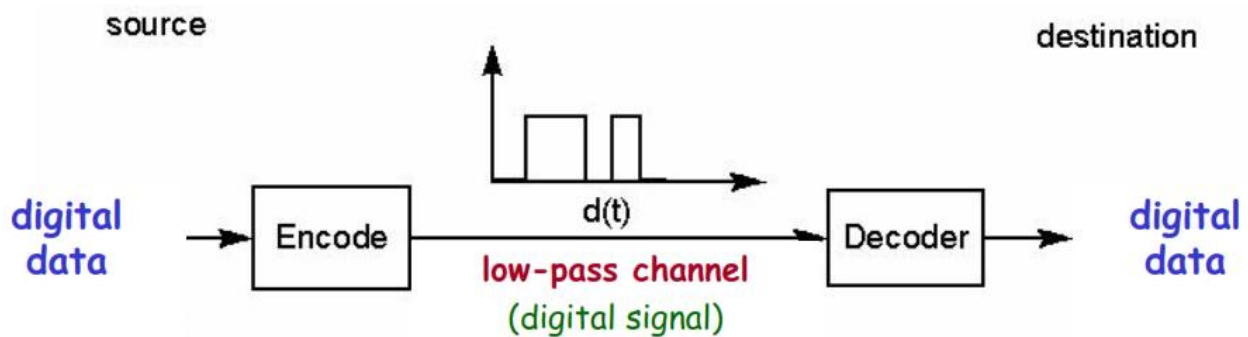


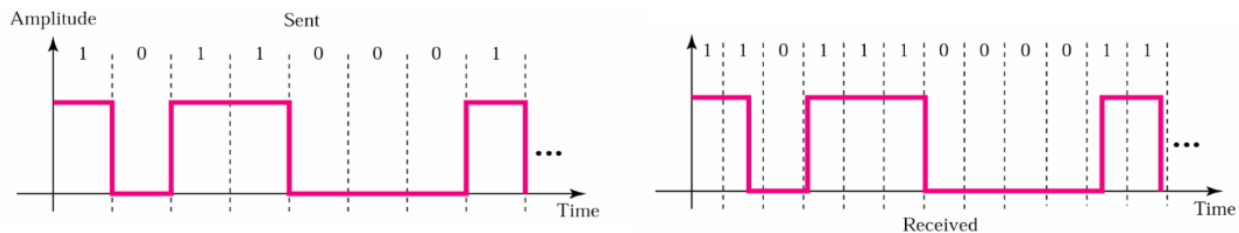
Line Encoding

- The assignment of pulses (an electrical signal) to the binary digits that come out of the PCM or DPCM system.
- Line coding encodes the bit stream for transmission through a line, or a cable.
- It is used for communications between the CPU and peripherals, and for short-distance baseband communications, such as the Ethernet.



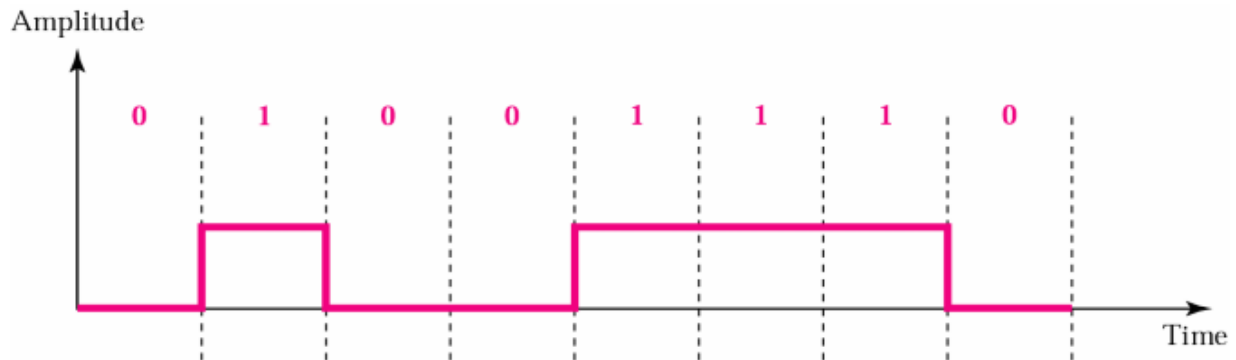
Two Design Considerations

- **DC Component in Line Coding:** Some line coding schemes have a residual (DC) component, which is generally undesirable.
 - Transformers do not allow passage of DC component.
 - DC component \Rightarrow extra energy – useless!
- **Self-Synchronization (clocking):** To correctly interpret signal received from sender, receiver's bit interval must exactly correspond to sender's bit intervals
 - If receiver clock is faster/slower, bit intervals not matched \Rightarrow receiver misinterprets signal
 - Self-synchronizing digital signals include timing information in itself, to indicate the beginning & end of each pulse



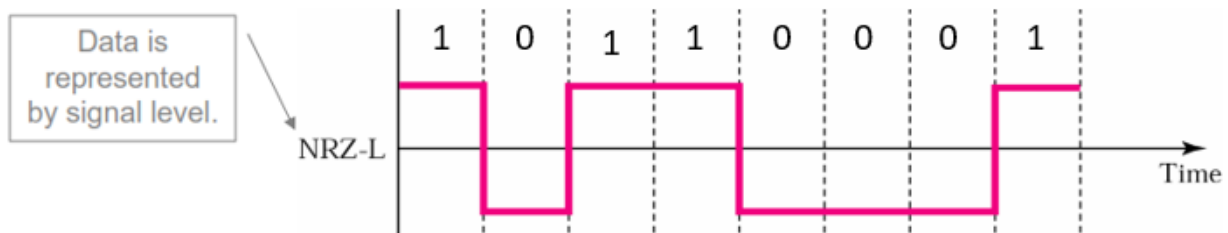
Unipolar Line Coding (Unipolar non-return to zero)

- Uses only one non-zero and one zero voltage level to represent binary digits 1 and 0
- Simple to implement, but obsolete due to two main problems:
 - Presence of a DC component.
 - Lack of synchronization for long series of 1-s or 0-s



Polar Line Coding: Polar non-return to zero

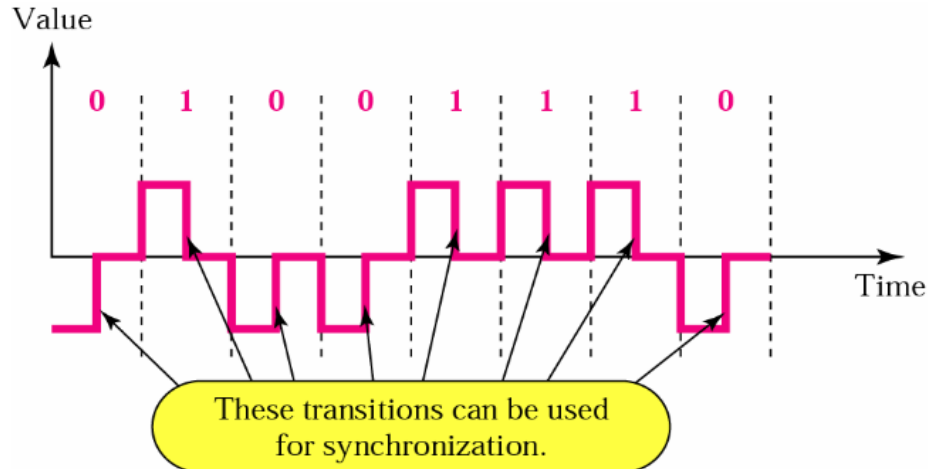
- Uses two non-zero voltage level to represent digits 1 and digit 0. +ve for 1 and -ve for 0
- No DC component is present
- Poor synchronization for long series of 1-s or 0-s



Polar Non-return to Zero

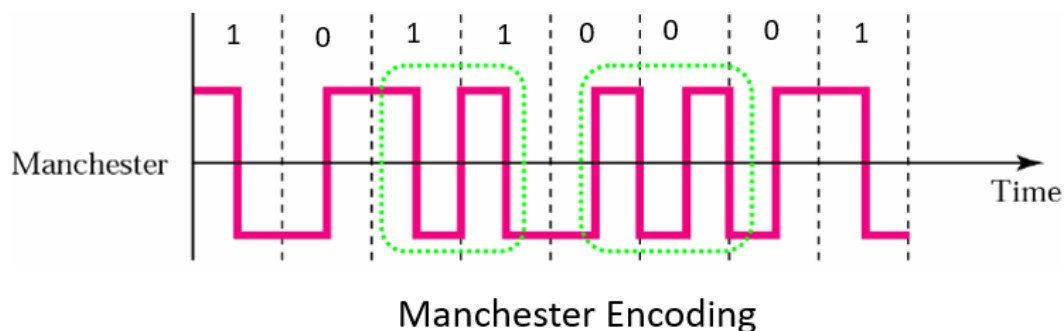
Polar Line Coding: Polar return to zero

- Uses two non-zero voltage level to represent digits 1 and digit 0. +ve for 1 and -ve for 0. **Must** return to zero halfway through each bit interval.
- No DC component is present.
- Perfect synchronization for long series of 1-s or 0-s.
- Twice the bandwidth required for polar non-return to zero, $B.W \propto \frac{1}{pulse\ width}$.



Manchester Line Coding

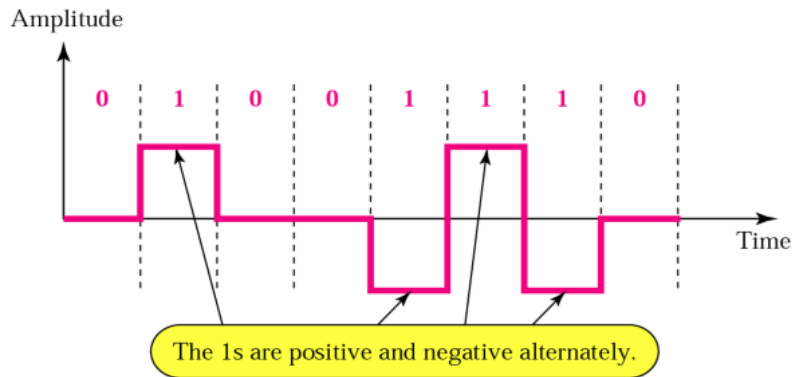
- Inversion at the middle of each bit interval is used for both synchronization and bit representation
- Digit 0 \Rightarrow neg-to-pos transition, 1 \Rightarrow pos-to-neg transition
- Perfect synchronization for long series of 1-s or 0-s
- There is always transition at the middle of the bit, and maybe one transition at the end of each bit.
- Fine for alternating sequences of bits (10101), but wastes bandwidth for long runs of 1-s or 0-s.
- Used by IEEE 802.3 (Ethernet).
- No DC component is present.
- Twice the bandwidth required for polar non-return to zero. Two pulses are used to represent one bit.



Bipolar Line Coding

- Uses two non-zero and zero voltage level for representation of two data levels.
- **0 = zero level; 1 = alternating positive and negative level.**

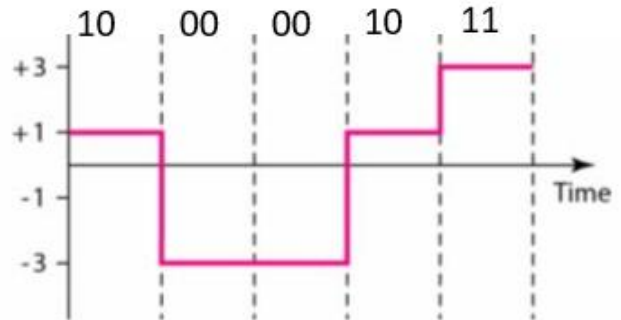
- If first bit 1 is represented by a positive amplitude, second will be represented by negative amplitude, third by positive, etc.
- Less bandwidth required than with Manchester coding (for any sequence of bits).
- Loss of synchronization is possible for long runs of 0-s.
- No DC component is present.



2B1Q (2 Bipolar to 1Quaternary) Line Coding

- Data patterns of size 2 bits are encoded as one signal element belonging to a four-level signal.
- Data is sent two time faster than with polar non-return to zero.
- Receiver has to discern 4 different thresholds

Binary Input	Output Voltage
00	-3
01	-1
10	1
11	3



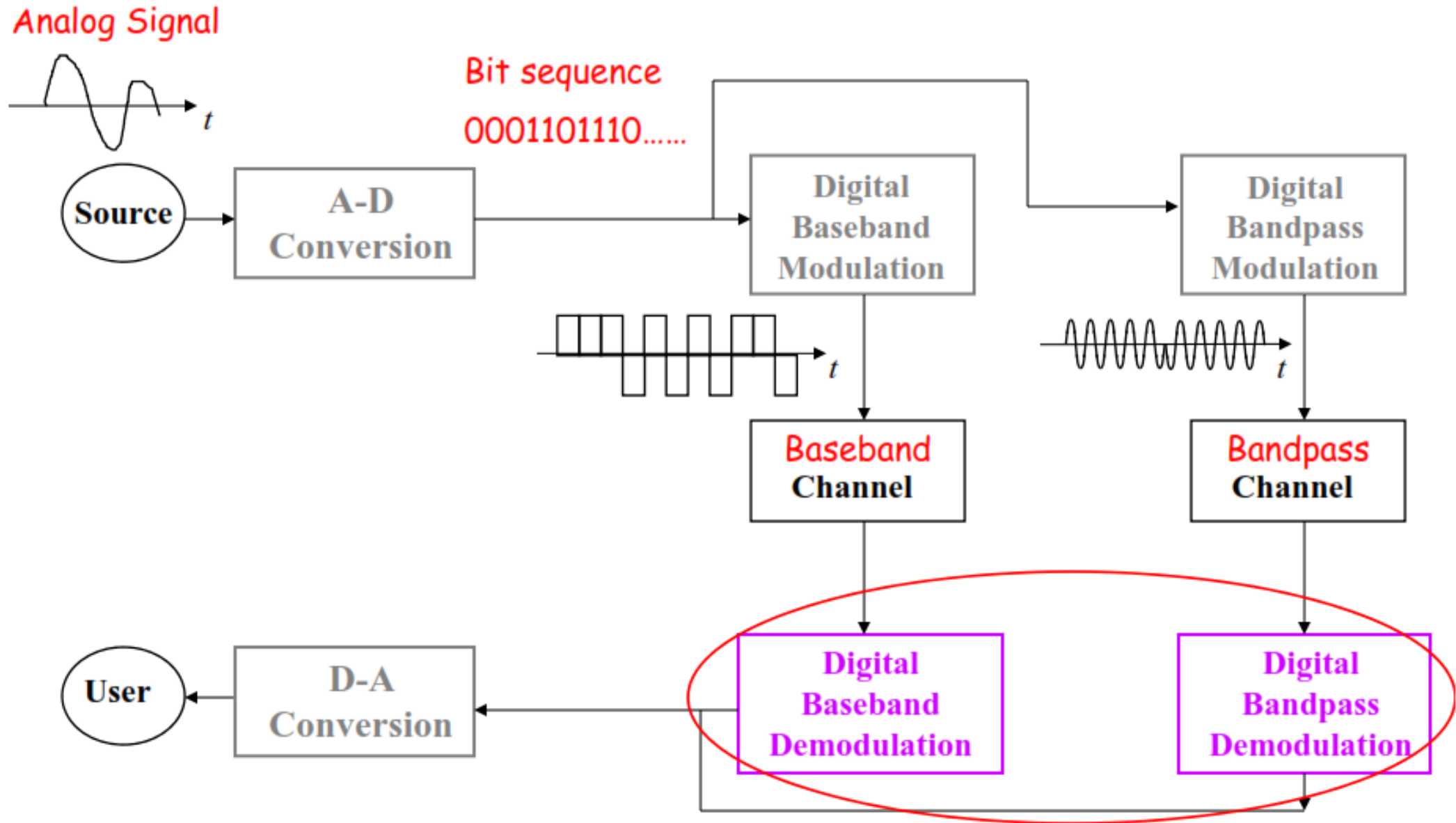
Optimum Receiver and Digital Binary Transmission

In binary data transmission over a communication channel, logic 1 is represented by a signal $s_1(t)$ and logic 0 by a signal $s_2(t)$. The time allocated for each signal is the symbol duration τ , where τ is related to the data rate by $r_b = 1/\tau$. We have two types of data transmission:

Baseband Data Transmission: Binary data transmission by means of two baseband waveforms (typically, two voltage levels) is referred to as baseband signaling. The spectrum of the transmitted signal occupies the low part of the frequency band (around the zero frequency). No high frequency carrier is used in this mode of transmission.

Bandpass Data Transmission: The baseband data modulates a high frequency carrier to produce a modulated signal, whose spectrum is centered around the carrier frequency.

Digital Communication Block Diagram

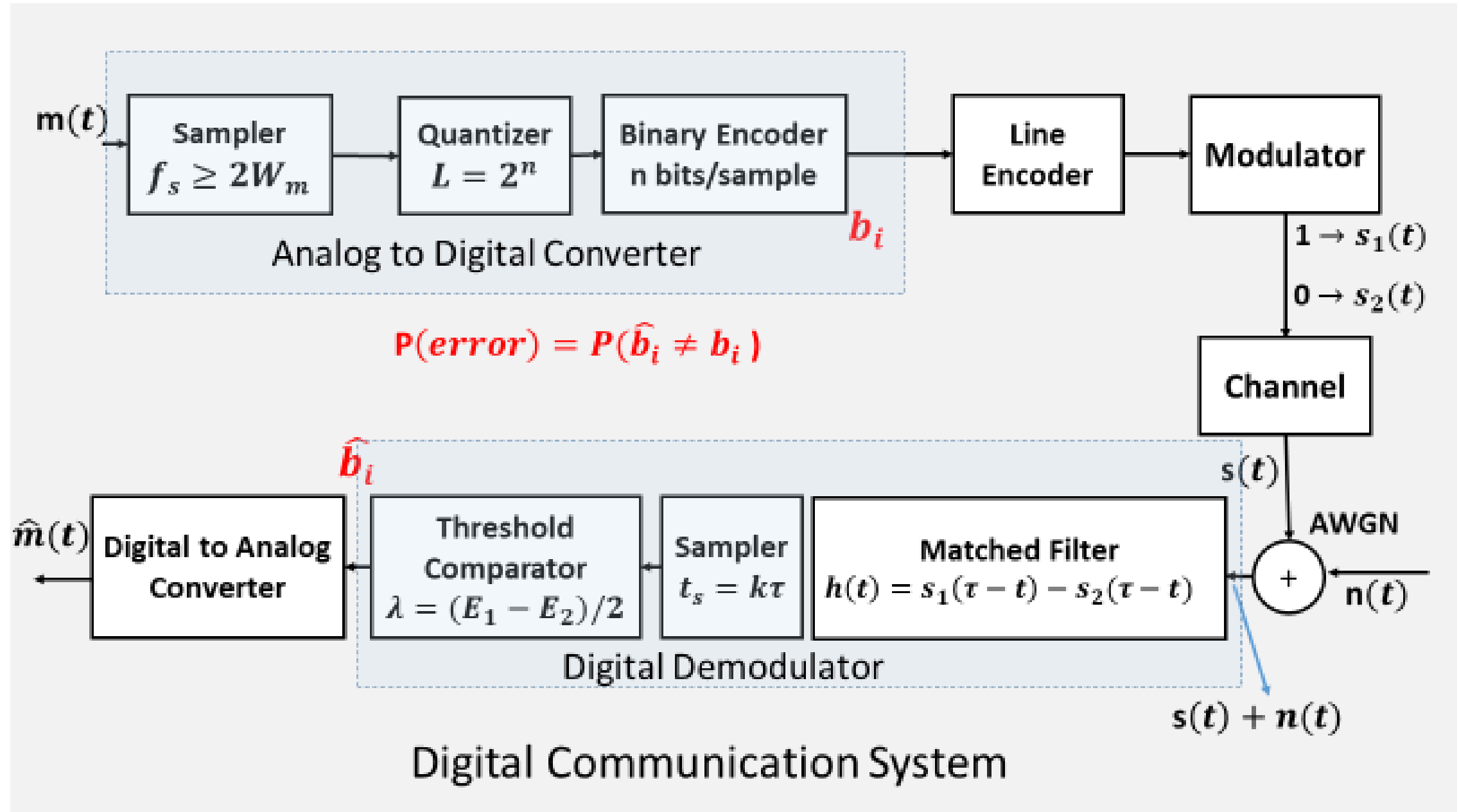


Assumptions

- The channel noise $n(t)$ is additive white Gaussian (AWGN) with a double-sided PSD of $N_0/2$. Noise is assumed to be added at the front end of the receiver.
- The data component at the front end of the receiver is assumed to be an exact replica of the transmitted signal, in the sense that the transmission bandwidth of the medium is wide enough to reproduce the signal without distortion.
- Bits in different time intervals are assumed independent.
- The signal to be processed by the receiver is the noisy signal $\mathbf{y}(t) = \mathbf{s}_i(t) + \mathbf{n}(t)$

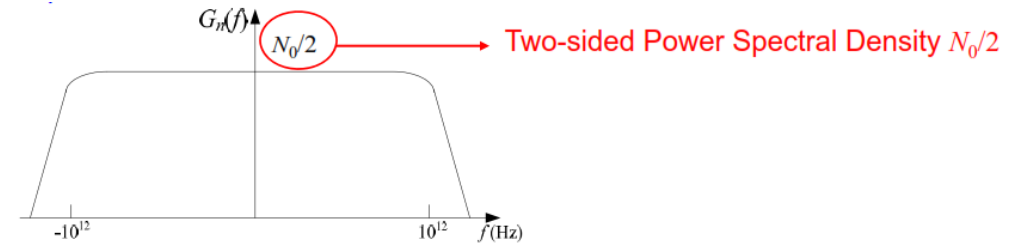
Based on $\mathbf{y}(t)$, the task of the receiver is to decide whether a 1 or a 0 was transmitted during each transmission slot τ with minimum probability of error.

Transmitter and Receiver Sides in Digital Communication System



Thermal Noise

- **Thermal Noise:** caused by the random motion of electrons within electronic devices
- Thermal noise, $n(t)$, is modeled as a **wide** sense stationary (WSS) Gaussian random process.
- The thermal noise has a power spectrum that is constant from dc to approximately 10^{12} Hz; hence, $n(t)$ can be approximately regarded as a white process.
- Thermal noise is superimposed (added) on the transmitted signal. The received signal is $y(t) = s(t) + n(t)$.
- The mean value of the thermal noise $n(t)$ is zero.
- At any given time t_0 the probability density function of $n(t_0)$ follows the Gaussian distribution; $N(0, \sigma_0^2)$; where $\sigma_0^2 = E(n(t))^2$ is the noise power.



$$f_n(n) = \frac{1}{\sqrt{2\pi}\sigma_0} e^{-n^2/2\sigma_0^2}$$

Effect of Noise and Channel on Received Data

1 0 1 1 0 0 0 0 1 1 1 0 1 0 0 1 1 1 1

Transmitted signal
 $s(t)$

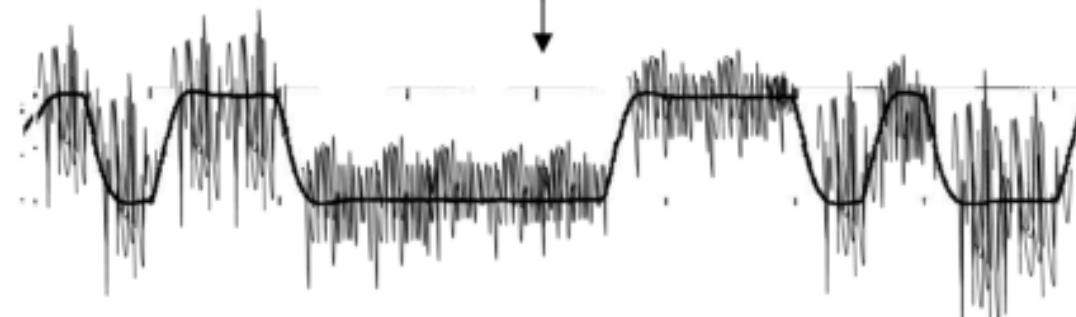


- Suppose that channel bandwidth is properly chosen such that most frequency components of the transmitted signal can pass through the channel.

Channel

- Thermal Noise: caused by the random motion of electrons within electronic devices.

Received signal
 $y(t)$



Basic Elements of the Receiver

To decide on whether logic 1 or logic 0 was transmitted during a given time slot τ , the received signal (transmitted signal and noise) passes through three basic units.

Filter: The optimum filter, which we will also call the matched filter.

Sampler: Samples the received signal (data component plus noise) at some time $t = t_0 = \tau = \text{symbol duration}$.

Threshold comparator: If the sampled value is larger than a given threshold, λ , digit 1 is declared true, otherwise digit 0 is declared true.

There are three design elements at the receiver

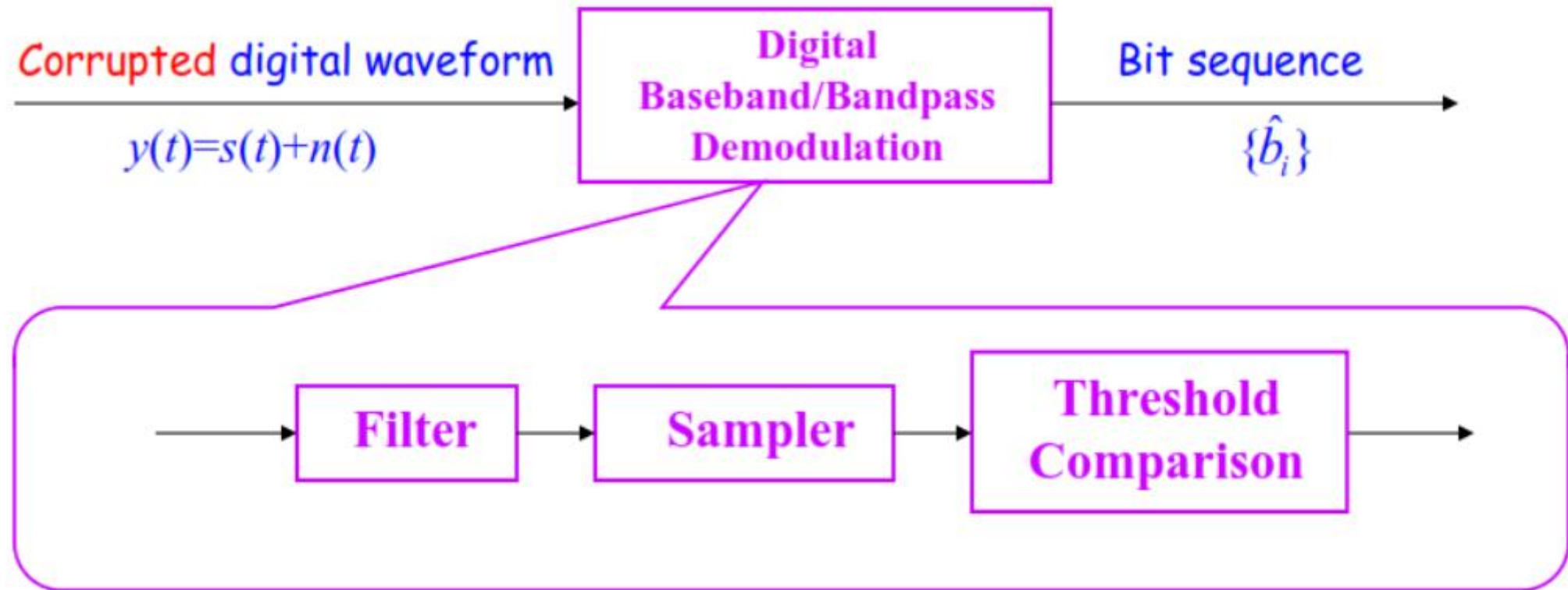
- a. The impulse response $h(t)$ of the filter
- b. The sampling time t_0
- c. The threshold λ

Basic Elements of the Receiver

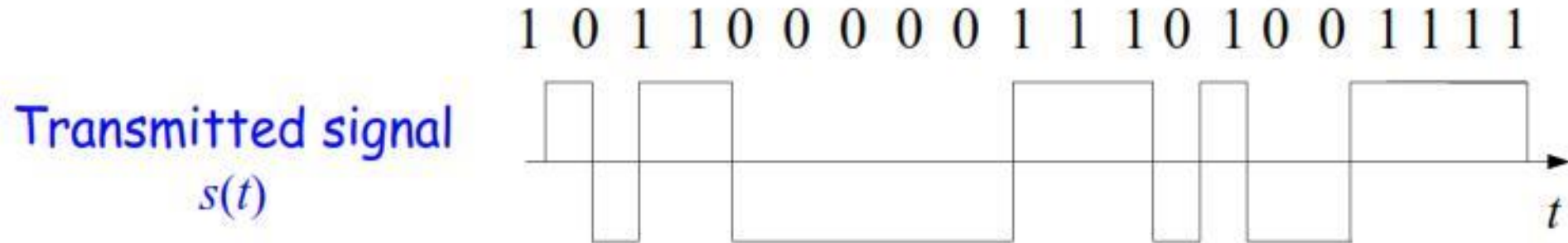
These parameters should be chosen so as to minimize the average probability of error (or bit error rate BER), defined as

$$P_b = P(b_i \neq \hat{b}_i)$$

$$P_b = \Pr\{\hat{b}_i=1, b_i=0\} + \Pr\{\hat{b}_i=0, b_i=1\}$$



Optimum Receiver and Digital Binary Transmission



Received signal $y(t)=s(t)+n(t)$

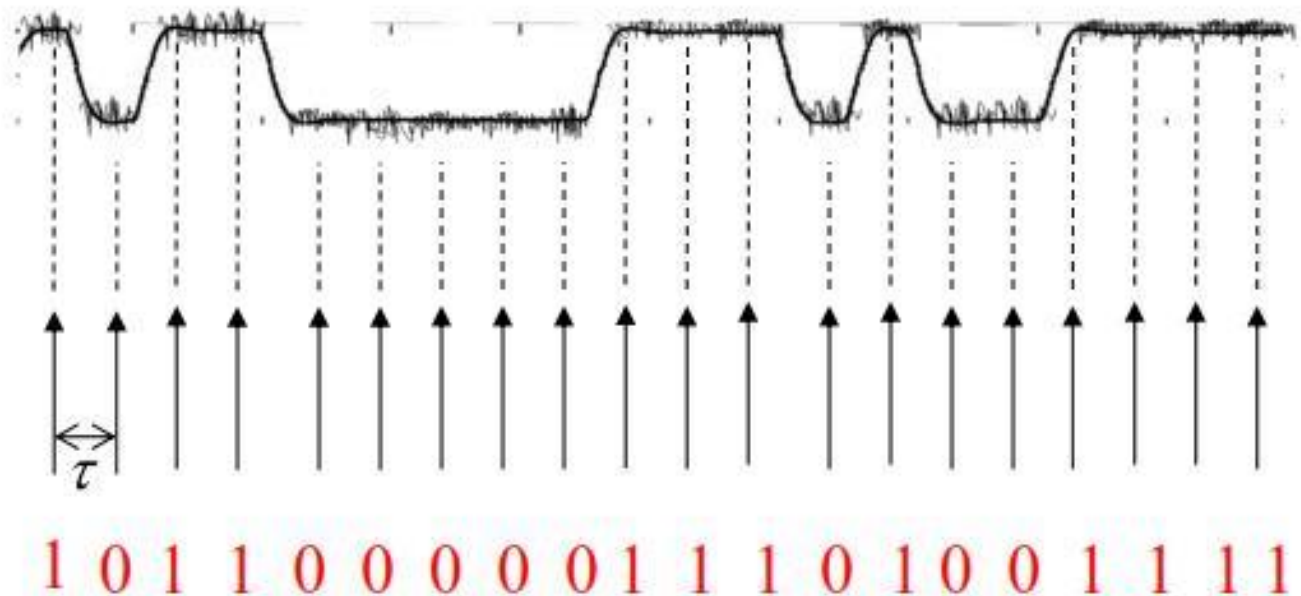
Step 1: Filtering

Step 2: Sampling

Step 3: Threshold Comparison

Sample $> 0 \Rightarrow 1$

Sample $< 0 \Rightarrow 0$



Theorem on the Optimum Binary Receiver

Consider a binary communication system, corrupted by AWGN with power spectral density $N_0/2$, where the equally probable binary digits 1 and 0 are represented by the signals $s_1(t)$ and $s_2(t)$, respectively. The transmission time for each signal is τ sec. The optimum receiver elements, i.e., the elements that minimize the receiver probability of error are given by

Impulse response of the matched filter: $h(t) = s_1(\tau - t) - s_2(\tau - t), 0 \leq t \leq \tau$

Optimum sampling time: $t_s = \tau$

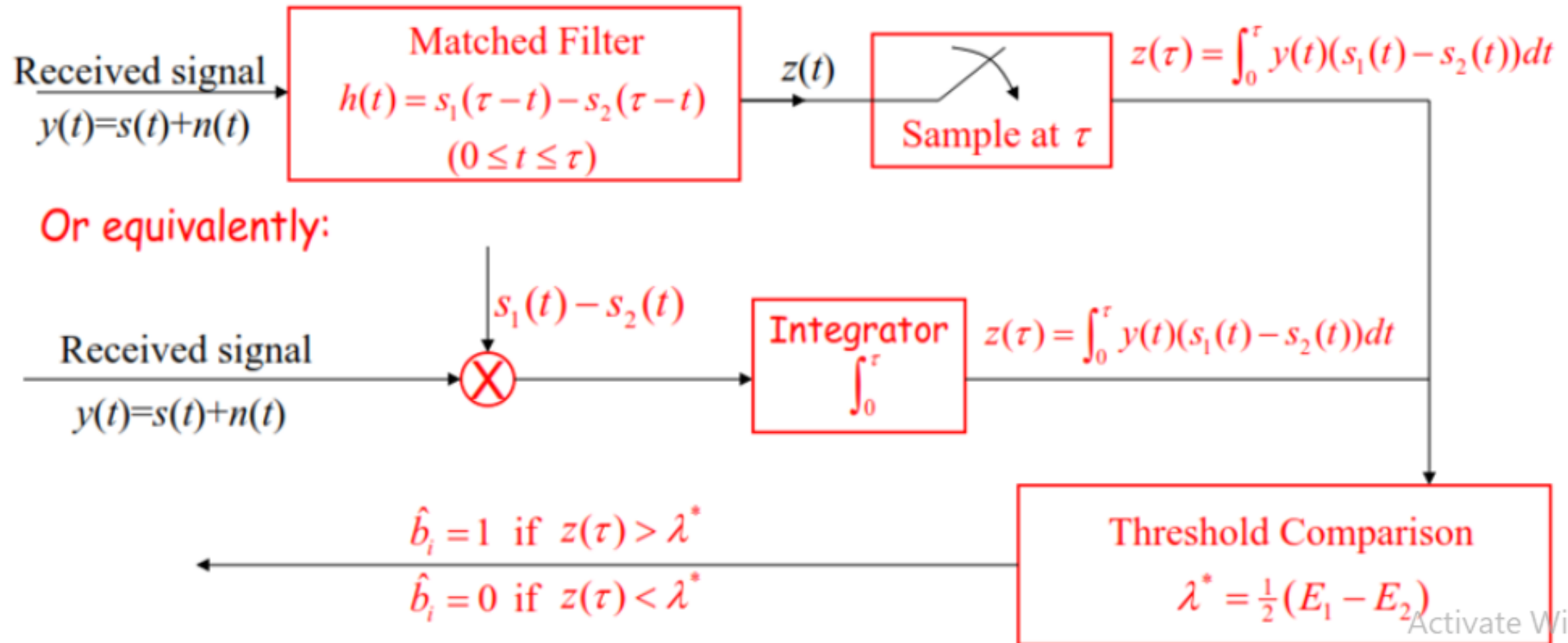
Optimum threshold of comparator: $\lambda^* = \frac{1}{2}(E_1 - E_2), E_k = \int_0^\tau (s_k(t))^2 dt, k = 1, 2$

When these elements are used, the system minimum probability of error is

$$P_b^* = Q \left(\sqrt{\frac{\int_0^\tau (s_1(t) - s_2(t))^2 dt}{2N_0}} \right)$$

Theorem on the Optimum Binary Receiver

The structure of the optimum receiver is depicted in the figure below. Note that the receiver can be implemented in terms of the matched filter and, equivalently, in terms of a correlator (a multiplier followed by an integrator).

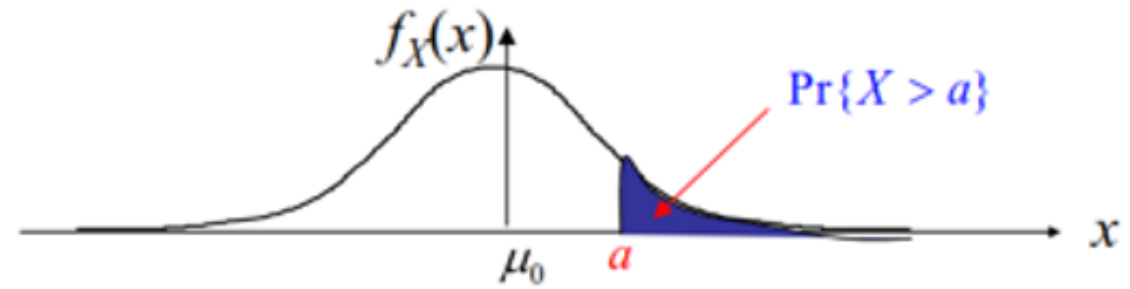
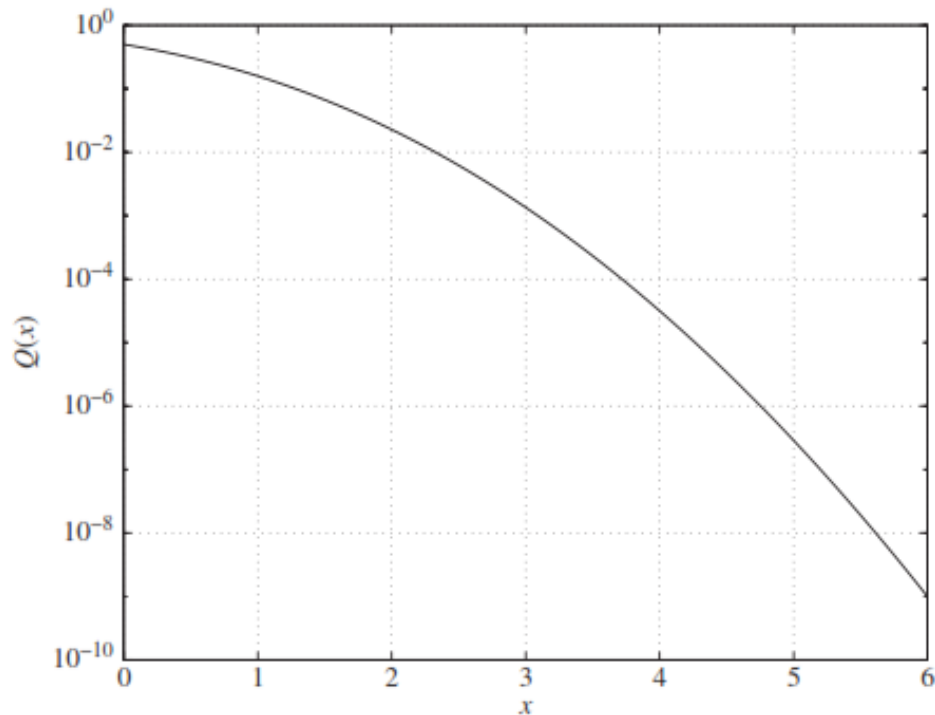


The Q-Function

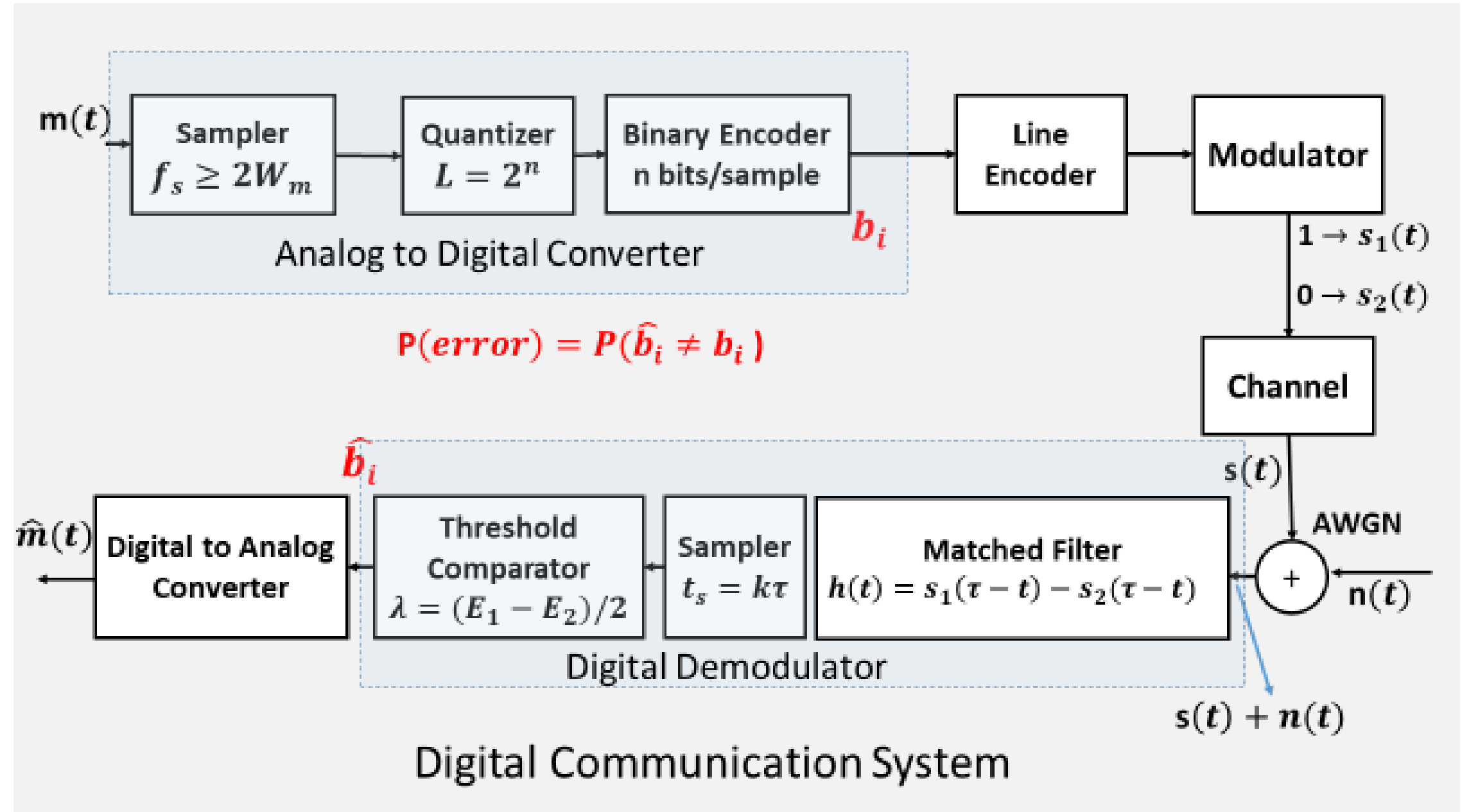
$$Q(\alpha) = \int_{\alpha}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{x^2}{2}\right\} dx$$

- $Q(\alpha)$ is a decreasing function of α .
- For $X \sim \mathcal{N}(\mu_0, \sigma_0^2)$,

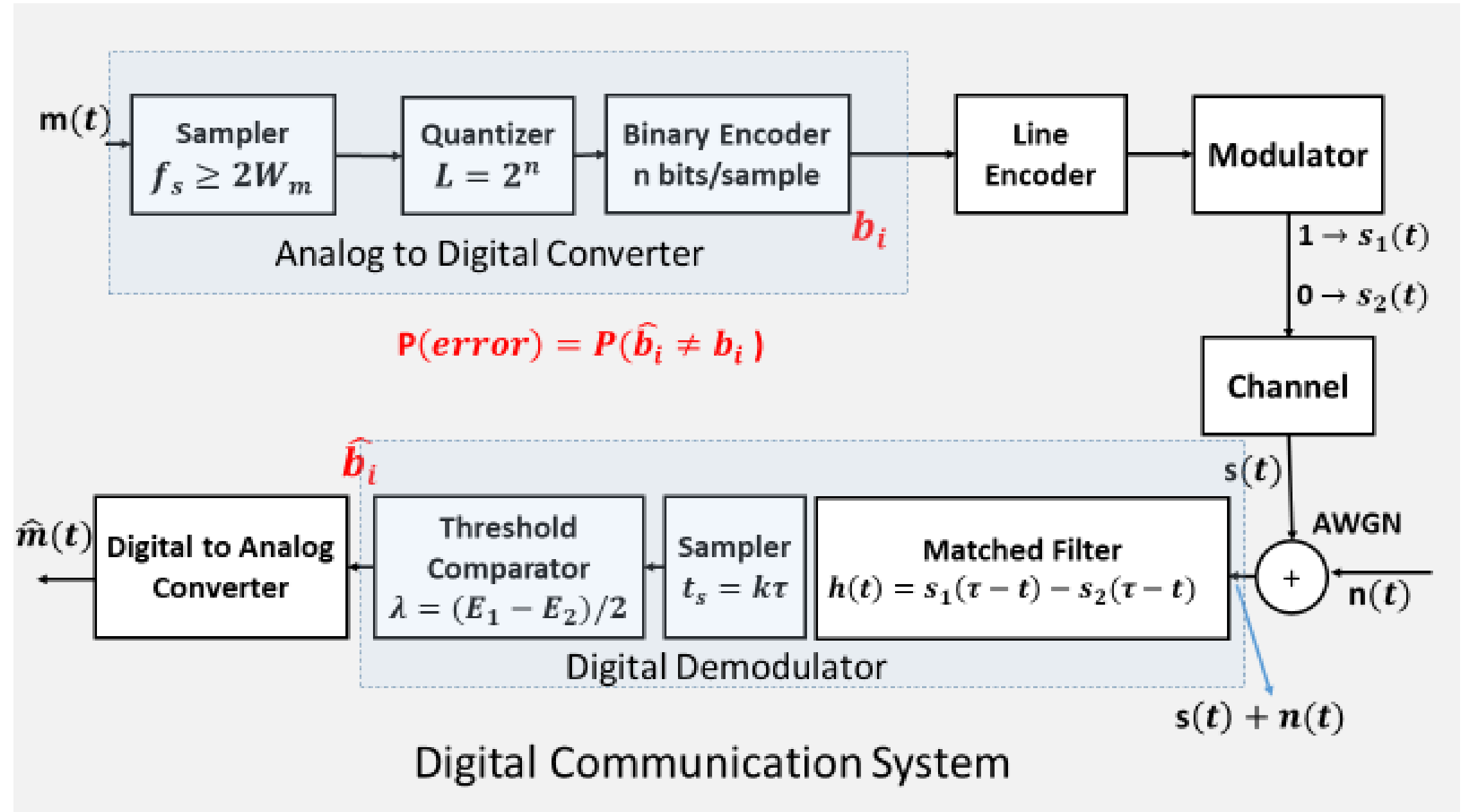
$$\Pr\{X > a\} = \int_a^{\infty} f_X(x) dx = \int_a^{\infty} \frac{1}{\sqrt{2\pi}\sigma_0} \exp\left\{-\frac{(x-\mu_0)^2}{2\sigma_0^2}\right\} dx = Q\left(\frac{a-\mu_0}{\sigma_0}\right)$$



Transmitter and Receiver Sides in Digital Communication System



Matched Filter and Performance of the Optimum Receiver



Theorem on the Optimum Binary Receiver

Consider a binary communication system, corrupted by AWGN with power spectral density $N_0/2$, where the equally probable binary digits 1 and 0 are represented by the signals $s_1(t)$ and $s_2(t)$, respectively. The transmission time for each signal is τ sec. The optimum receiver elements, i.e., the elements that minimize the receiver probability of error are given by

Impulse response of the matched filter: $h(t) = s_1(\tau - t) - s_2(\tau - t), 0 \leq t \leq \tau$

Optimum sampling time: $t_s = \tau$

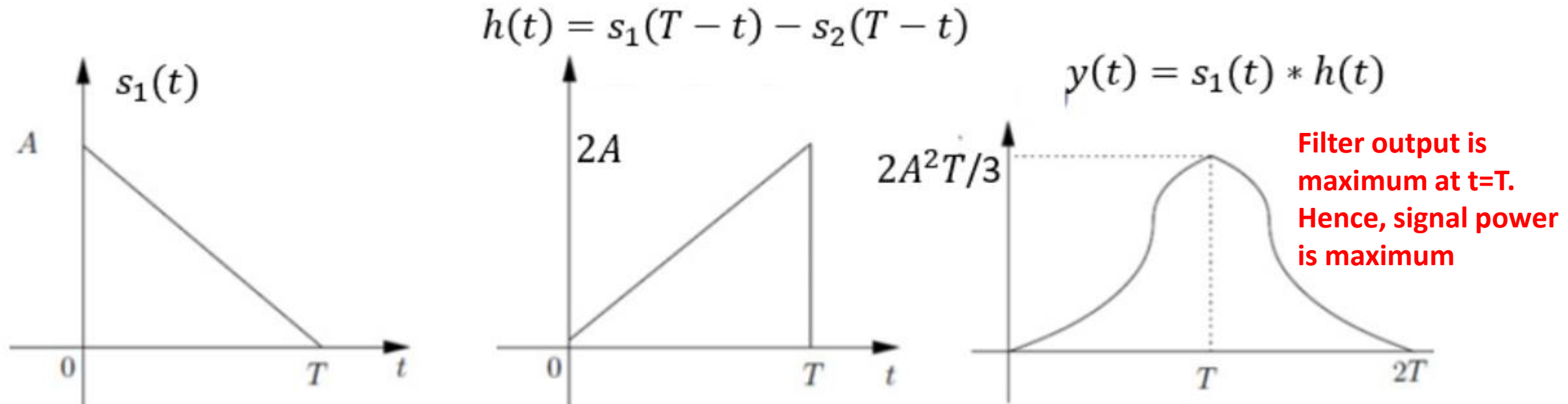
Optimum threshold of comparator: $\lambda^* = \frac{1}{2}(E_1 - E_2), E_k = \int_0^\tau (s_k(t))^2 dt, k = 1, 2$

When these elements are used, the system minimum probability of error is

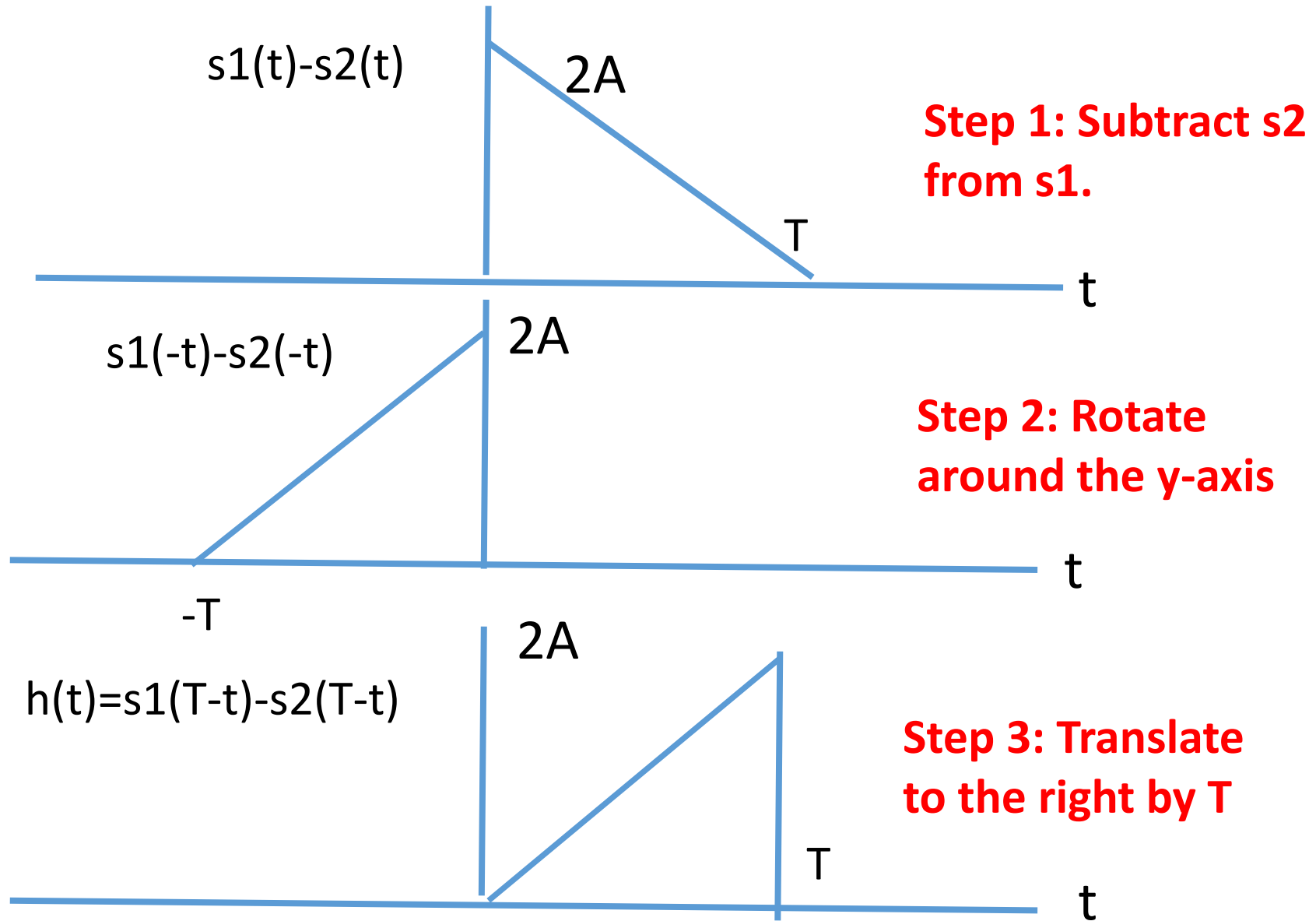
$$P_b^* = Q \left(\sqrt{\frac{\int_0^\tau (s_1(t) - s_2(t))^2 dt}{2N_0}} \right)$$

Output of a Matched Filter

Example 2: The next figure shows a signaling scheme where $s_2(t) = -s_1(t)$. The impulse response of the matched filter is $h(t) = s_1(T - t) - s_2(T - t)$. The figure shows the filter output when $s_1(t)$ is applied to the filter. Note that the output attains its maximum value at time $t=T$, which is the sampling time chosen to maximize the output SNR.

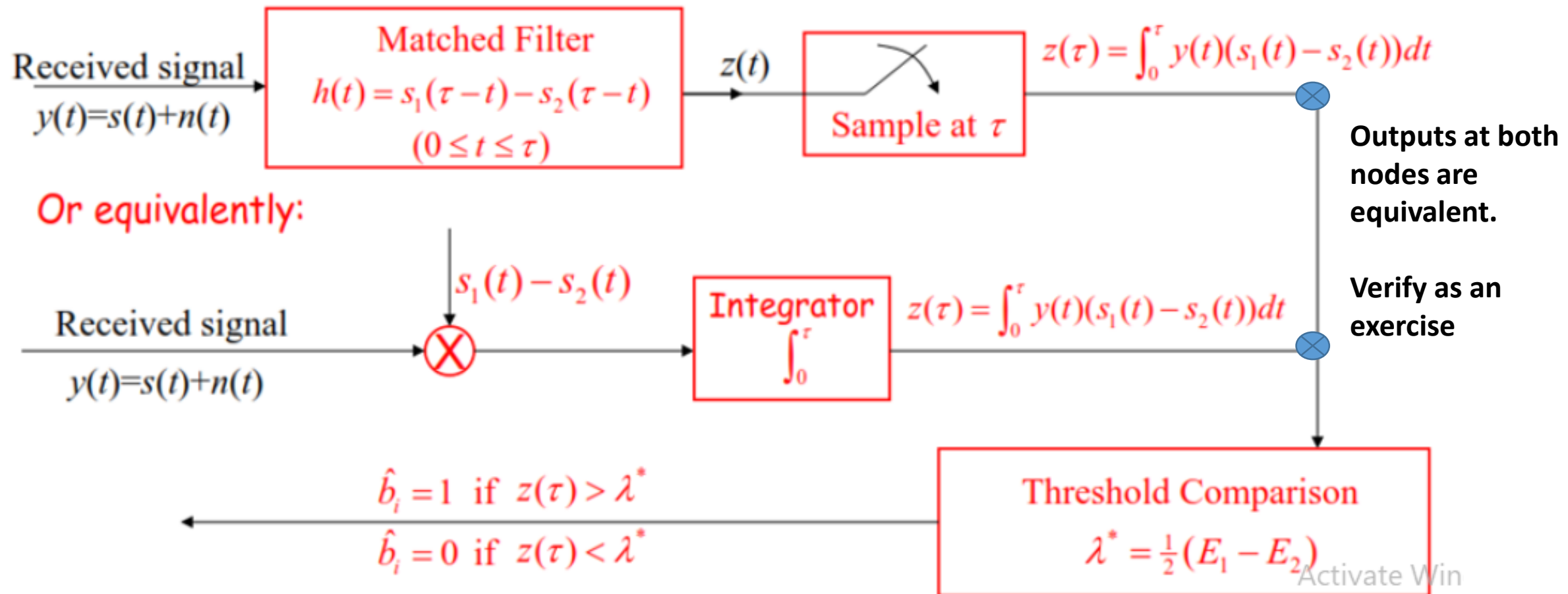


Matched Filter Derived from Signals



Equivalent Implementations of the Optimum Receiver

The structure of the optimum receiver is depicted in the figure below. Note that the receiver can be implemented in terms of the matched filter and, equivalently, in terms of a correlator (a multiplier followed by an integrator).



Example: Antipodal Binary Transmission

Let us consider a digital binary communication system where bits 1 and 0 are represented by the signals $s_1(t)$ and $-s_1(t)$, respectively.

For this case, $E_1 = E_2 = E = \int_0^\tau (s_1(t))^2 dt$

Therefore, the threshold is $\lambda^* = (E_1 - E_2) = 0$

The probability of error is:

$$P_b^* = Q \left(\sqrt{\frac{\int_0^\tau (s_1(t) - s_2(t))^2 dt}{2N_0}} \right)$$

$$P_b^* = Q \left(\sqrt{\frac{4 \int_0^\tau (s_1(t))^2 dt}{2N_0}} \right)$$

$$P_b^* = Q \left(\sqrt{\frac{\int_0^\tau (s_1(t) + s_1(t))^2 dt}{2N_0}} \right)$$

$$P_b^* = Q \left(\sqrt{\frac{2E_b}{N_0}} \right)$$

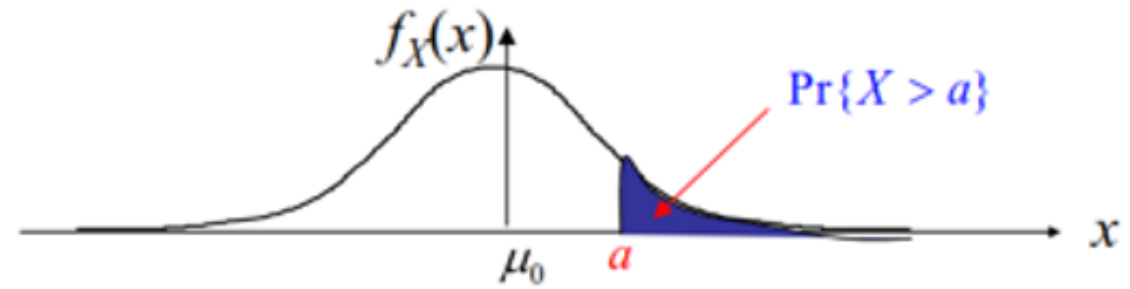
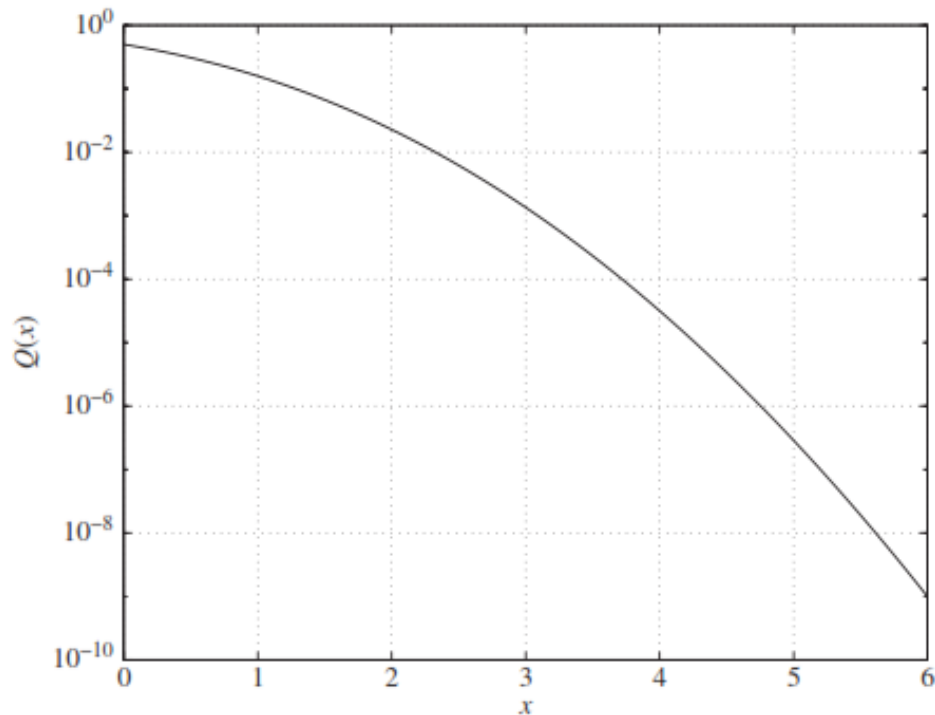
Probability of error decreases as the signal to noise ratio increases

The Q-Function

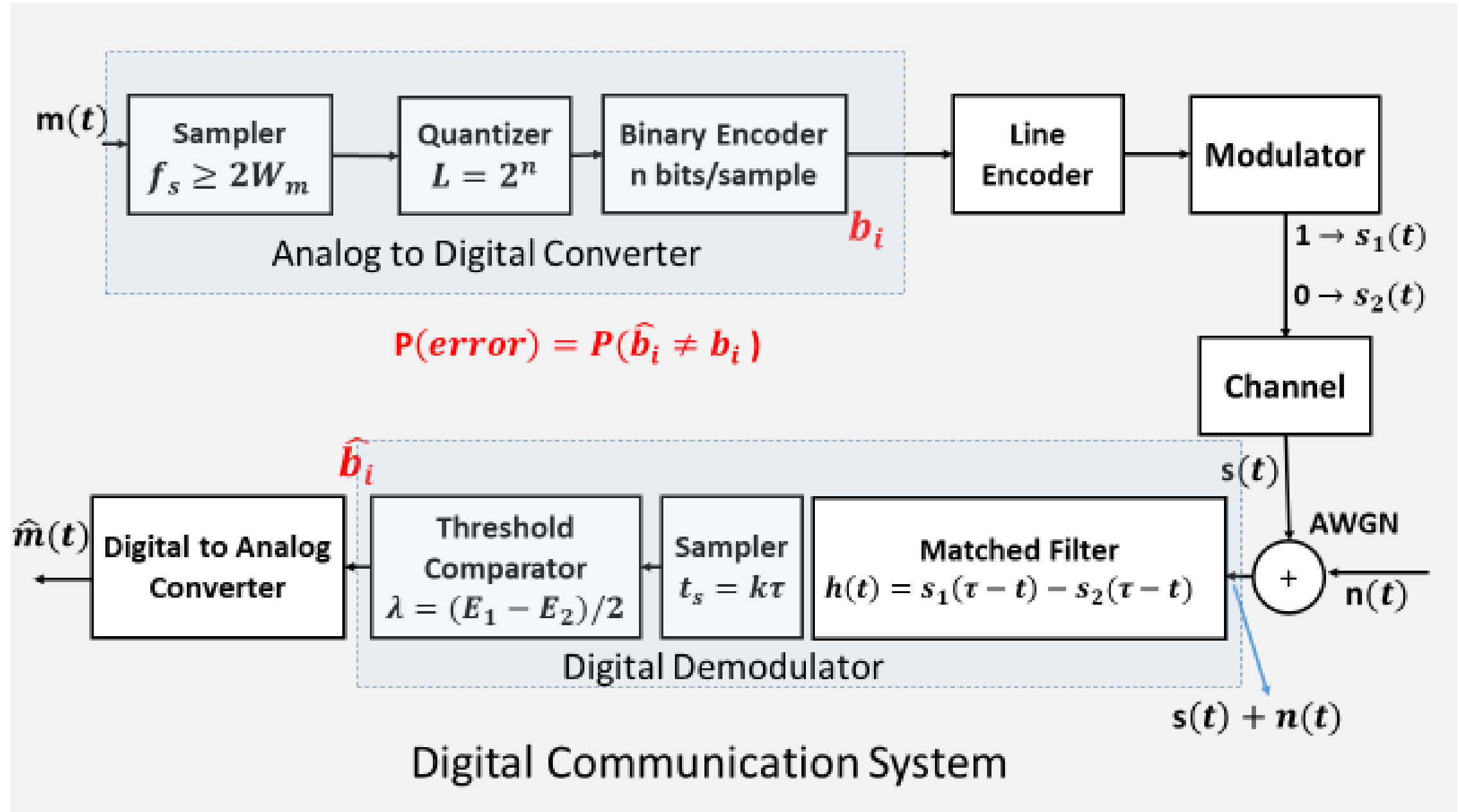
$$Q(\alpha) = \int_{\alpha}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{x^2}{2}\right\} dx$$

- $Q(\alpha)$ is a decreasing function of α .
- For $X \sim \mathcal{N}(\mu_0, \sigma_0^2)$,

$$\Pr\{X > a\} = \int_a^{\infty} f_X(x) dx = \int_a^{\infty} \frac{1}{\sqrt{2\pi}\sigma_0} \exp\left\{-\frac{(x-\mu_0)^2}{2\sigma_0^2}\right\} dx = Q\left(\frac{a-\mu_0}{\sigma_0}\right)$$



Baseband Data Transmission (Low-pass Channel)



Baseband Data Transmission

Binary data transmission by means of two voltage levels is referred to as baseband signaling. Manchester encoding, for example, is used in the Ethernet local area network as the signaling scheme. Here, we consider polar non-return to zero baseband transmission scheme, in terms of probability of error, optimum receiver structure, power spectral density and bandwidth.

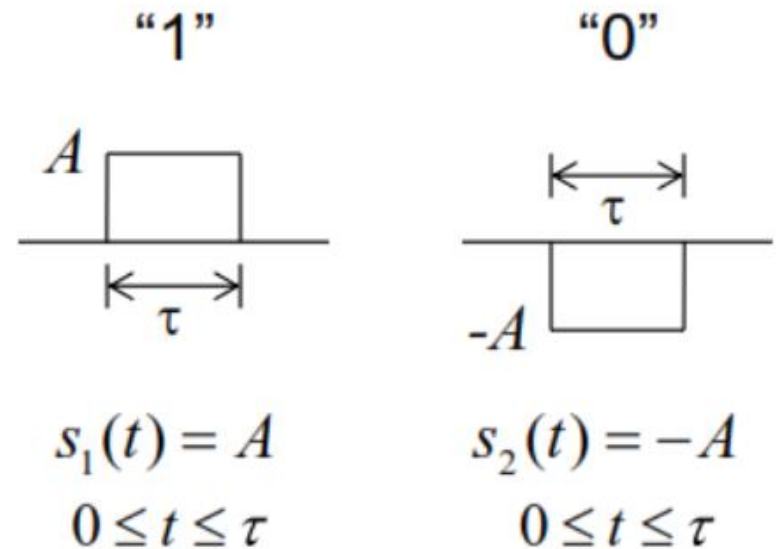
Polar nonreturn to zero (also known as binary pulse amplitude modulation)

Signal Representation

The baseband signals representing digits 1 and 0 are:

$$s_1(t) = A, \quad 0 \leq t \leq \tau$$

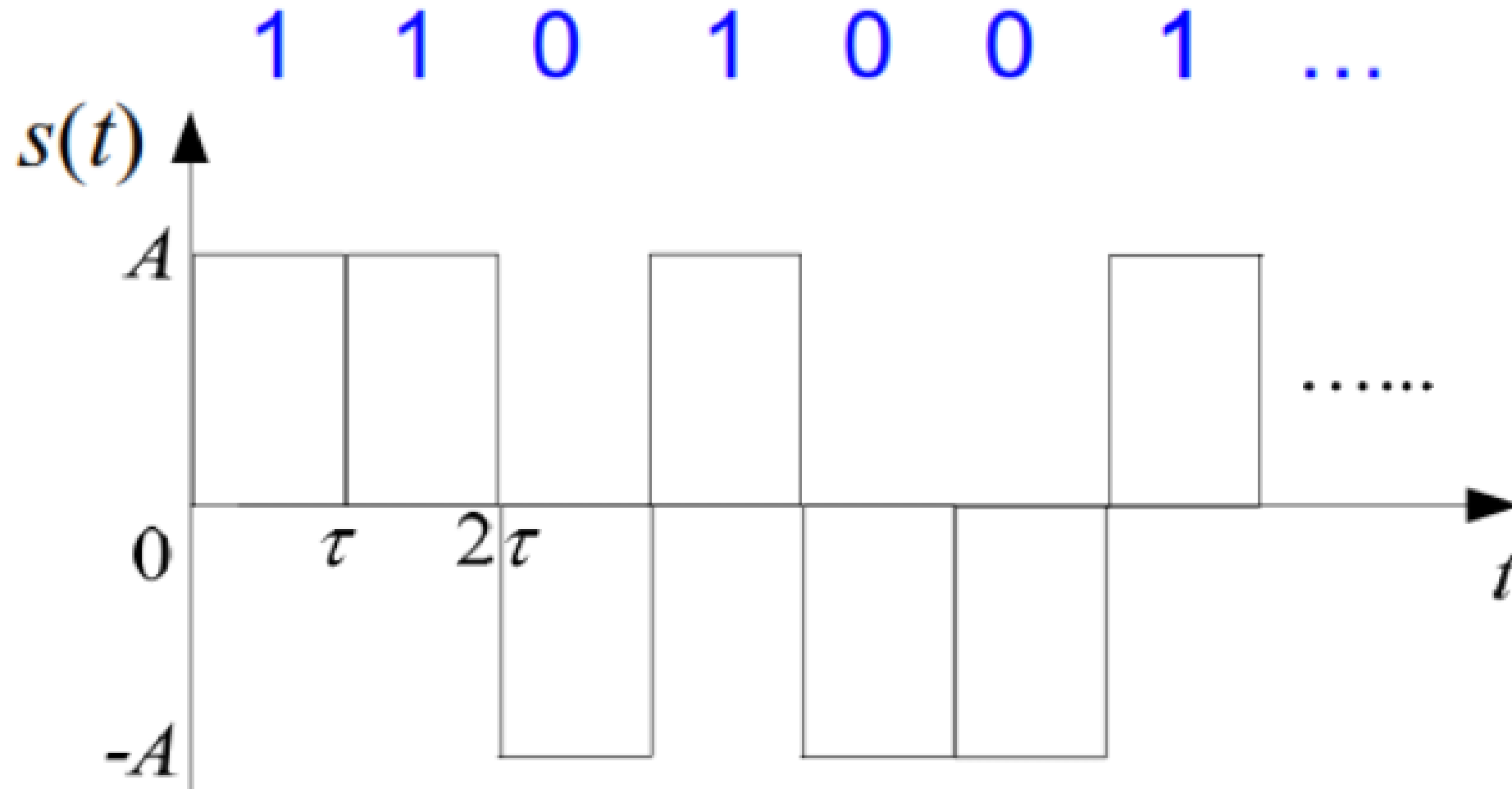
$$s_0(t) = -A, \quad 0 \leq t \leq \tau$$



where, τ is the symbol duration and $R_b = 1/\tau$ is the data rate in bits/sec.

Baseband Data Transmission

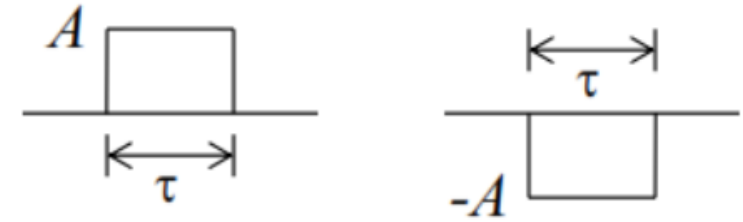
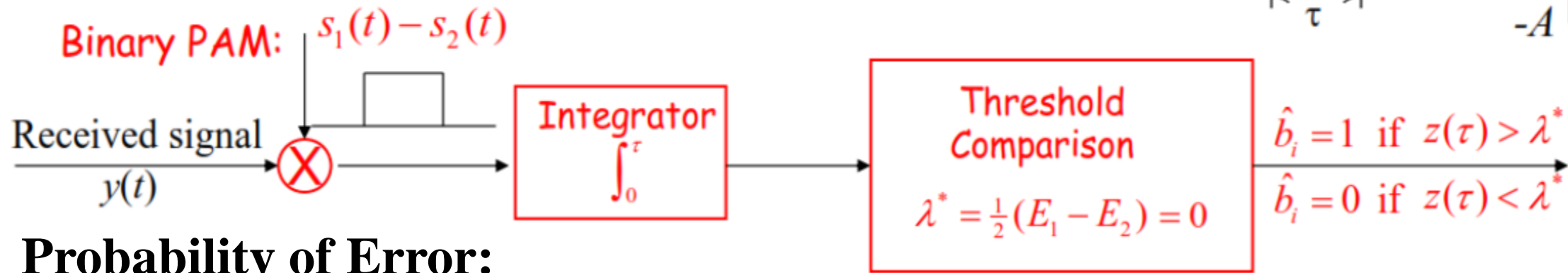
- Generation: Convert data into polar non-return to zero format



Baseband Data Transmission

Optimum Receiver

The optimum receiver is, of course, the matched filter, also implemented as a correlator, as shown in this figure.



Probability of Error:

$$P_b^* = Q\left(\sqrt{\frac{\int_0^\tau (s_1(t) - s_2(t))^2 dt}{2N_0}}\right)$$

Receiver Implemented
as a Correlator

Optimal BER:

Note that: $E_1 = E_2 = \int_0^\tau A^2 dt = A^2\tau \Rightarrow \lambda^* = (E_1 - E_2) = 0$

$$P_b^* = Q\left(\sqrt{\frac{2A^2\tau}{N_0}}\right) = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

Average Energy per bit: $E_b = \frac{1}{2}(E_1 + E_2) = A^2\tau$

General Result on the Power Spectral Density of a digital M-ary baseband signal

The time-domain representation of a digital M-ary baseband signal is

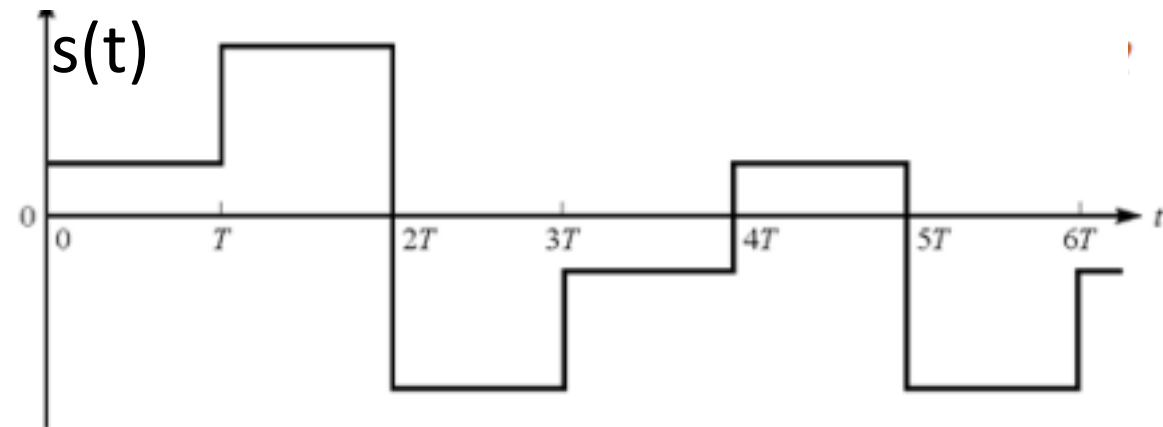
$$s(t) = \sum_{n=-\infty}^{\infty} Z_n \cdot v(t - n\tau)$$

where Z_n is a discrete random variable with $\Pr\{Z_n = a_i\} = 1/M, i = 1, \dots, M,$

$v(t)$ is a unit-baseband signal, and symbols in different time slots are assumed independent.

Under these assumptions, the power spectral density of $s(t)$ is given by

$$G_s(f) = \frac{1}{\tau} |V(f)|^2 \cdot \left(\sigma_Z^2 + \frac{\mu_Z^2}{\tau} \sum_{m=-\infty}^{\infty} \delta\left(f - \frac{m}{\tau}\right) \right)$$



Power Spectral Density of the Polar Non-return to Zero baseband signal

The general result stated above for the M-ary baseband signal can be specialized to the polar nonreturn to zero transmission as follows

- The signal amplitude assumes two equally likely values. i.e., $P\{Z_n = \pm 1\} = 1/2$

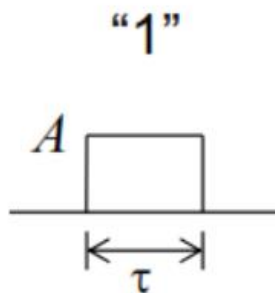
- The basic unit pulse is $v(t) = \begin{cases} A, & 0 \leq t \leq \tau \\ 0, & \text{otherwise} \end{cases}$

- The Fourier transform of the basic unit pulse is $V(f) = A\tau \text{sinc}(f\tau)$

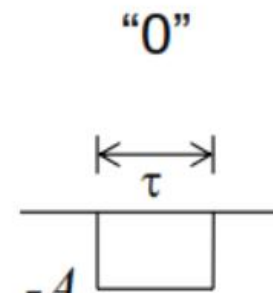
- The mean and variance of Z are: $\mu_Z = 0, \sigma_Z^2 = 1$

$$E(Z) = \sum_{\text{all } z_i} z_i P(Z = z_i)$$

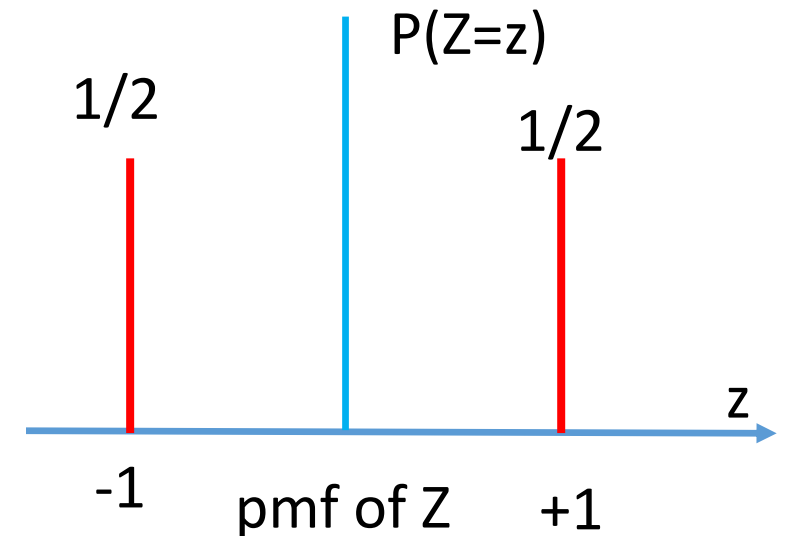
$$\text{Var}(Z) = \sigma_Z^2 = \sum_{\text{all } z_i} (z_i - E(Z))^2 P(Z = z_i)$$



$$s_1(t) = A \\ 0 \leq t \leq \tau$$



$$s_2(t) = -A \\ 0 \leq t \leq \tau$$



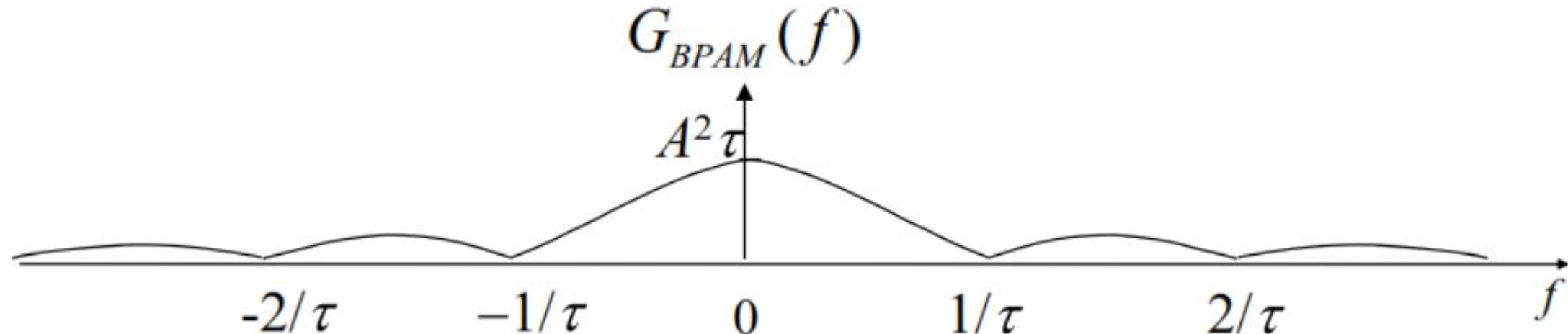
Power Spectral Density of the Polar Non-return to Zero baseband signal

- The general power spectral density formula

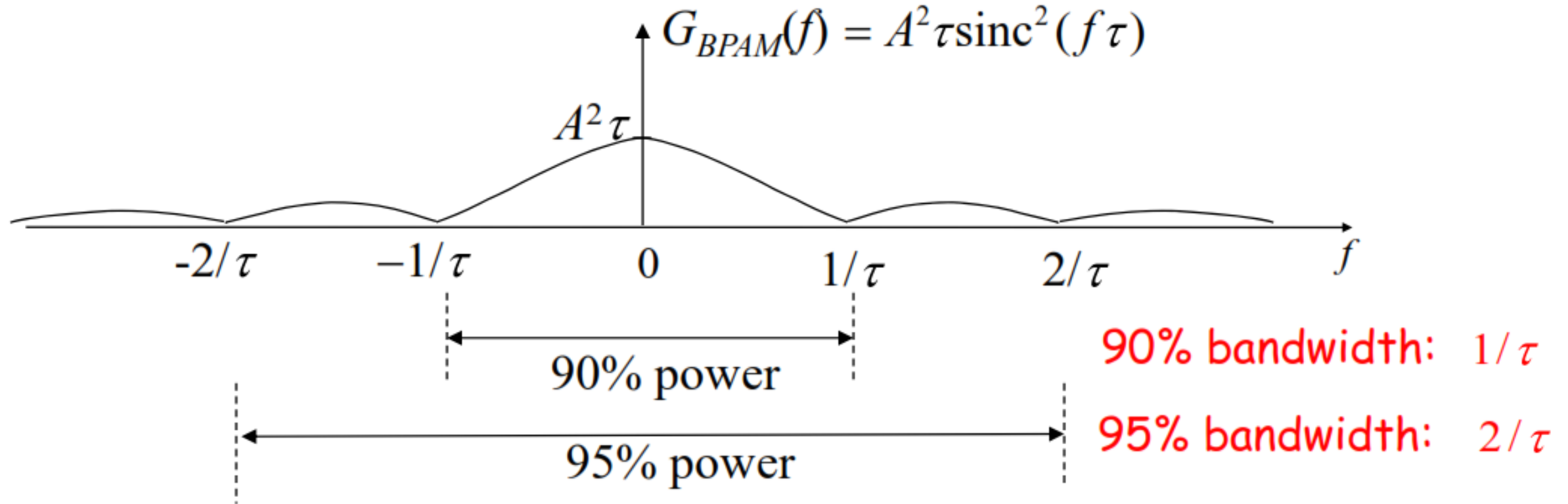
$$G_s(f) = \frac{1}{\tau} |V(f)|^2 \cdot \left(\sigma_Z^2 + \frac{\mu_Z^2}{\tau} \sum_{m=-\infty}^{\infty} \delta\left(f - \frac{m}{\tau}\right) \right)$$

- Substituting: $E(Z)=0$, $\text{Var}(Z)=1$, and the Fourier transform of the rectangular pulse $v(t)$, we get:

$$G_{BPAM}(f) = A^2 \tau \text{sinc}^2(f\tau)$$



Bandwidth of the Polar Non-return to Zero baseband signal



The 90% power bandwidth $= \frac{1}{\tau} = R_b$ (data rate)

The 95% power bandwidth $= \frac{2}{\tau} = 2R_b$ (twice the data rate)

Binary Phase Shift Keying (BPSK)

Binary Digital Bandpass Modulation

Here, the baseband data modulates a high frequency carrier to produce a modulated signal, whose spectrum is centered on the carrier frequency. We will consider four types of bandpass transmission schemes; Amplitude Shift Keying (ASK), Phase Shift Keying (PSK), Frequency Shift Keying (FSK), and Quadri-phase Shift Keying (QPSK). For each type, we consider the generation, optimum receiver, probability of error, power spectral density, and bandwidth.

Binary Phase Shift Keying: Signal Representation

Signal Representation:

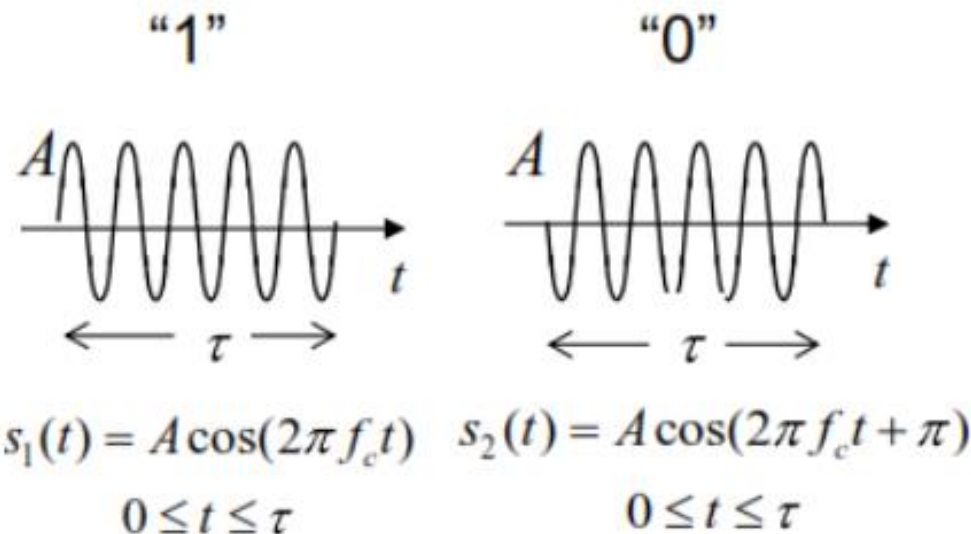
Send: $s_1(t) = A \cos(2\pi f_c t)$ if the information bit is “1”;

Send: $s_2(t) = A \cos(2\pi f_c t + \pi)$

$s_2(t) = -A \cos(2\pi f_c t)$ if the information bit is “0”;

$$\tau = nT_c$$

τ : is the time allocated to transmit the binary digit.
 $T_c = 1/f_c$ is the carrier period



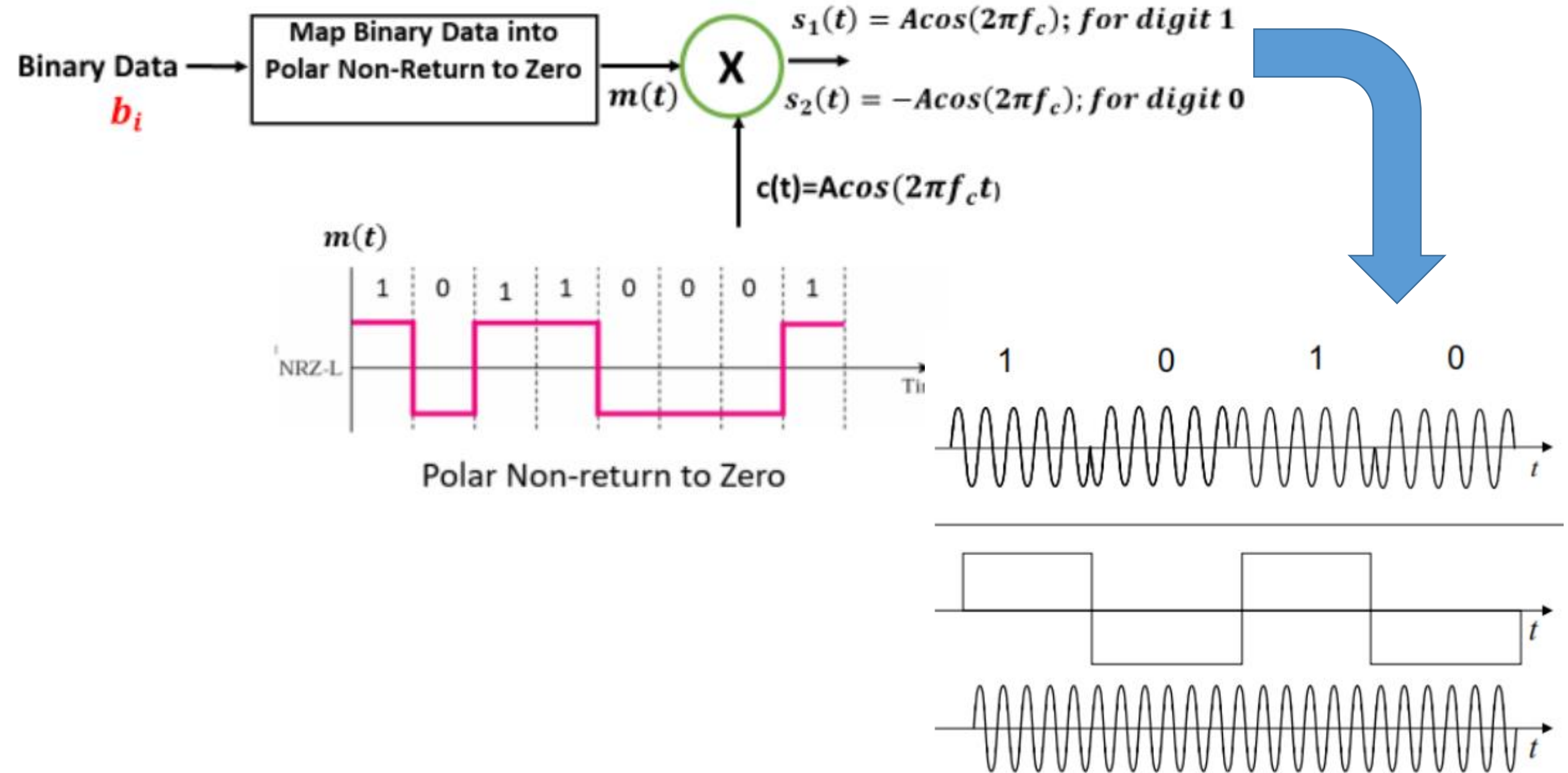
(τ is an integer number of $1/f_c$)

$$s_2(t) = s_1(t + \pi) = -s_1(t)$$

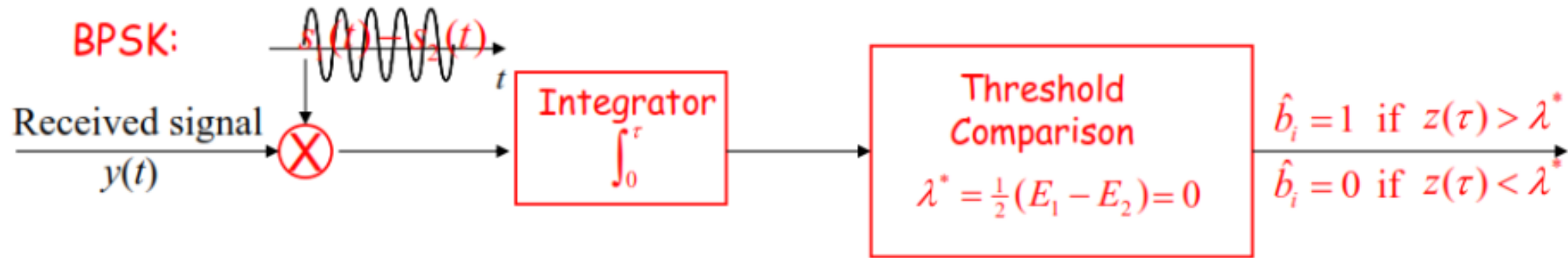
$$\tau = nT_c$$

In this figure $n=5$

Binary Phase Shift Keying: Generation



Binary Phase Shift Keying: The Optimum Receiver



Optimum Receiver Implemented as a Correlator Followed by a Threshold Detector

Probability of Error:

$$P_b^* = Q \left(\sqrt{\frac{\int_0^\tau (s_1(t) - s_2(t))^2 dt}{2N_0}} \right)$$

Energy of $s_i(t)$: $E_1 = E_2 = \frac{1}{2}A^2\tau$

Average Energy per bit: $E_b = \frac{1}{2}(E_1 + E_2) = \frac{1}{2}A^2\tau$

$$E = \int_0^\tau (s(t))^2 dt$$

With $\tau = nT_c$

$$E = A^2\tau/2$$

Verify this result

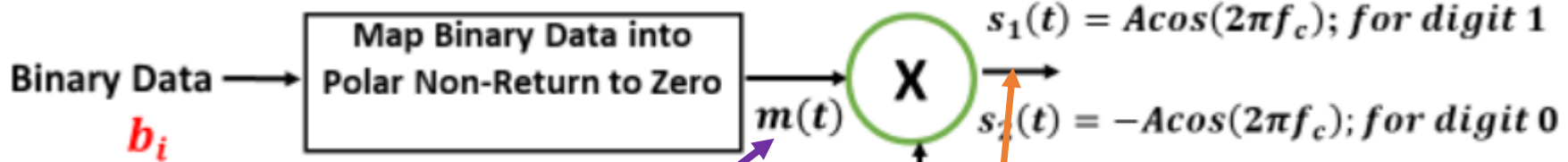
$$s_1(t) = A\cos(2\pi f_c t)$$

$$s_2(t) = -A\cos(2\pi f_c t)$$

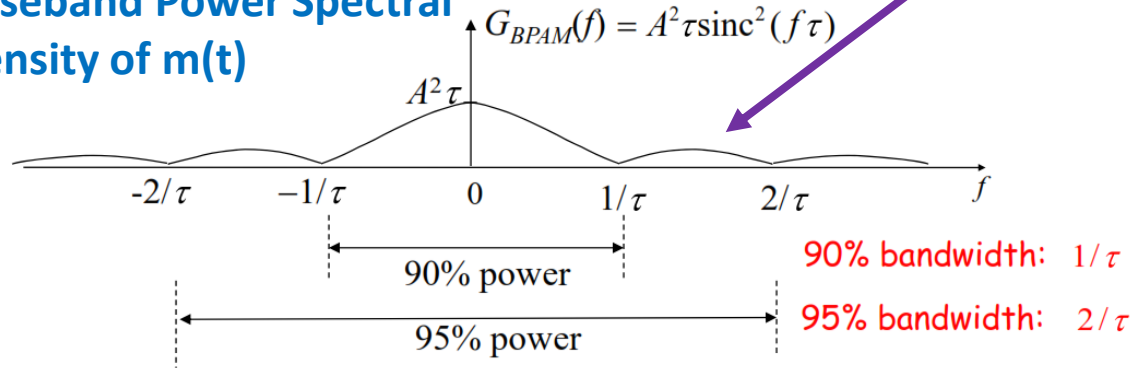
Optimal BER:

$$P_b^* = Q \left(\sqrt{\frac{A^2\tau}{N_0}} \right) = Q \left(\sqrt{\frac{2E_b}{N_0}} \right)$$

Binary Phase Shift Keying: Power Spectral Density and Bandwidth



Baseband Power Spectral Density of $m(t)$

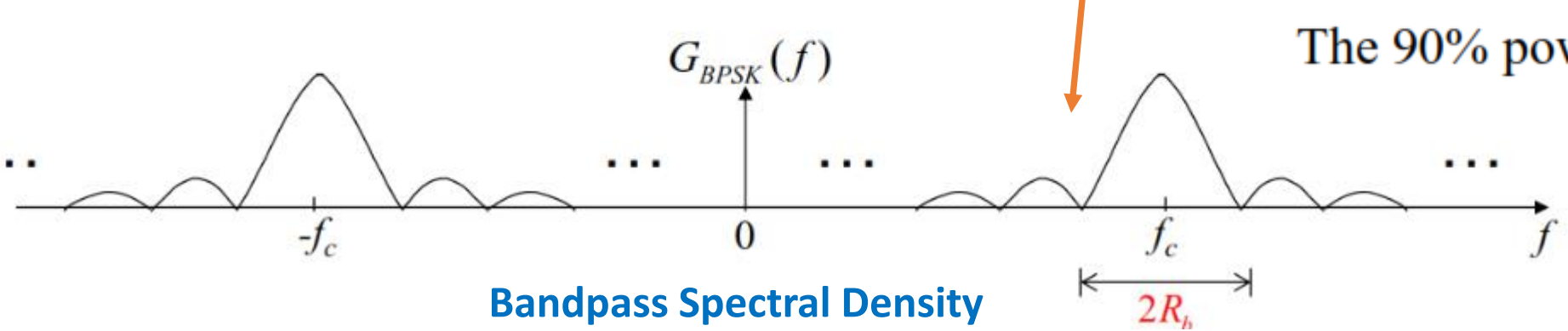


$s(t) = m(t) \cos(2\pi f_c t)$

Bandwidth of BPSK $s(t)$

Power Spectral Density

$G_{BPSK}(f) = \frac{1}{4} [G_{BPAM}(f - f_c) + G_{BPAM}(f + f_c)]$



The 90% power bandwidth = $\frac{2}{\tau} = 2R_b$
 (twice the data rate);
 Same as that of BASK

Extra Material on the Power Spectral Density

The Wiener –Khintchine Theorem:

The power spectral density $G_X(f)$ and the autocorrelation function $R_X(\tau)$ of a stationary random process $X(t)$ form a Fourier transform pairs:

$$G_X(f) = \int_{-\infty}^{\infty} R_X(\tau) e^{-j2\pi f\tau} d\tau \text{ (Fourier Transform)}$$

$$R_X(\tau) = \int_{-\infty}^{\infty} G_X(f) e^{j2\pi f\tau} df \text{ (Inverse Fourier Transform)}$$

Example: Mixing of a random process with a sinusoidal signal.

- A random process $X(t)$ with an autocorrelation function $R_X(\tau)$ and a power spectral density $G_X(f)$ is mixed with a sinusoidal function $\cos(2\pi f_c t + \theta)$; θ is a r.v uniformly distributed over $(0, 2\pi)$ to form a new process

$$Y(t) = X(t)\cos(2\pi f_c t + \theta). \text{ Find } R_Y(\tau) \text{ and } G_Y(f)$$

- **Solution:** We first find $R_Y(\tau)$

- $R_Y(\tau) = E\{Y(t)Y(t + \tau)\}$

- $= E\{X(t)\cos(2\pi f_c t + \theta) \cdot X(t + \tau) \cos(2\pi f_c t + 2\pi f_c \tau + \theta)\}$

When $X(t)$ and θ are independent, then

- $= E\{X(t) X(t + T)\}E\{\cos(2\pi f_c t + \theta) \cdot \cos(2\pi f_c t + 2\pi f_c \tau + \theta)\}$

- $= R_X(\tau)E\left\{\frac{\cos(4\pi f_c t + 2\pi f_c \tau + 2\theta) + \cos 2\pi f_c \tau}{2}\right\}$

- $R_Y(\tau) = \frac{R_X(\tau)}{2} \cdot \cos 2\pi f_c \tau$;

- The power spectral density is

- $S_Y(f) = \frac{1}{4}\{G_X(f - f_c) + G_X(f + f_c)\}$

- Which is quite similar to the modulation property of the Fourier transform.

Binary Amplitude Shift Keying (BASK): Signal Representation

Send: $s_1(t) = A \cos(2\pi f_c t)$, if the information bit is “1” $\Rightarrow E_1 = \frac{A^2 \tau}{2}$

Send: $s_2(t) = 0$, if the information bit is “0”; $\Rightarrow E_2 = 0$

The average energy per bit $E_b = \frac{1}{2} (E_1 + E_2) = \frac{A^2 \tau}{4}$

$$\tau = nT_c$$

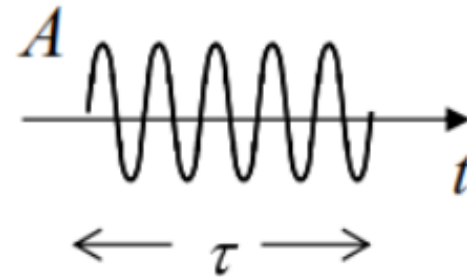
τ : is the time allocated to transmit the binary digit.

$T_c = 1/f_c$ is the carrier period

$R_b = \frac{1}{\tau}$: Data rate bits/sec

“1”

“0”



$$\tau = nT_c$$

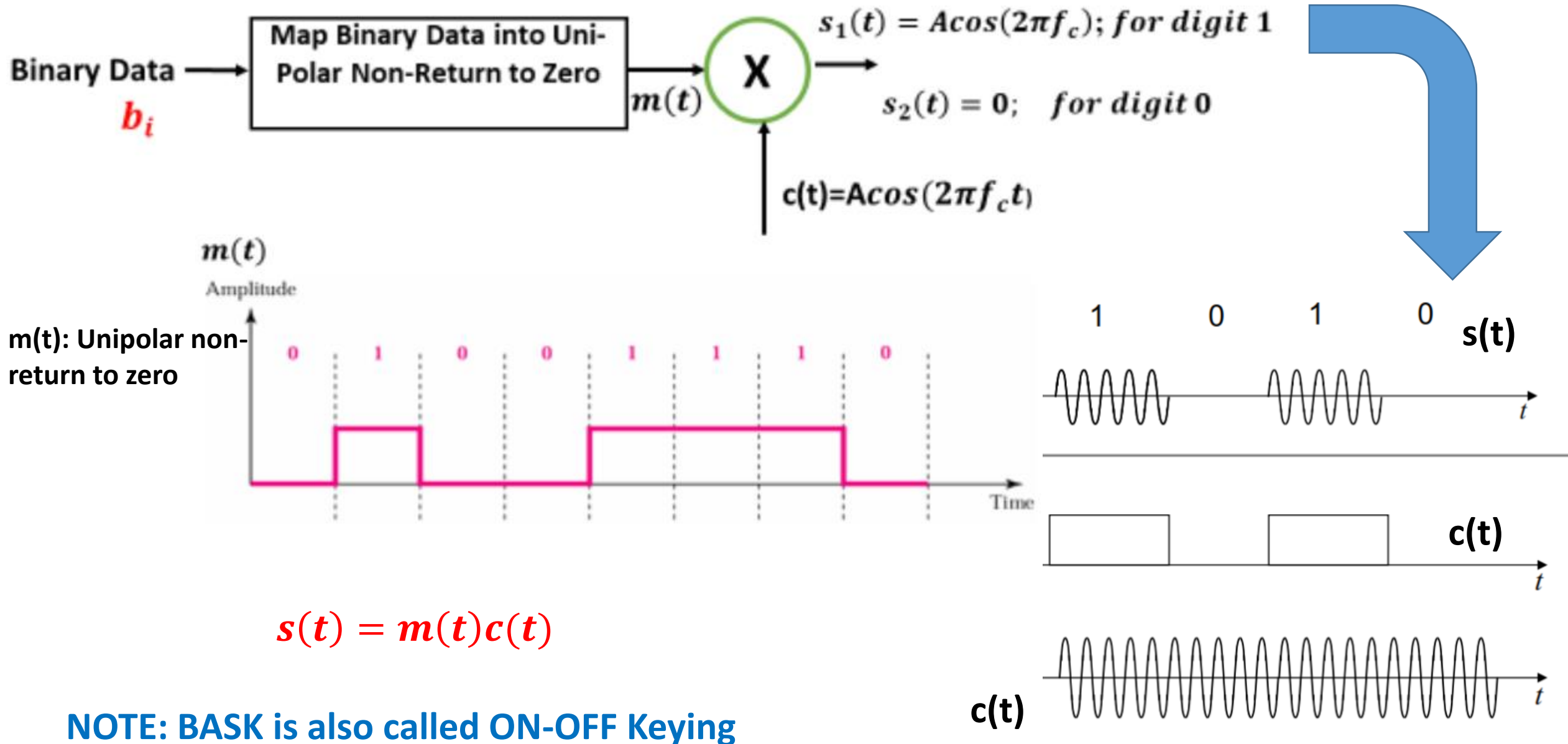
In this figure $n=5$

$$s_1(t) = A \cos(2\pi f_c t)$$

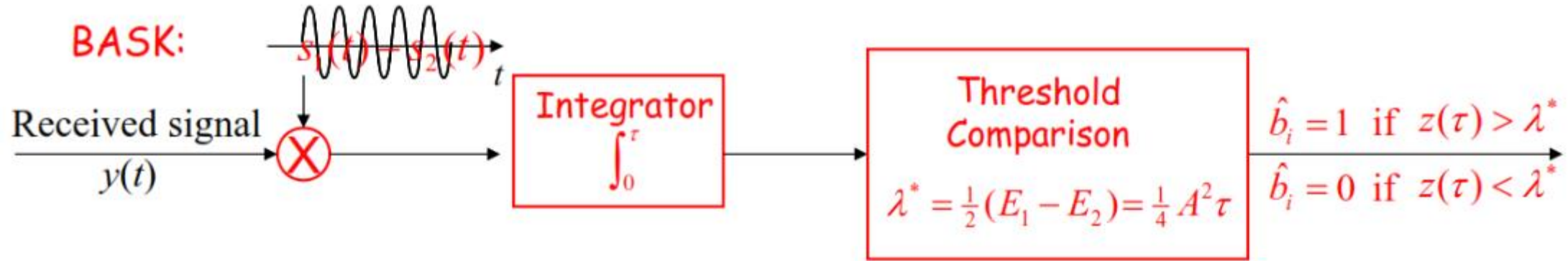
$$s_2(t) = 0$$

$$0 \leq t \leq \tau$$

Binary Amplitude Shift Keying : Generation



Binary Amplitude Shift Keying : The Optimum Receiver



Optimum Receiver Implemented as a Correlator Followed by a Threshold Detector

Probability of Error:

$$P_b^* = Q\left(\sqrt{\frac{\int_0^\tau (s_1(t) - s_2(t))^2 dt}{2N_0}}\right)$$

$$E_1 = \int_0^\tau (s_1(t))^2 dt$$

With $\tau = nT_c$

$$E_1 = A^2\tau/2$$

$$s_1(t) = A\cos(2\pi f_c t)$$

$$s_2(t) = 0$$

Optimal BER:

$$E_1 = \frac{A^2\tau}{2}$$

$$E_b = \frac{1}{2}(E_1 + E_2) = \frac{A^2\tau}{4}$$

$$E_2 = 0$$

$$P_b^* = Q\left(\sqrt{\frac{A^2\tau}{4N_0}}\right) = Q\left(\sqrt{\frac{E_b}{N_0}}\right)$$

Binary Amplitude Shift Keying: Power Spectral Density

Let $m(t)$ be the unipolar NRZ signal with autocorrelation function $R_m(\tau)$ and power spectral density $G_m(f)$.

- You can easily verify that the unipolar non-return to zero signal $m(t)$ is related to the polar non-return signal $m'(t)$ (used in the generation of the BPSK) by:

- $$m(t) = \frac{1}{2}(1 + m'(t))$$

The autocorrelation function of $m(t)$ is

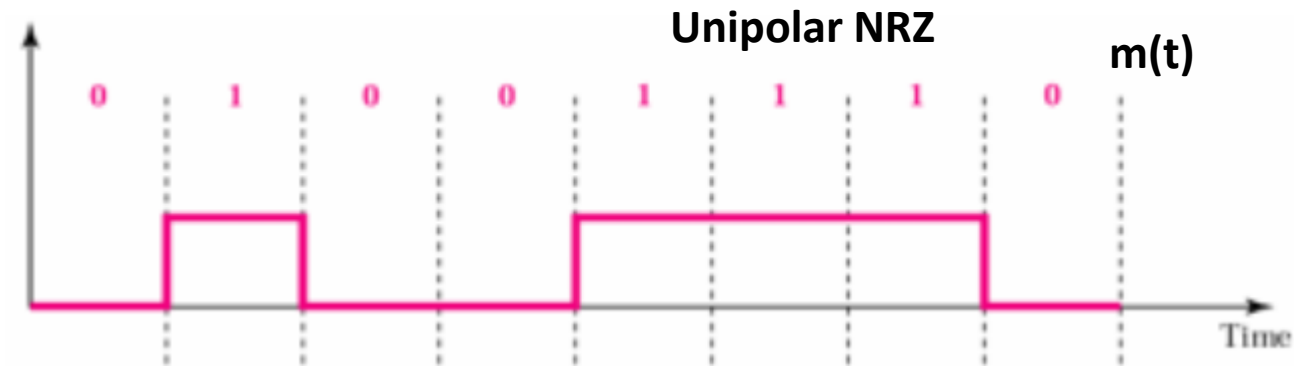
- $$R_Y(\tau) = E\{m(t)m(t + \tau)\} =$$

$$= E\left\{\frac{1}{2}(1 + m'(t))\frac{1}{2}(1 + m'(t + \tau))\right\} = \frac{1}{4} + \frac{1}{4}R_{m'}(\tau);$$

Note that for the polar-NRZ $E\{m'(t)\} = 0$

- The power spectral density of $m(t)$ is:

- $$G_m(f) = \frac{1}{4}\delta(f) + \frac{1}{4}G_{m'}(f)$$



Binary Amplitude Shift Keying: Power Spectral Density

The Wiener –Khinchine Theorem: The power spectral density $G_X(f)$ and the autocorrelation function $R_X(\tau)$ of a stationary random process $X(t)$ form a Fourier transform pairs:

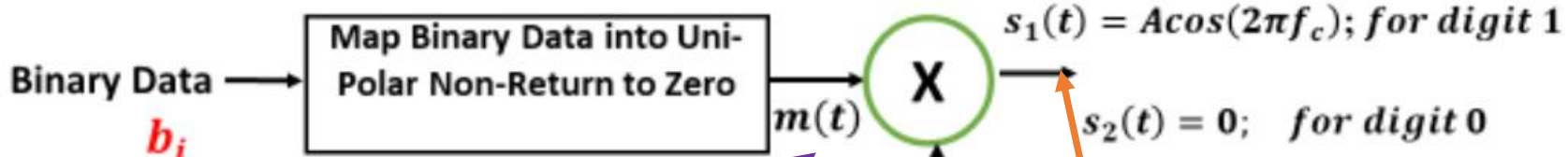
- $G_X(f) = \int_{-\infty}^{\infty} R_X(\tau) e^{-j2\pi f\tau} d\tau$ (Fourier Transform)
- $R_X(\tau) = \int_{-\infty}^{\infty} G_X(f) e^{j2\pi f\tau} df$ (Inverse Fourier Transform)
- The power spectral density of $m(t)$, the unipolar NRZ is:
- $G_m(f) = \frac{1}{4} \delta(f) + \frac{1}{4} G_{m'}(f)$
- In the previous video we saw that if a random process $X(t)$ with an autocorrelation function $R_X(\tau)$ and a power spectral density $G_X(f)$ is mixed with a sinusoidal function $\cos(2\pi f_c t + \theta)$; θ is a r.v uniformly distribution over $(0, 2\pi)$ to form a new process

$$Y(t) = X(t)\cos(2\pi f_c t + \theta). \quad \text{Our Problem: } s(t) = m(t)\cos(2\pi f_c t + \theta)$$

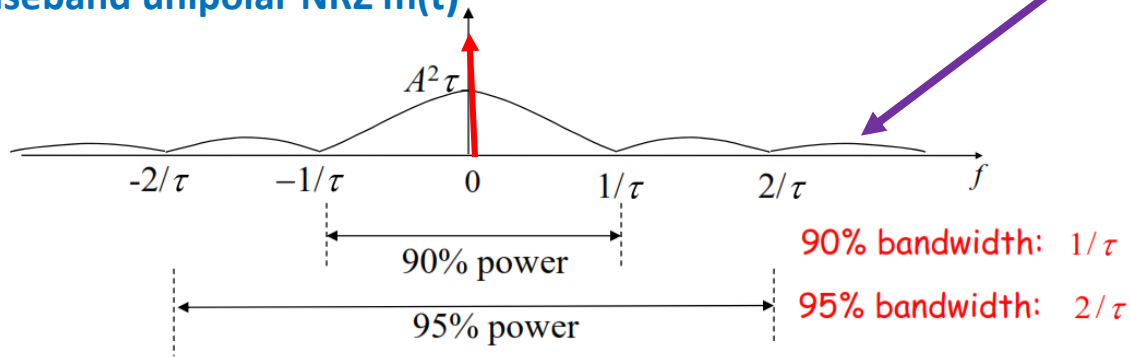
then the autocorrelation function and power spectral density of $Y(t)$ are given by:

- $R_Y(\tau) = E\{Y(t)Y(t + \tau)\} = \frac{R_X(\tau)}{2} \cdot \cos 2\pi f_c \tau$;
- $G_Y(f) = \frac{1}{4} \{G_X(f - f_c) + G_X(f + f_c)\}$
- Hence, $G_{BASK}(f) = \frac{1}{4} \{G_m(f - f_c) + G_m(f + f_c)\}$

Binary Amplitude Shift Keying : Power Spectral Density and Bandwidth



Power Spectral Density of the baseband unipolar NRZ $m(t)$

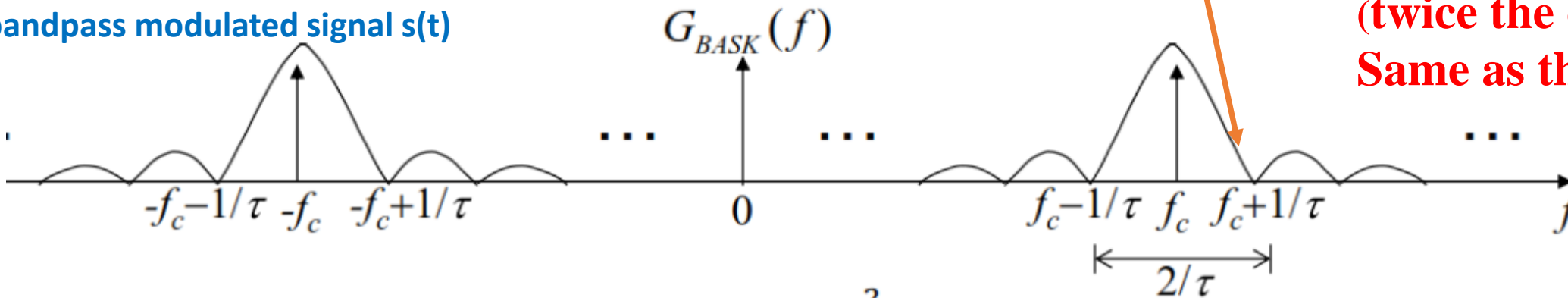


$$s(t) = m(t) \cos(2\pi f_c t)$$

$$G_{BASK}(f) = \frac{1}{4} [G_{BOOK}(f - f_c) + G_{BOOK}(f + f_c)]$$

Bandwidth of BASK $s(t)$

Power Spectral Density of the bandpass modulated signal $s(t)$

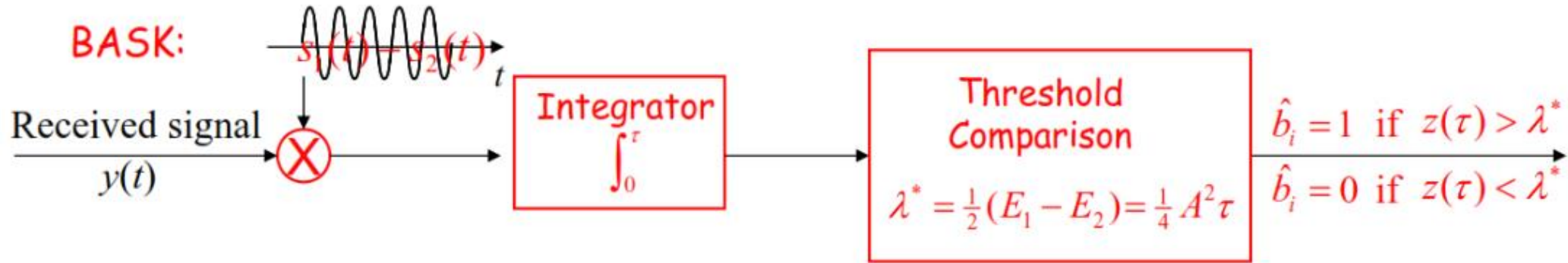


(twice the data rate);
Same as that of BPSK

$$\text{The 90\% power bandwidth} = \frac{2}{\tau} = 2R_b$$

Non-coherent Demodulation of the Binary ASK Signal

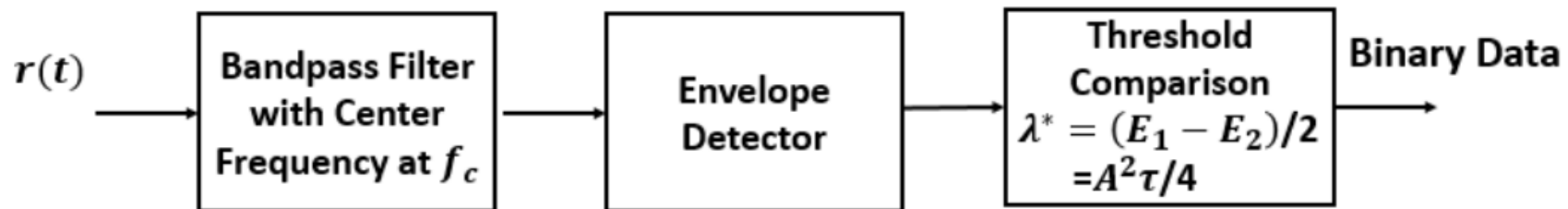
The demodulator which uses the signal difference $s_1(t) - s_2(t) = A\cos(2\pi f_c t)$ is called coherent demodulator



In non-coherent demodulation, there is no need for the carrier frequency at the receiver. The basic elements of the receiver are a bandpass filter with center frequency at the carrier, an envelope detector, and a threshold comparator. The receiver is simple, however it is not optimal in terms of the probability of error. The details are shown in the following block diagram

$$r(t) = A\cos(2\pi f_c t) + n(t)$$

$$r(t) = n(t)$$



Non-Coherent Binary ASK Demodulation

Binary Frequency Shift Keying (BFSK): Signal Representation

In binary FSK, the frequency of the carrier signal is varied to represent the binary digits 1 and 0 by two distinct frequencies. The amplitude and frequency remain constant during each bit interval.

Signal Representation (coherent FSK)

Send: $s_1(t) = A \cos(2\pi(f_c + \Delta f)t)$ if the information bit is “1”;

Send: $s_2(t) = A \cos(2\pi(f_c - \Delta f)t)$ if the information bit is “0”;

Δf is an offset frequency (from the unmodulated carrier f_c) chosen so that $s_1(t)$ and $s_2(t)$ are orthogonal, i.e.,

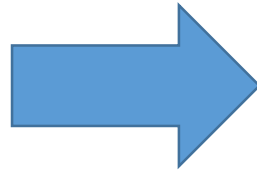
$$\int_0^{\tau} s_1(t)s_2(t)dt = 0$$

$$\frac{\sin(2\pi(2f_c)\tau)}{2f_c} + \frac{\sin(2\pi(2\Delta f)\tau)}{2\Delta f} = 0$$

Binary Frequency Shift Keying (BFSK): Signal Representation

Orthogonality condition

$$\frac{\sin(2\pi(2f_c)\tau)}{2f_c} + \frac{\sin(2\pi(2\Delta f)\tau)}{2\Delta f} = 0$$



$$2f_c = \frac{n}{2\tau} = \frac{nR_b}{2}, n = 1, 2, \dots \quad f_c = \frac{nR_b}{4} = kR_b$$

$$2\Delta f = \frac{mR_b}{2}, m = 1, 2, \dots \quad \Delta f = \frac{mR_b}{4}$$

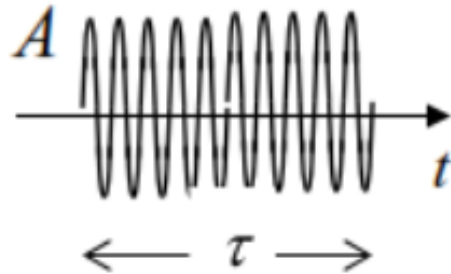
Note that $\sin(x) = 0$ when $x = n\pi$ The minimum frequency separation $2\Delta f = R_b/2$.

τ : is the time allocated to transmit the binary digit.

$T_c = 1/f_c$ is the carrier period

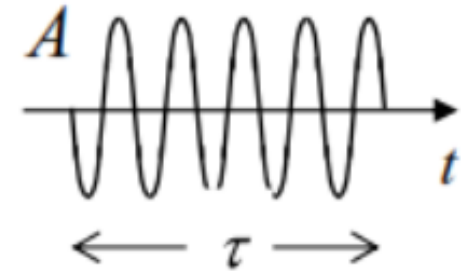
$R_b = \frac{1}{\tau}$: Data rate bits/sec

“1”



$$s_1(t) = A \cos(2\pi(f_c + \Delta f)t) \quad 0 \leq t \leq \tau$$

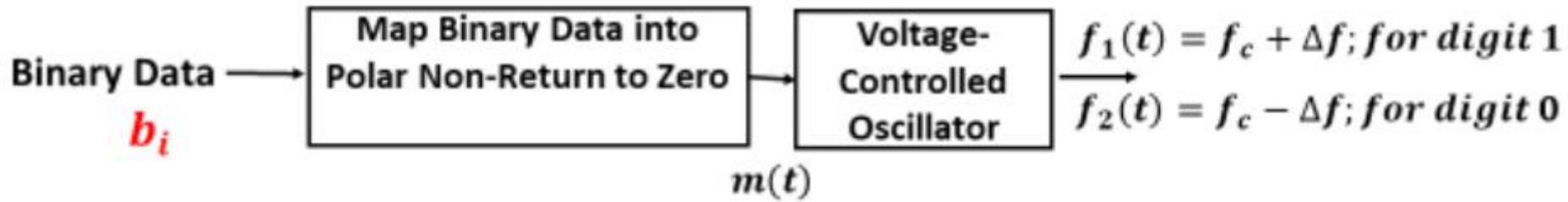
“0”



$$s_2(t) = A \cos(2\pi(f_c - \Delta f)t) \quad 0 \leq t \leq \tau$$

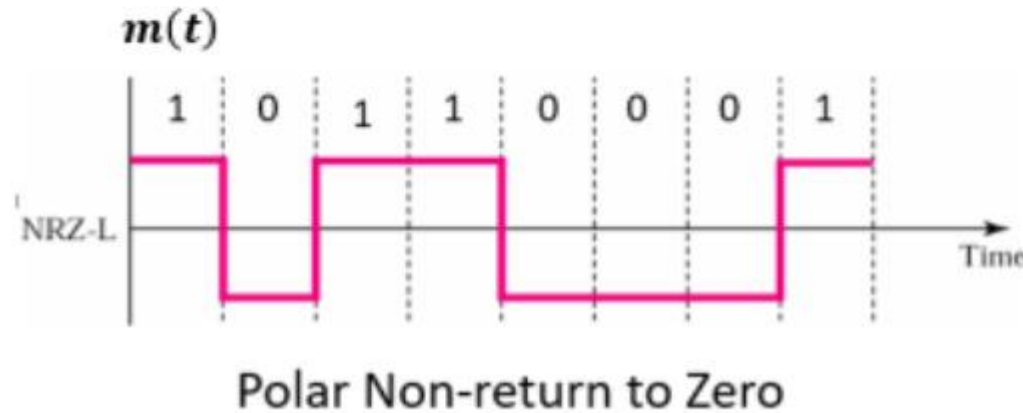
(τ is an integer number of $1/(f_c \pm \Delta f)$)

Binary FSK : Generation using the Single Oscillator Method



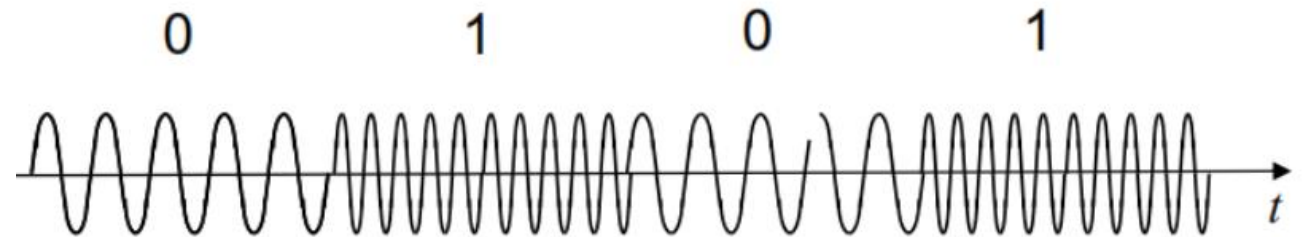
$m(t)$: Polar non-return to zero

$$f_i(t) = f_c + k_f m(t); \text{ for VCO}$$



$$s_1(t) = A \cos(2\pi(f_c + \Delta f)t)$$

$$s_2(t) = A \cos(2\pi(f_c - \Delta f)t)$$

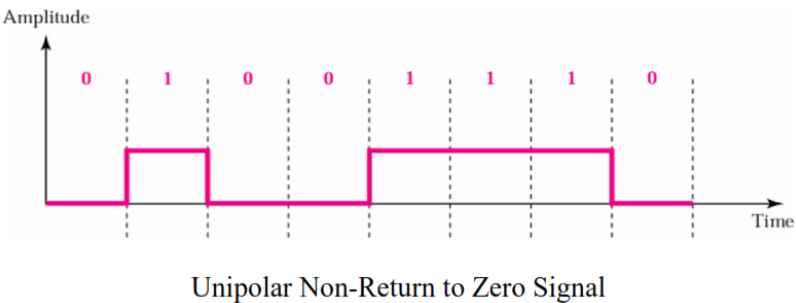


Binary FSK : Generation using the Two-oscillator Method

$s_{BFSK}(t) = \text{ASK of } m(t) \text{ on first carrier frequency}$

$+ \text{ASK of } (1 - m(t)) \text{ on second carrier frequency}$

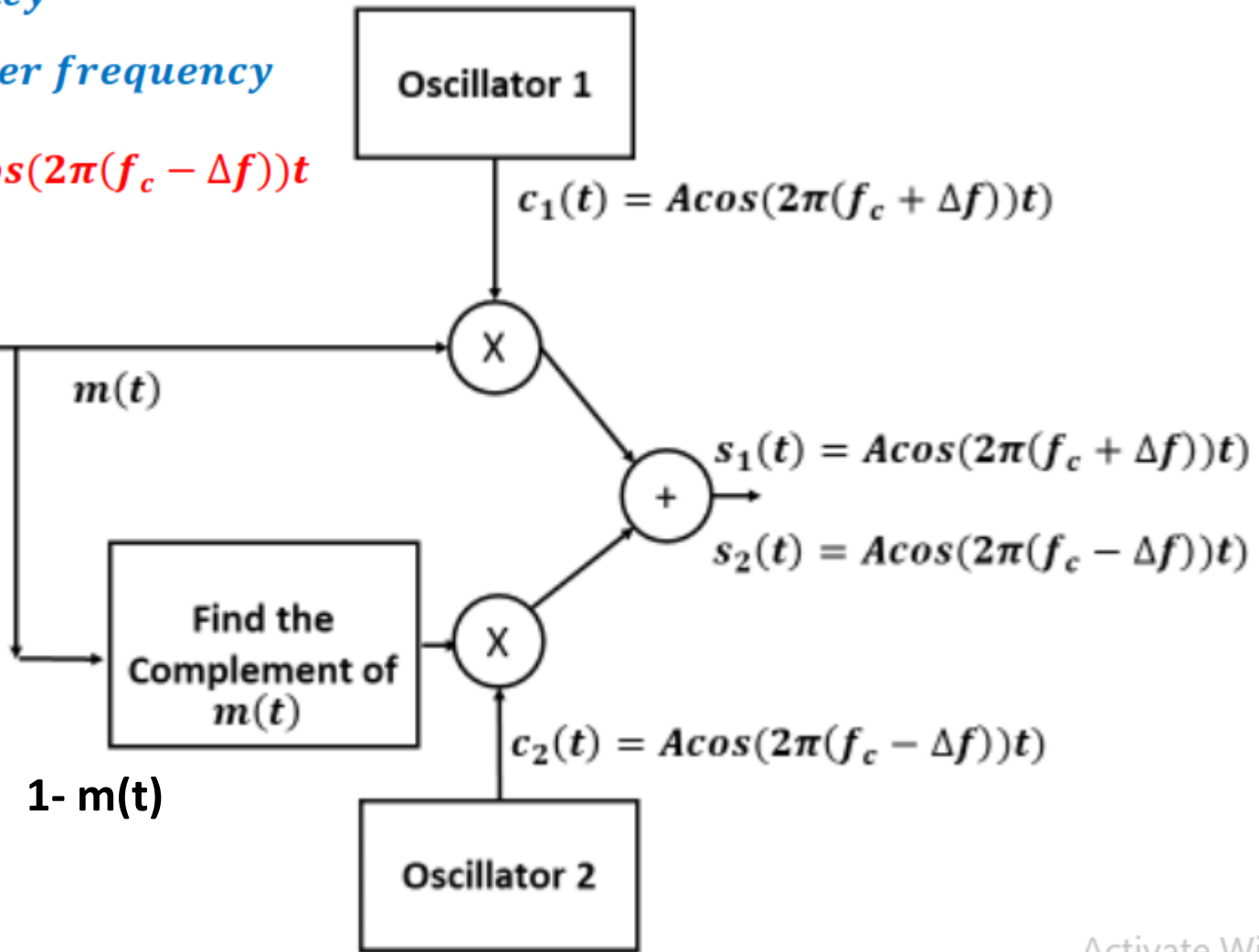
$$s_{BFSK}(t) = m(t)A\cos(2\pi(f_c + \Delta f)t) + (1 - m(t))A\cos(2\pi(f_c - \Delta f)t)$$



Map Binary Data into Unipolar Non-Return to Zero

Binary Data b_i

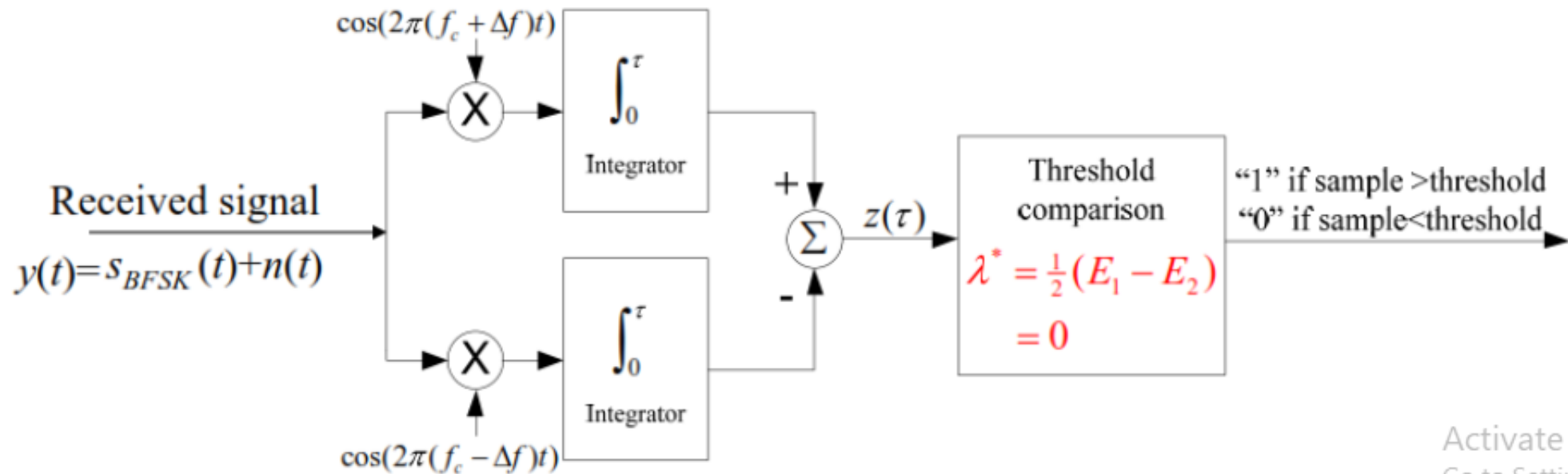
- This representation will be used to find the power spectral density of $s(t)$ since it is envisaged as the superposition of two ASK signals.
- The power spectral density of an ASK signal was derived in a previous video titled: Binary ASK



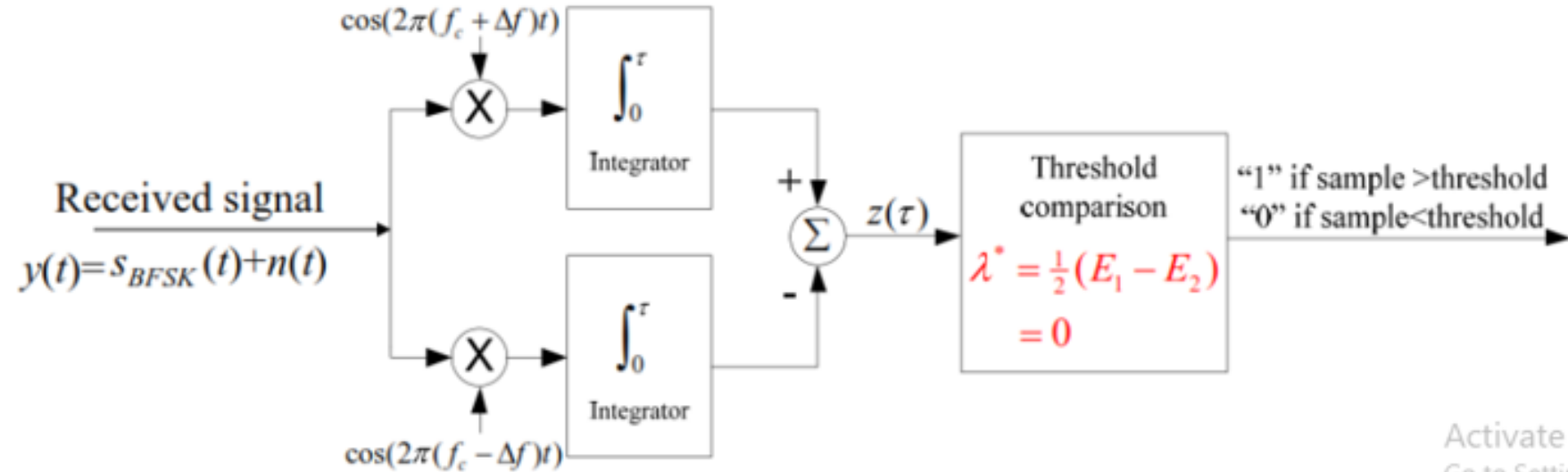
FSK: modeled as a sum of two ASK signals

Binary FSK : Coherent Demodulation

The optimum coherent receiver consists of two correlators. The operation of the receiver makes use of the orthogonality condition imposed on the signals $s_1(t)$ and $s_2(t)$. In the absence of noise, if $s_1(t)$ is received, then the output of the upper correlator will have a value greater than zero, while the output of the lower correlator is zero. The converse is true when $s_2(t)$ is received. In the presence of noise, the system decides 1 when $z(\tau) > 0$. That is, when the output of the upper correlator is greater than the output of the lower one. Otherwise, it decides 0.



Binary FSK : Probability of Error



Probability of Error

$$\text{Energy of } s_i(t) : E_1 = E_2 = \frac{1}{2}A^2\tau$$

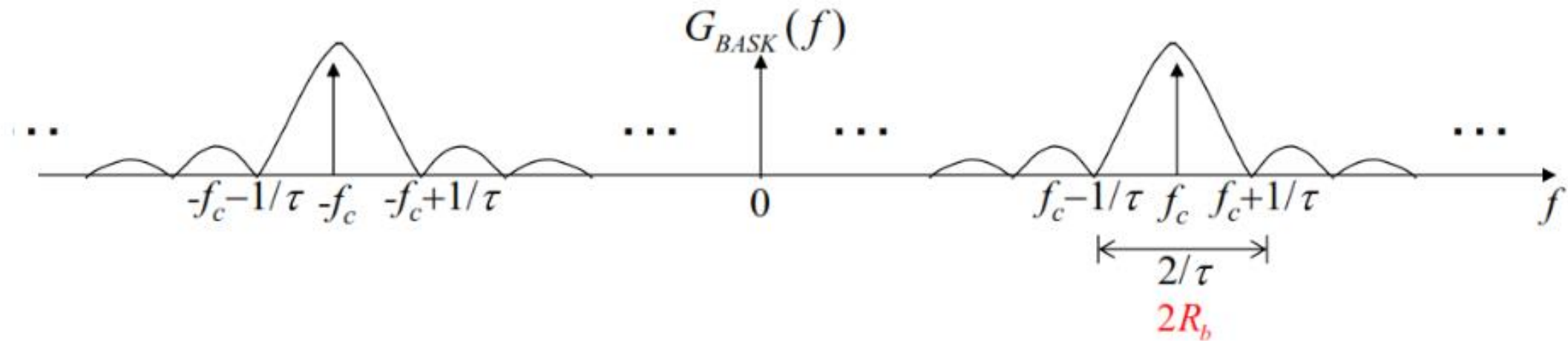
$$\text{Average Energy per bit: } E_b = \frac{1}{2}(E_1 + E_2) = \frac{1}{2}A^2\tau$$

When the signals are orthogonal, i.e., when $\int_0^\tau s_1(t)s_2(t)dt = 0$, the probability of error is given by

$$P_b^* = Q\left(\sqrt{\frac{A^2\tau}{2N_0}}\right) = Q\left(\sqrt{\frac{E_b}{N_0}}\right)$$

Binary FSK : Power Spectral Density

Since the FSK signal is the superposition of two ASK signals on two orthogonal frequencies, the spectrum is also the superposition of that of the ASK signals. We recall that the spectrum of the ASK signal is as shown below

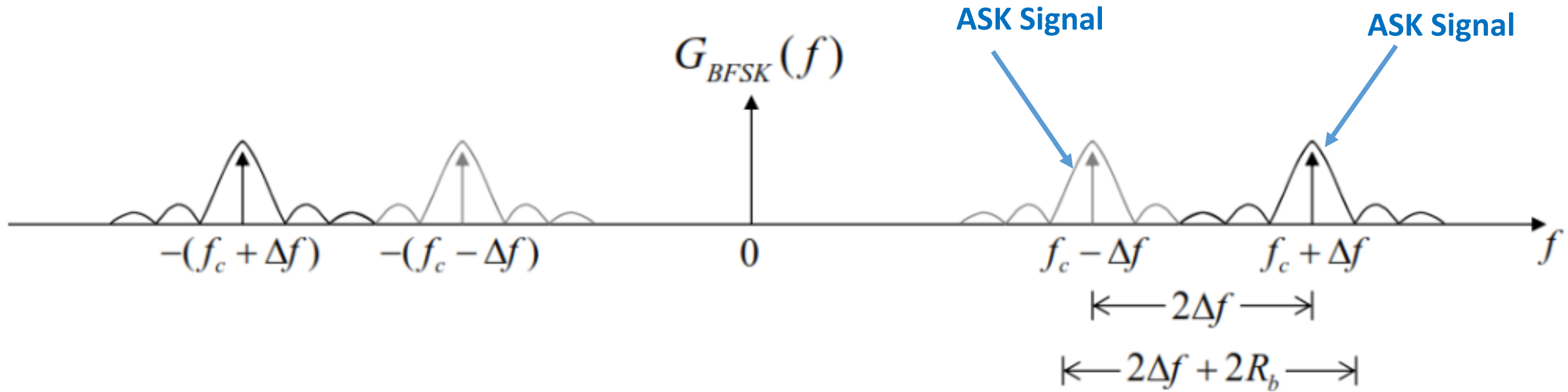


$s_{BFSK}(t) = \text{ASK of } m(t) \text{ on first carrier frequency}$

$+ \text{ASK of } (1 - m(t)) \text{ on second carrier frequency}$

$$s_{BFSK}(t) = m(t)A\cos(2\pi(f_c + \Delta f))t + (1 - m(t))A\cos(2\pi(f_c - \Delta f))t$$

Binary FSK : Power Spectral Density and Bandwidth



The required channel bandwidth for 90% in-band power

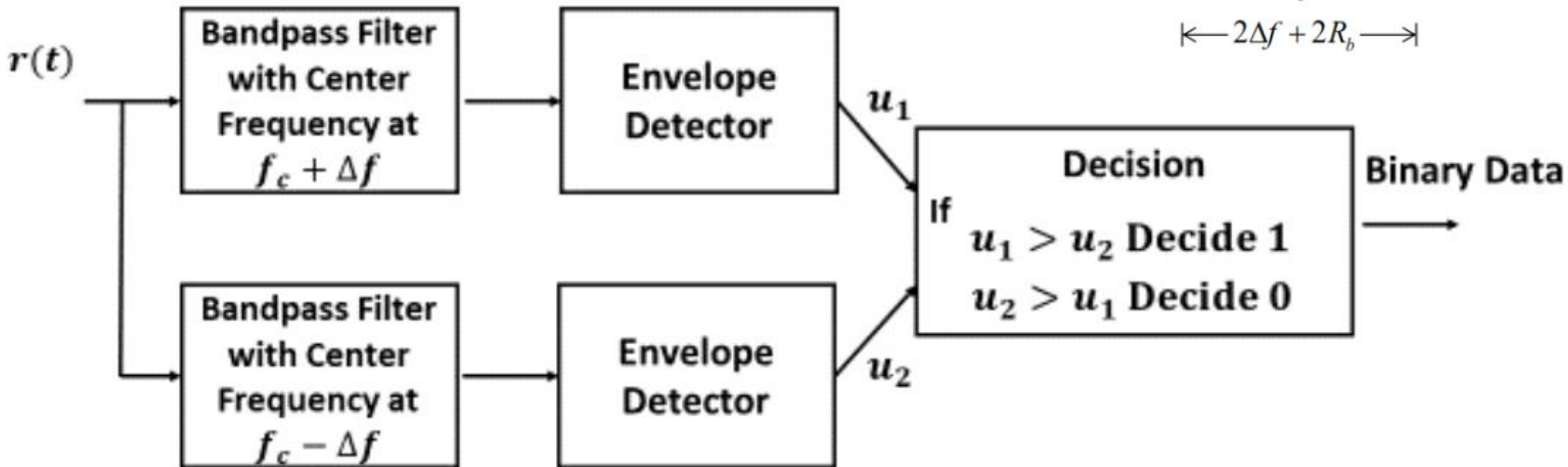
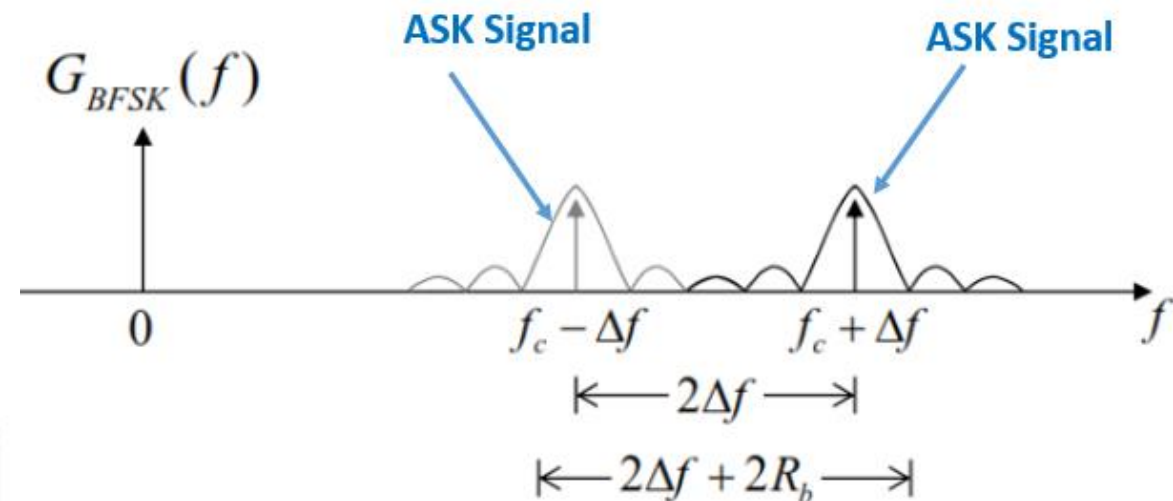
$$B_{h_{90\%}} = 2\Delta f + 2R_b$$

$$B.W = (f_1 - f_2) + 2R_b = \frac{R_b}{2} + 2R_b$$

Binary FSK : Non-coherent Demodulation

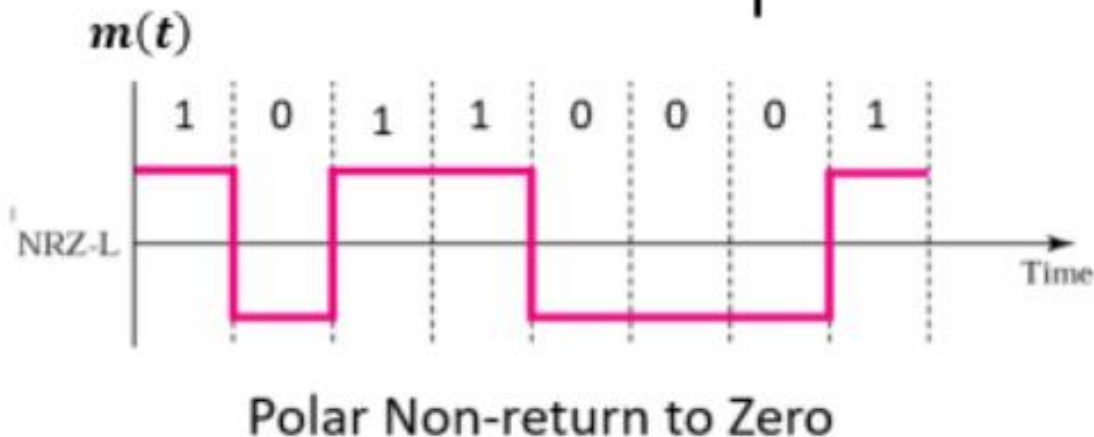
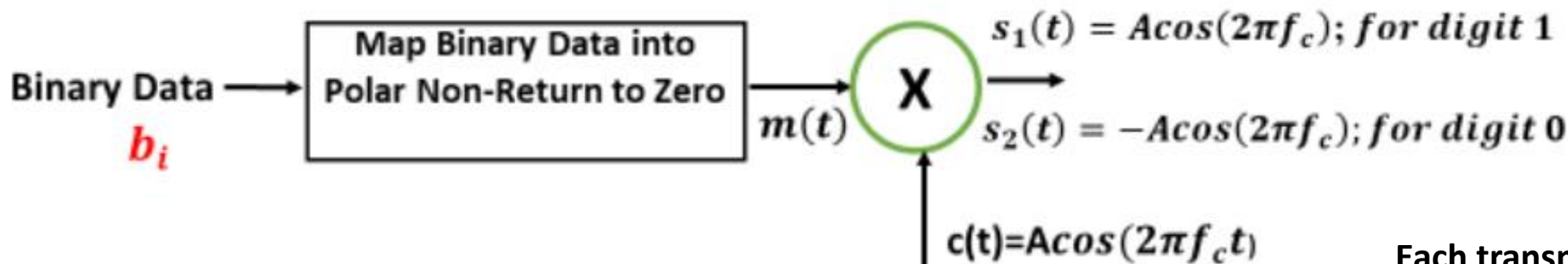
$$r(t) = A \cos(2\pi(f_c + \Delta f)t) + n(t)$$

$$r(t) = A \cos(2\pi(f_c - \Delta f)t) + n(t)$$

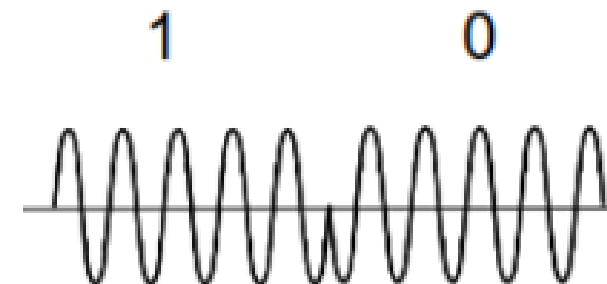


Quadri-phase Shift Keying (QPSK)

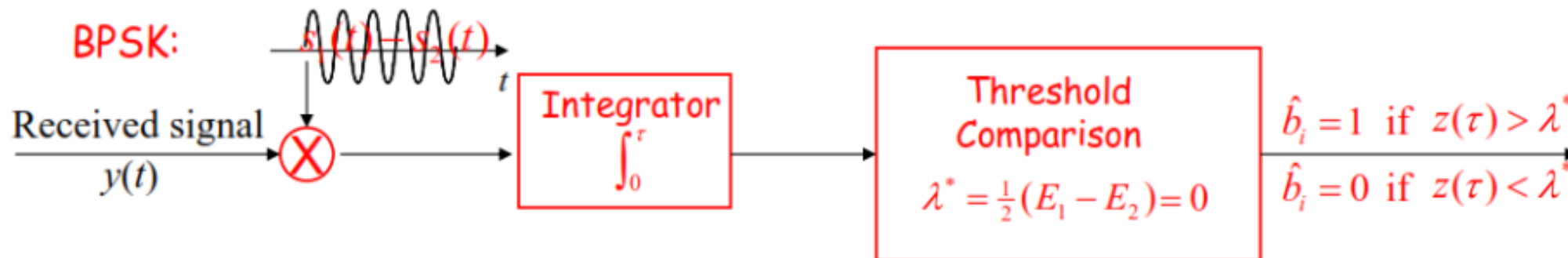
Review: Binary Phase Shift Keying Modulation and Demodulation



Each transmitted signal corresponds to one binary digit



$$s_1(t) - s_2(t) = 2A \cos(2\pi f_c t)$$



Quadri-phase Shift Keying (QPSK): Signal Representation

"1 1" $s_1(t) = A \cos(2\pi f_c t - \pi / 4) = +\frac{A}{\sqrt{2}} \cos(2\pi f_c t) + \frac{A}{\sqrt{2}} \sin(2\pi f_c t)$

"1 0" $s_2(t) = A \cos(2\pi f_c t + \pi / 4) = +\frac{A}{\sqrt{2}} \cos(2\pi f_c t) - \frac{A}{\sqrt{2}} \sin(2\pi f_c t)$

"0 0" $s_3(t) = A \cos(2\pi f_c t + 3\pi / 4) = -\frac{A}{\sqrt{2}} \cos(2\pi f_c t) - \frac{A}{\sqrt{2}} \sin(2\pi f_c t)$

"0 1" $s_4(t) = A \cos(2\pi f_c t + 5\pi / 4) = -\frac{A}{\sqrt{2}} \cos(2\pi f_c t) + \frac{A}{\sqrt{2}} \sin(2\pi f_c t)$

$$s_{QPSK}(t) = d_I \frac{A}{\sqrt{2}} \cos(2\pi f_c t) + d_Q \frac{A}{\sqrt{2}} \sin(2\pi f_c t)$$

Odd bits $d_I = \begin{cases} 1 & \text{if } b_{2i-1} = 1 \\ -1 & \text{if } b_{2i-1} = 0 \end{cases}$

Even bits $d_Q = \begin{cases} 1 & \text{if } b_{2i} = 1 \\ -1 & \text{if } b_{2i} = 0 \end{cases}$

$$s_{QPSK}(t) = A_k \cos(2\pi f_c t) + B_k \sin(2\pi f_c t)$$

$$s_{QPSK}(t) = \text{Binary PSK on } \cos(2\pi f_c t) + \text{Binary PSK on } \sin(2\pi f_c t)$$

- In this type of modulation two binary digits are grouped together to form one message that phase modulates the carrier $A \cos(2\pi f_c t)$.
- The transmitted signal assumes one of four possible phases (+45, -45, +135, -135) $A \cos(2\pi f_c t + \theta_i)$
- A QPSK signal can be decomposed into a sum of two PSK signals; an in-phase component and a quadrature component. The serial to parallel converter splits the incoming data sequence into two sequences that consist of the odd and even bits of the main sequence. The odd bit stream sequence modulates the in-phase carrier, while the even bit stream sequence modulates the quadrature carrier.

Quadri-phase Shift Keying (QPSK): Signal Representation

$$s_{QPSK}(t) = d_I \frac{A}{\sqrt{2}} \cos(2\pi f_c t) + d_Q \frac{A}{\sqrt{2}} \sin(2\pi f_c t)$$

$$d_I = \begin{cases} 1 & \text{if } b_{2i-1} = 1 \\ -1 & \text{if } b_{2i-1} = 0 \end{cases}$$

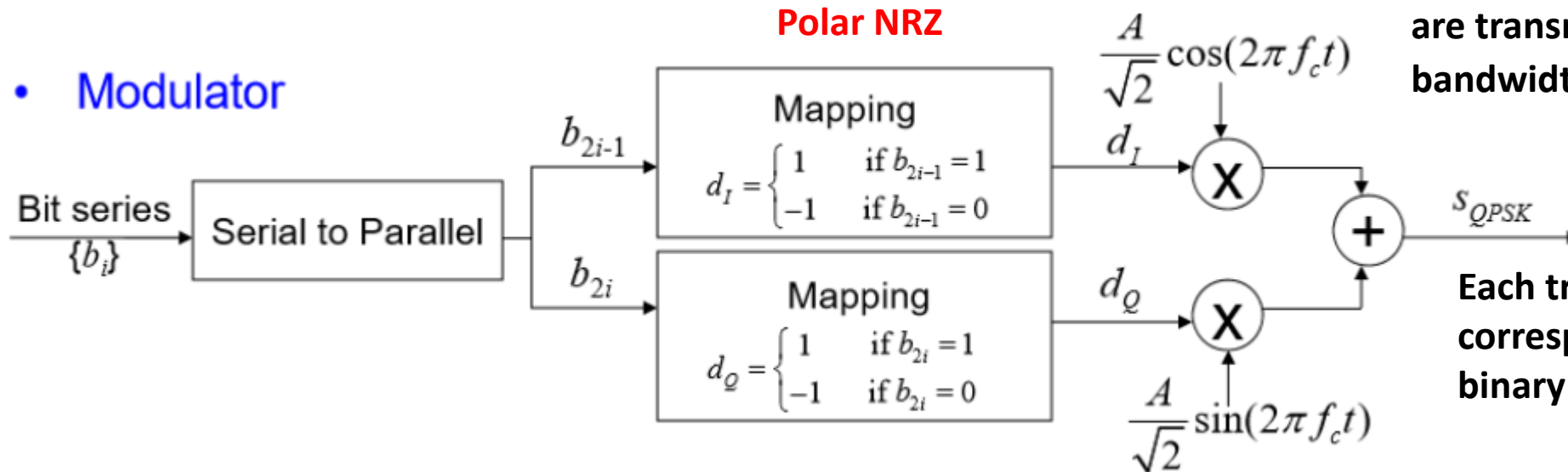
$$d_Q = \begin{cases} 1 & \text{if } b_{2i} = 1 \\ -1 & \text{if } b_{2i} = 0 \end{cases}$$

$$s_{QPSK}(t) = A_k \cos(2\pi f_c t) + B_k \sin(2\pi f_c t)$$

$$s_{QPSK}(t) = \text{Binary PSK on } \cos(2\pi f_c t) + \text{Binary PSK on } \sin(2\pi f_c t)$$

- The serial to parallel converter splits the incoming data sequence into two sequences that consist of the odd (A_k) and even bits (B_k) of the main sequence. The odd bit stream sequence modulates the in-phase carrier, while the even bit stream sequence modulates the quadrature carrier.
- Both in phase and quadrature BPSK are transmitted over the same bandwidth.

Modulator



Each transmitted signal corresponds to two binary digits

Quadri-phase Shift Keying (QPSK): Modulation

One message (or symbol) consists of two bits

$$T_s = 2T_b$$

$$R_s = R_b/2$$

• Modulator

Bit series $\{b_i\}$

Serial to Parallel

b_{2i-1}

b_{2i}

Mapping

$$d_I = \begin{cases} 1 & \text{if } b_{2i-1} = 1 \\ -1 & \text{if } b_{2i-1} = 0 \end{cases}$$

Mapping

$$d_Q = \begin{cases} 1 & \text{if } b_{2i} = 1 \\ -1 & \text{if } b_{2i} = 0 \end{cases}$$

$$\frac{A}{\sqrt{2}} \cos(2\pi f_c t)$$

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

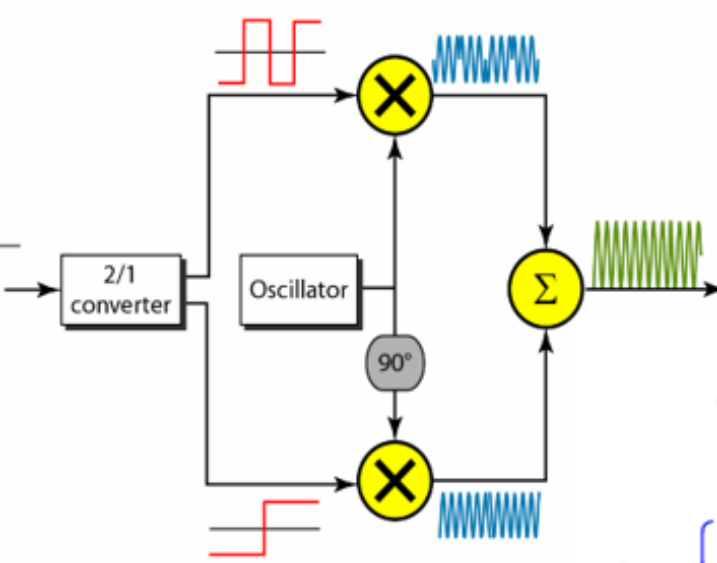
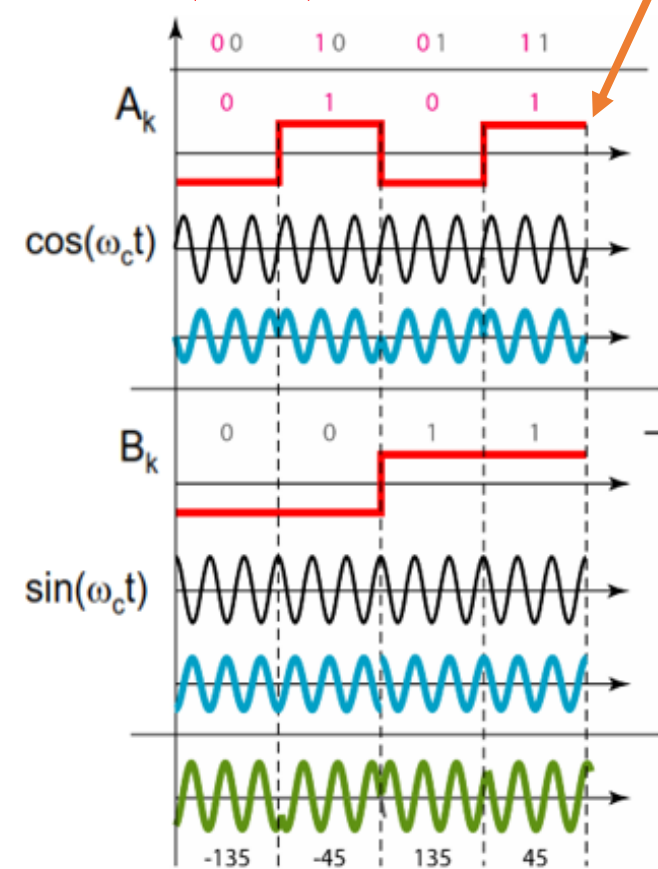
S_{QPSK}

Message duration $T_s = 2T_b$
Message Rate $R_s = R_b/2$

$$s_{QPSK}(t) = d_I \frac{A}{\sqrt{2}} \cos(2\pi f_c t) + d_Q \frac{A}{\sqrt{2}} \sin(2\pi f_c t)$$

$$d_I = \begin{cases} 1 & \text{if } b_{2i-1} = 1 \\ -1 & \text{if } b_{2i-1} = 0 \end{cases}$$

$$d_Q = \begin{cases} 1 & \text{if } b_{2i} = 1 \\ -1 & \text{if } b_{2i} = 0 \end{cases}$$



Quadri-phase Shift Keying (QPSK): Demodulation

$$z_1(\tau) = \int_0^\tau [s_{QPSK}(t) + n(t)] \cos(2\pi f_c t) dt$$

$$z_2(\tau) = \int_0^\tau [s_{QPSK}(t) + n(t)] \sin(2\pi f_c t) dt$$

$$z_1(\tau) = \int_0^\tau [A_k \cos(2\pi f_c t) + B_k \sin(2\pi f_c t) + n(t)] \cos(2\pi f_c t) dt$$

$$z_2(\tau) = \int_0^\tau [A_k \cos(2\pi f_c t) + B_k \sin(2\pi f_c t) + n(t)] \sin(2\pi f_c t) dt$$

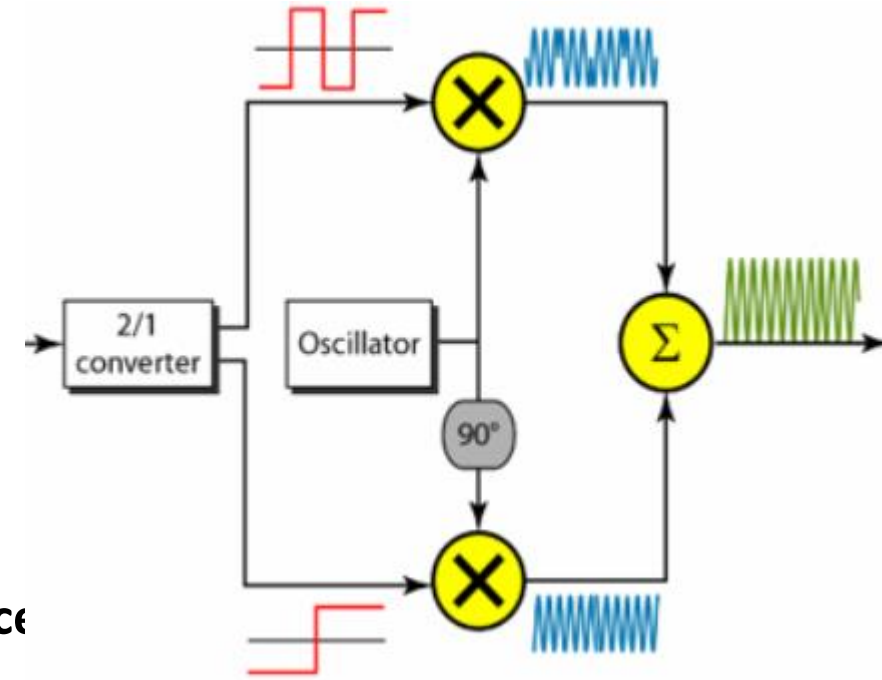
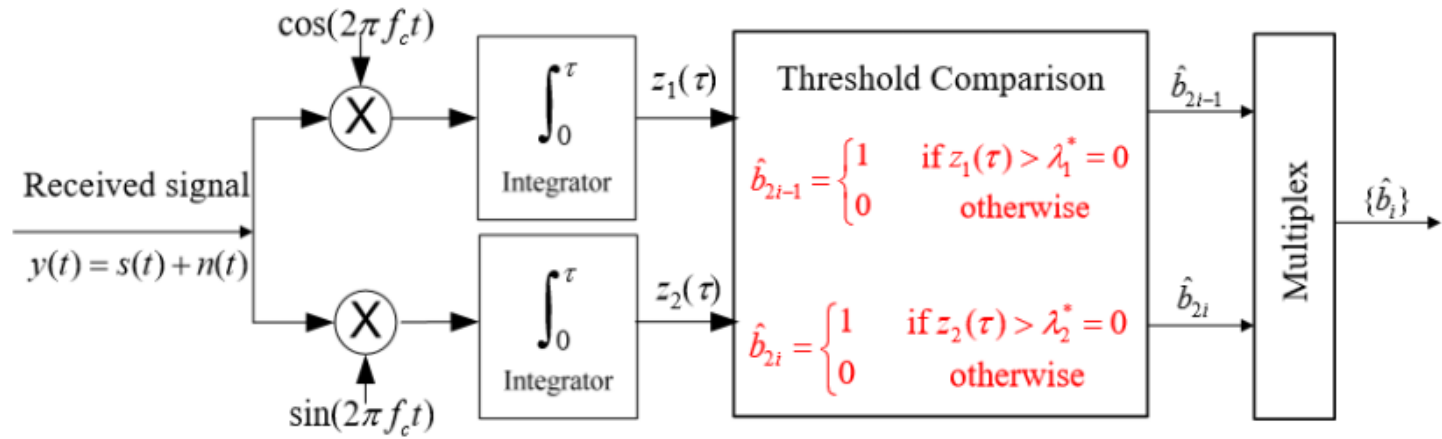
$$z_1(\tau) = \frac{A_k}{2} \tau + N_1 = \frac{Ad_I}{2\sqrt{2}} \tau + N_1 \quad \text{signal component proportional to } d_i$$

$$z_2(\tau) = \frac{B_k}{2} \tau + N_2; = \frac{Ad_Q}{2\sqrt{2}} \tau + N_2 \quad \text{signal component proportional to } d_q$$

The odd and even bits can be recovered using the decision rules

$$d_I = \begin{cases} 1, & z_1(\tau) \geq 0 \\ -1, & z_1(\tau) < 0 \end{cases} \Rightarrow b_{2i-1} = \begin{cases} 1, & d_I = 1 \\ 0, & d_I = -1 \end{cases}$$

$$d_Q = \begin{cases} 1, & z_2(\tau) \geq 0 \\ -1, & z_2(\tau) < 0 \end{cases} \Rightarrow b_{2i} = \begin{cases} 1, & d_Q = 1 \\ 0, & d_Q = -1 \end{cases}$$



Odd sequence

Even sequence

QPSK: Probability of Error

- The symbol error probability is twice the bit error probability, and is given as (will also be derived in the next chapter when we consider M-ary PSK).

$$P_b^* = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) = Q\left(\sqrt{\frac{E_s}{N_0}}\right)$$

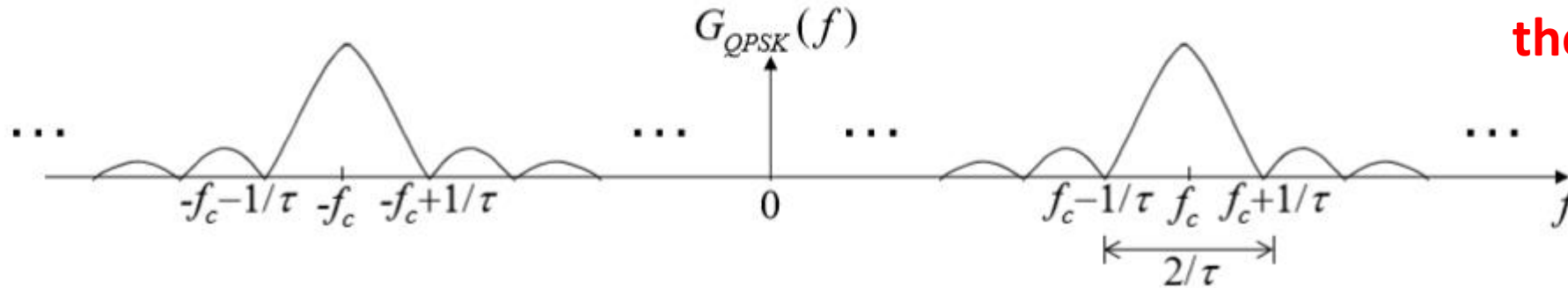
- This is the same as that for binary PSK, provided that both message bits have the same energy. The advantage of QPSK is that it is more bandwidth efficient than BPSK (**can transmit twice the data rate within the same bandwidth**)

QPSK: Power Spectral Density and Bandwidth

The power spectral density has the same shape as that for BPSK (the QPSK is the sum of

two BPSK signals one modulated on $\cos(2\pi f_c t)$ and the other on $\sin(2\pi f_c t)$.

Remember that the symbol duration τ is twice the bit duration.



$$R_s = \frac{1}{\tau} = \frac{R_b}{2}$$

$$s_{QPSK}(t) = A_k \cos(2\pi f_c t) + B_k \sin(2\pi f_c t)$$

$$s_{QPSK}(t) = \text{Binary PSK on } \cos(2\pi f_c t) + \text{Binary PSK on } \sin(2\pi f_c t)$$

$$\text{Here, } \tau = T_s = 2T_b$$

$$\text{B.W} = \frac{2}{\tau} = \frac{2}{2T_b} = R_b$$

Note that for QPSK, the data rate is R_b bits/sec and the **B.W = R_b Hz**

Which means we can transmit **$2R_b$ bits/sec** and the **B.W = $2R_b$ Hz**

While for regular BPSK, when the data rate is R_b bits/sec the **B.W = $2R_b$ Hz**

Hence, QPSK is more bandwidth efficient than BPSK since in W Hz, we can transmit W bits/sec while in BPSK we can transmit half that value $W/2$ bits/sec for the same probability of error.