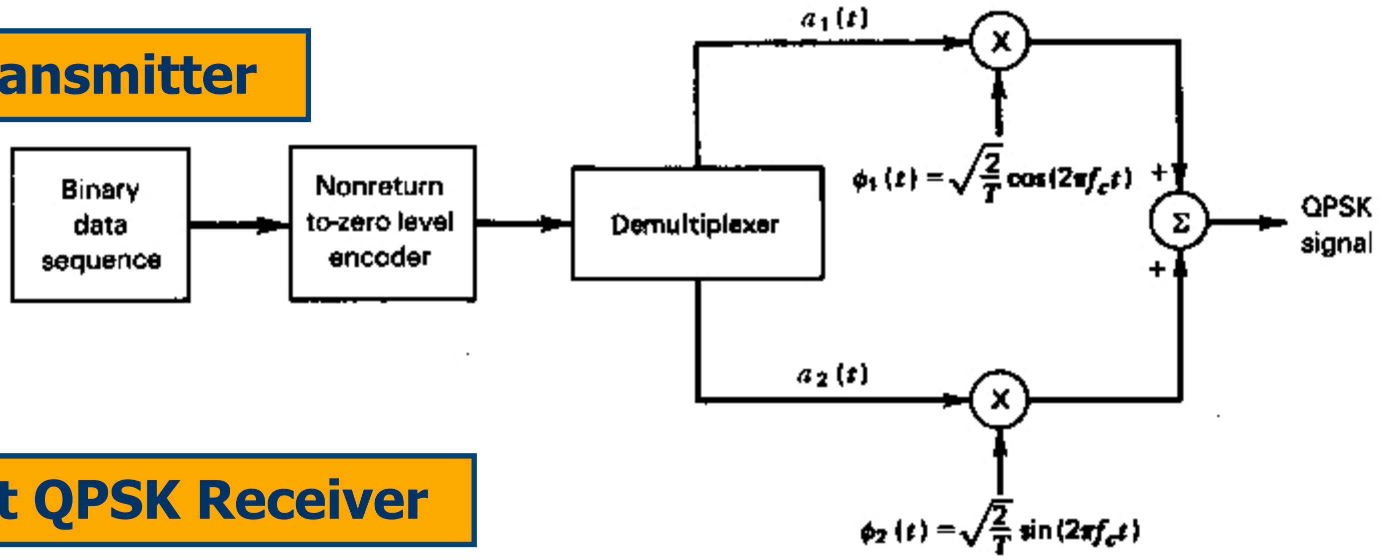
Identical to BPSK

QPSK waveform: 01101000

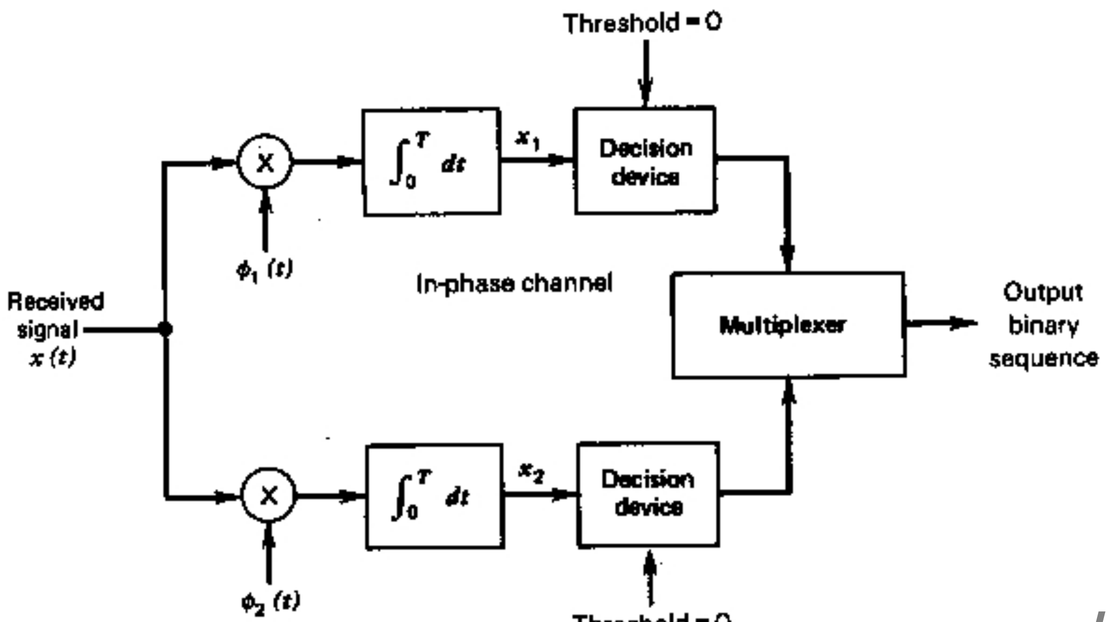


Generation and Detection of Coherent QPSK Signals

QPSK Transmitter



Coherent QPSK Receiver



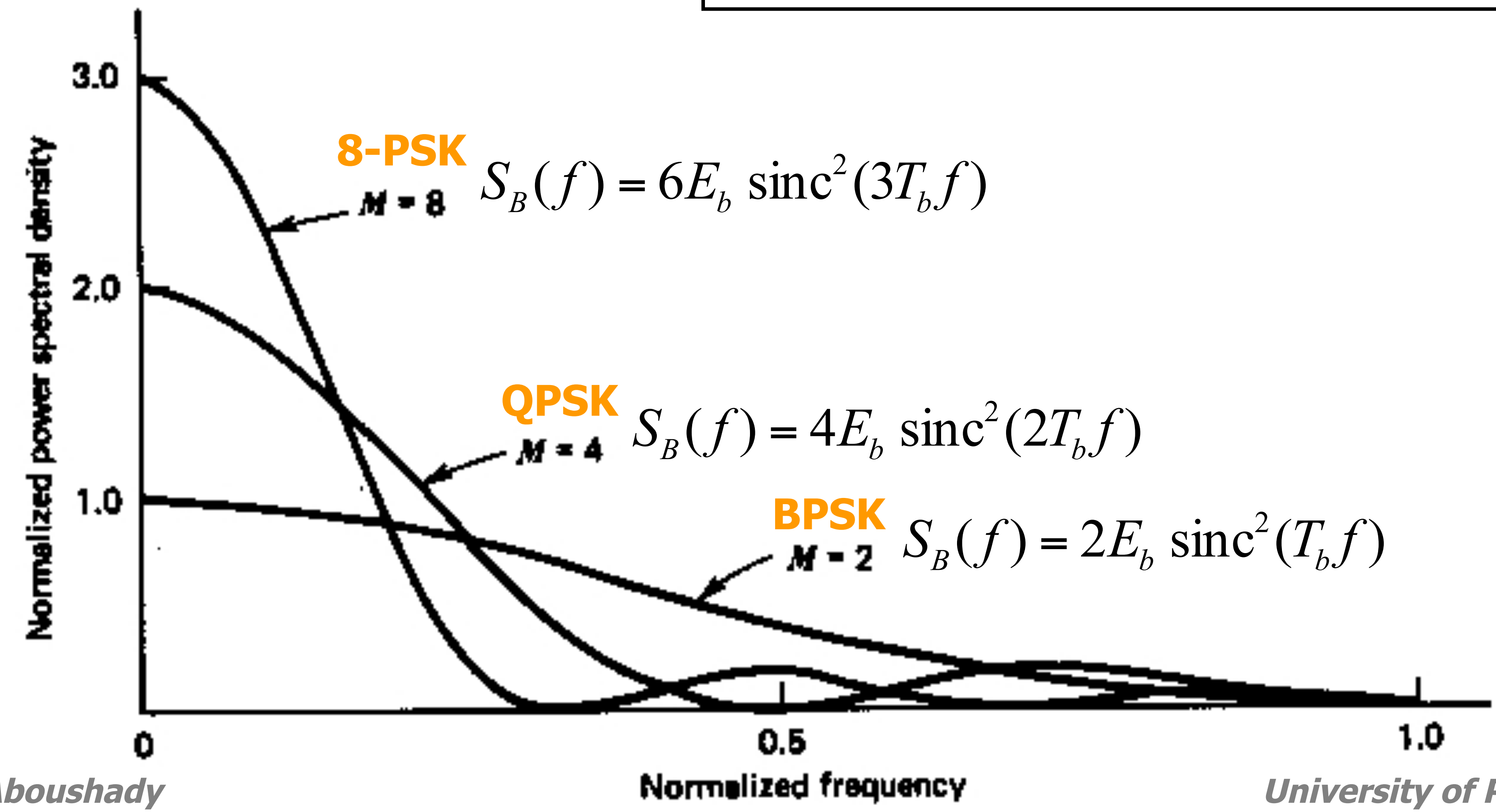
Power Spectra of BPSK ,QPSK and M-ary PSK

- **Symbol Duration:**

$$T = T_b \log_2 M$$

- **Power Spectral Density of an M-ary PSK signal:**

$$\begin{aligned} S_B(f) &= 2E \operatorname{sinc}^2(Tf) \\ &= 2E_b \log_2 M \operatorname{sinc}^2(T_b f \log_2 M) \end{aligned}$$



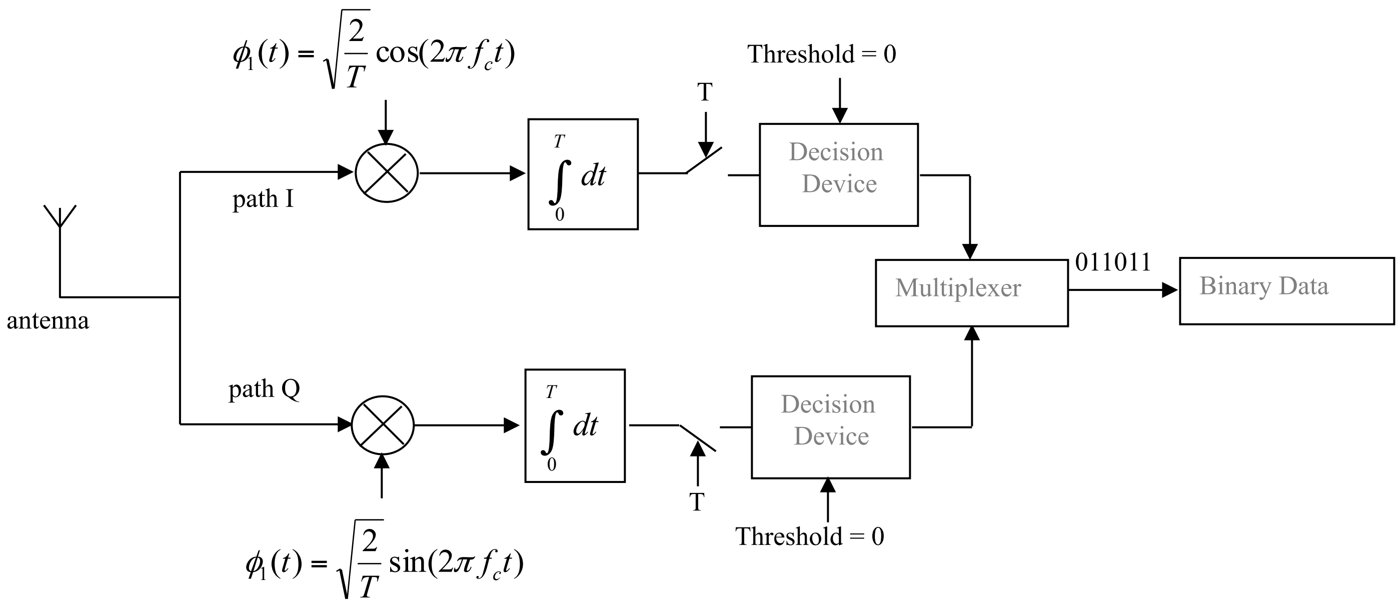
CIRF
Circuit Intégré Radio Fréquence

Lecture I

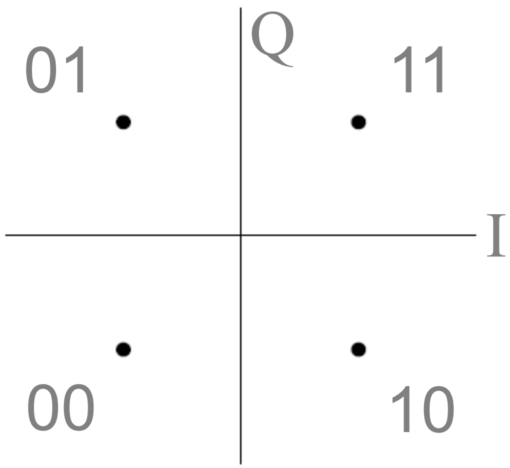
- Introduction
- Baseband Pulse Transmission
- Digital Passband Transmission
- Circuit Non-idealities Effect

Hassan Aboushady
Université Paris VI

QPSK Receiver



QPSK Constellation Diagram



Receiver Circuit Non-Idealities

Circuit Noise (Thermal, 1/f)

Gain Mismatch

Phase Mismatch

DC Offset

Frequency Offset

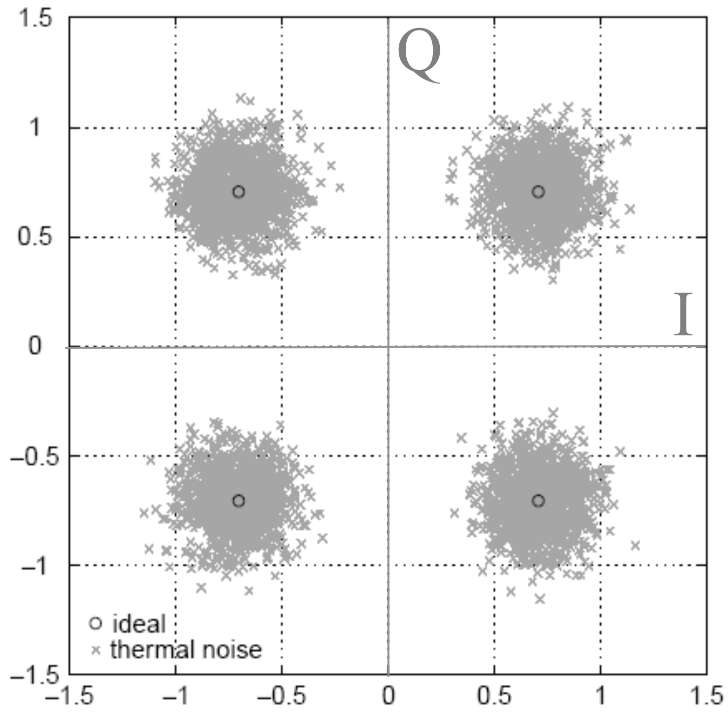
Local Oscillator phase noise

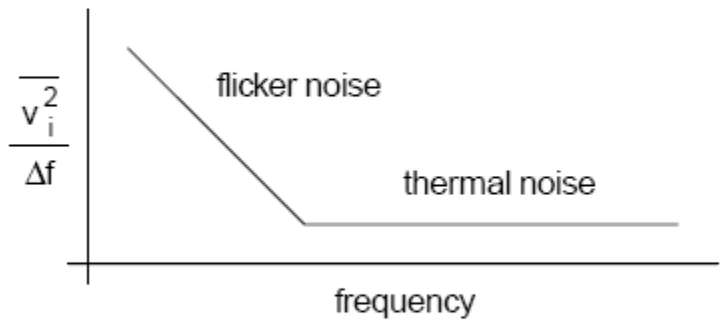
Circuit Noise

Circuit Noise:

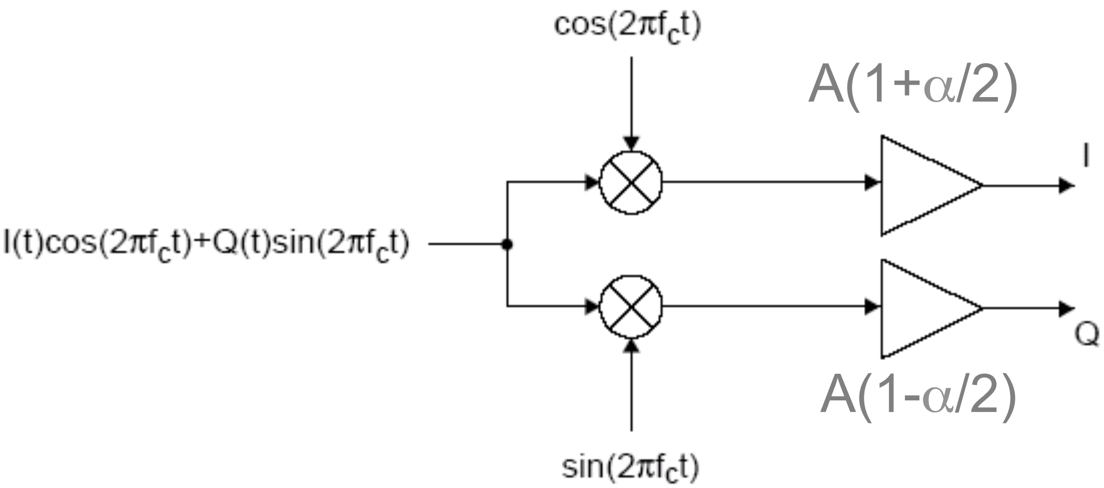
- Thermal Noise
  - Resistors
  - Transistors

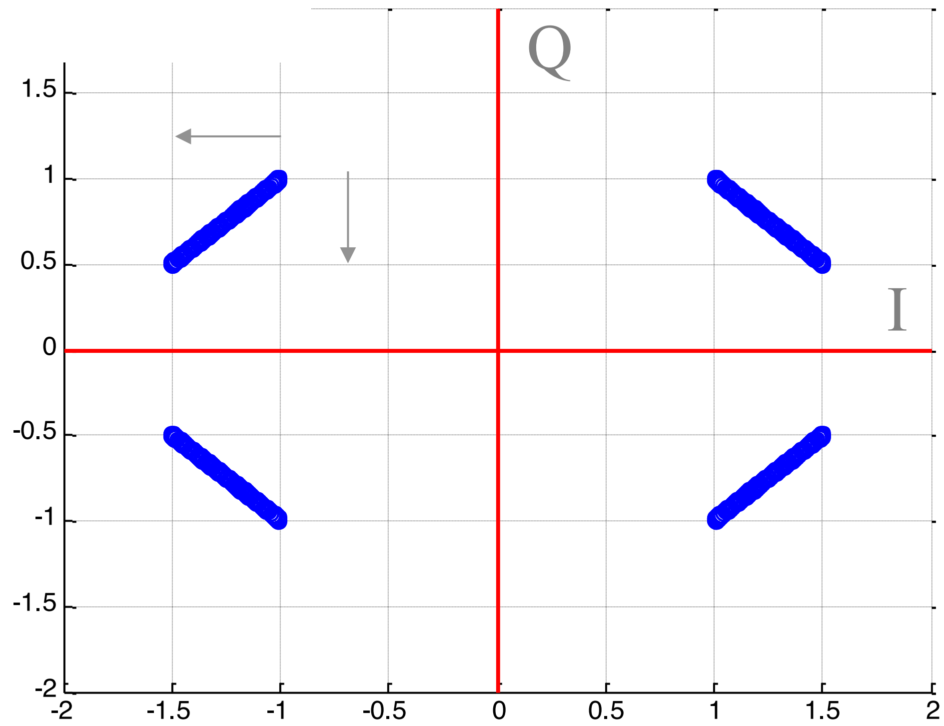
- Flicker (1/f) Noise
  - MOS transistors



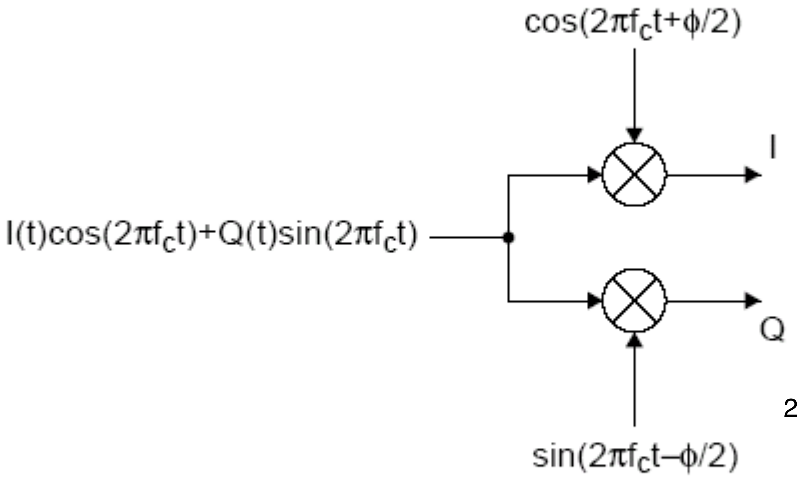


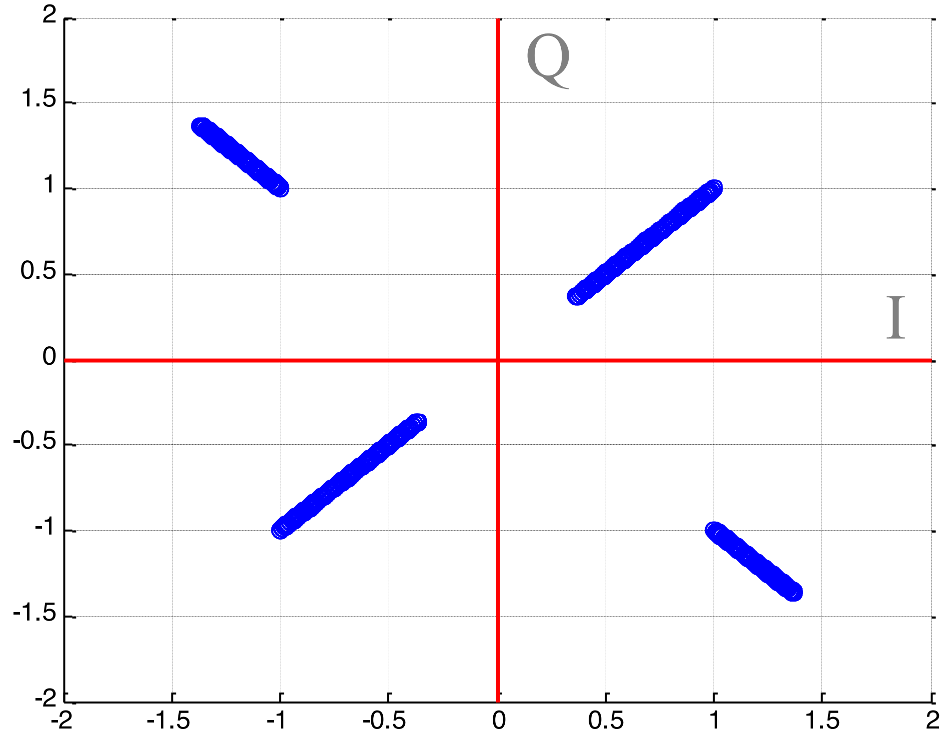
Gain Mismatch



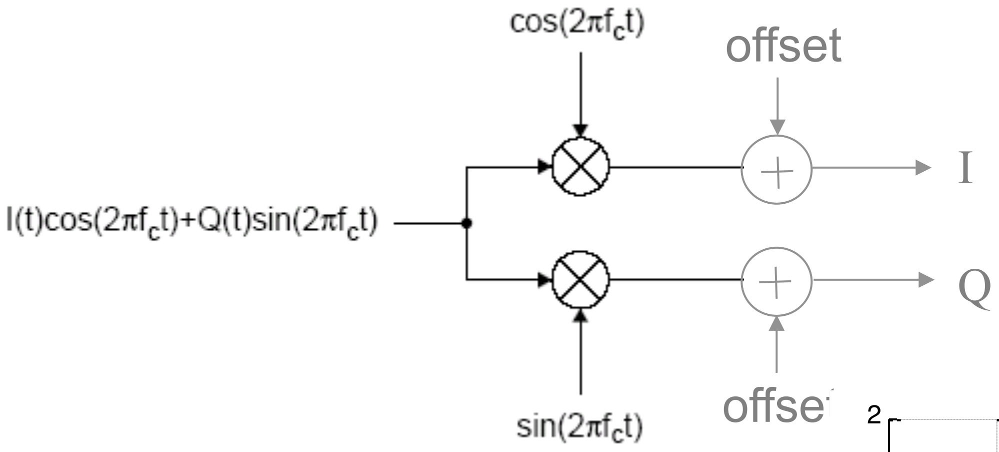


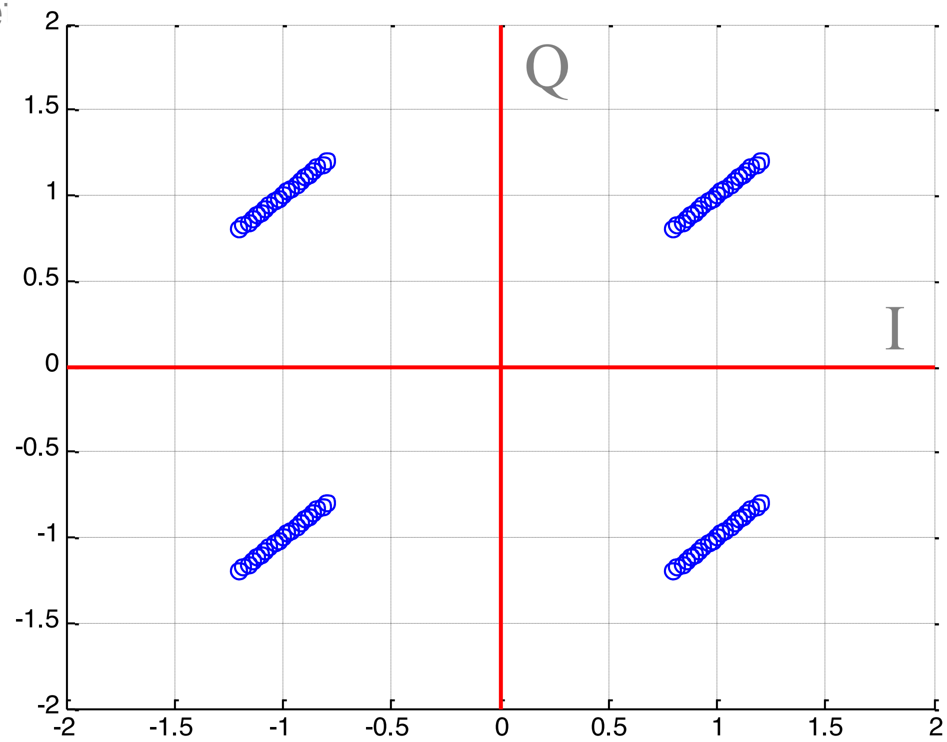
Phase Mismatch



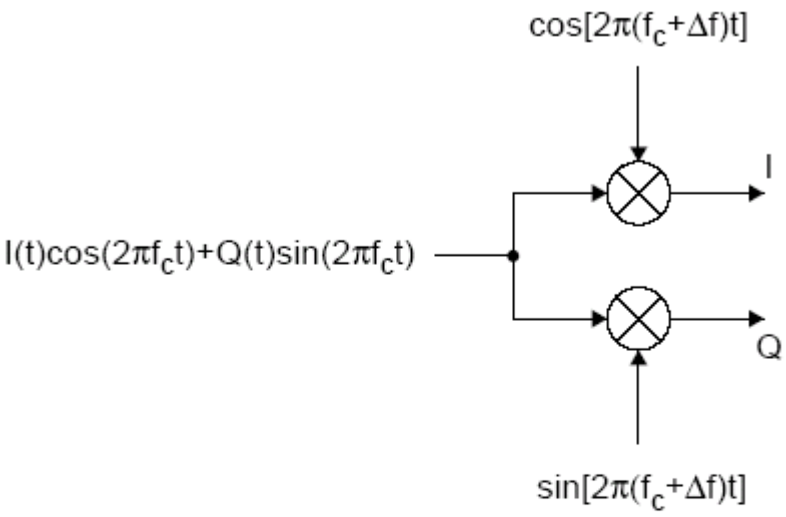


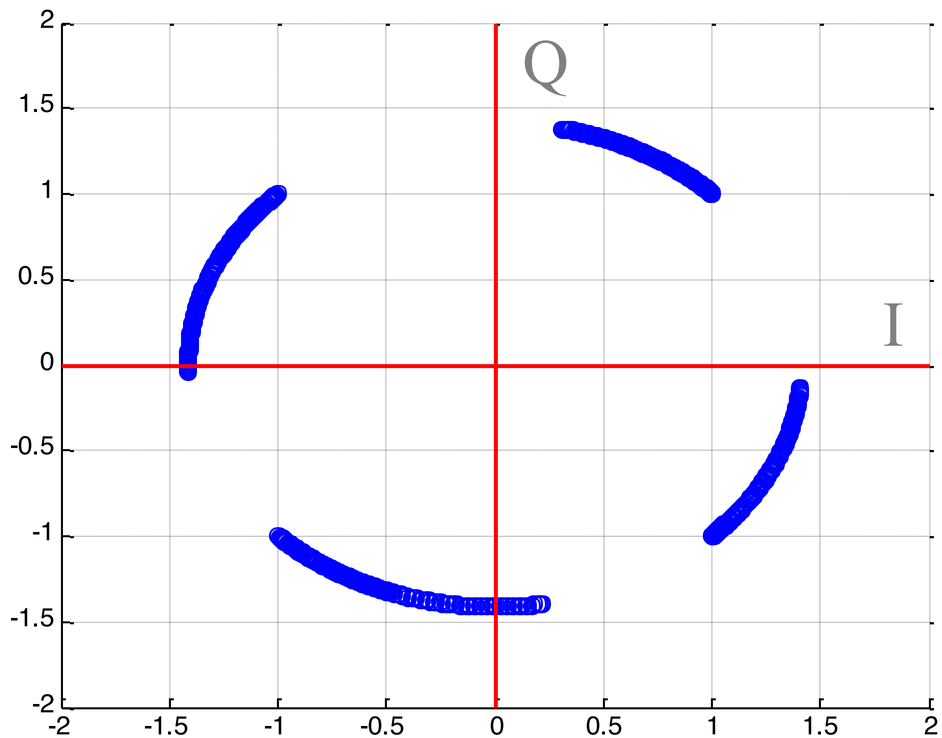
DC Offset


cos(2πf_ct)
offset
I
I(t)cos(2πf_ct)+Q(t)sin(2πf_ct)
Q
sin(2πf_ct)
offse

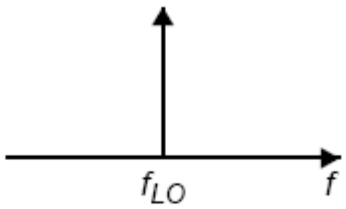

Q
I
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2

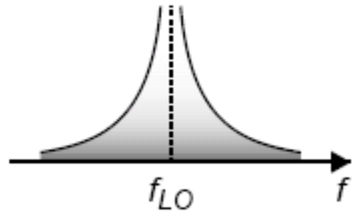
Frequency Offset

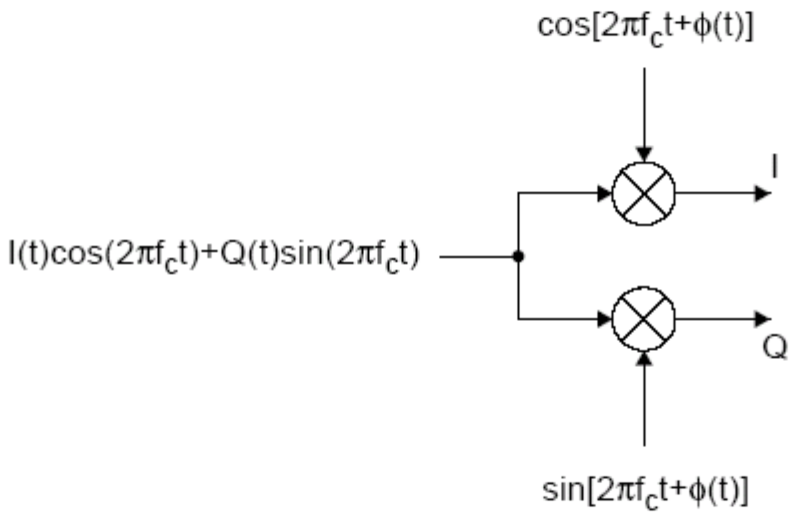


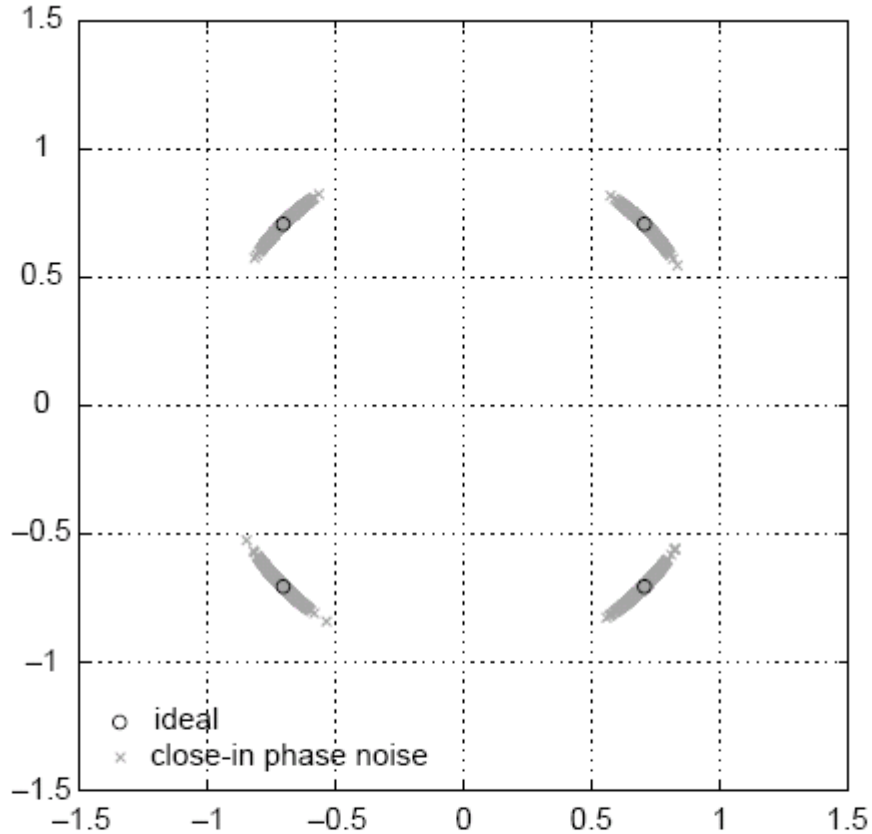


Local Oscillator Phase Noise









Reciprocal Mixing