Block Diagram of Digital COMM. Systems
Figure 2. VSB data frame. Synchronization
Figure 1. VSB transmitter.

Figure 10.1. VSB receiver.
Figure 10.65  Block diagram of IS-95 forward link.
IS-95 CDMA Cellular Phone

2. Mobile user → base station

Figure 10.66  Block diagram of IS-95 reverse link.
Figure 10.64  Functional block diagram of modulator and demodulator for GSM.

Global System of Mobile Communications
• Baseband?
  passband?

• Background knowledge:
  1. Probability and random process
  2. Signal processing: filter, Fourier
  3. System theory
  4. Analog communications
Chapter 1: Signals and Spectra (A Review)

1.1.3 Basic nomenclature

- Information source → binary sequence
- bit → symbol \((M=2^k)\)
- Symbol alphabet, symbol stream
- Data rate: (bits/sec)
  Symbol rate \(R_s\), bit rate \(R_b\)
  Symbol interval \(T_s\), bit interval \(T_b\)
  What are their relationship?
- Symbol sequence → digital waveform
- Probability of error (\(P_e\)) v.s.
  Signal to noise ratio (SNR)
1.3 to 1.4

Auto-correlation

<table>
<thead>
<tr>
<th>Power Signal</th>
<th>Energy Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_x(t) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t) x(t+\tau) dt )</td>
<td>( R_x(\tau) = \int_{-\infty}^{\infty} x(t) x(t+\tau) dt )</td>
</tr>
</tbody>
</table>

- Property:
  1) \( R_x(\tau) \leq R_x(0) \), Signal power/energy
  2) \( R_x(\tau) = R_x(-\tau) \)
  3) \( R_x(\tau) \xleftarrow{\text{FT}} \{G_x(f)\}, \text{PSD} \xrightarrow{\text{IFT}} \{Y_x(f)\}, \text{ESD} \)

- Example: \( x(t) = \sin(2\pi ft) \), \( R_x(\tau) = ? \)
2) **Spectral density.**

<table>
<thead>
<tr>
<th>Power Signal (Power Spectral density)</th>
<th>Energy Signal (Energy Spectral density)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_x(f) = \lim_{T \to \infty} \frac{1}{T}</td>
<td>X_T(f)</td>
</tr>
</tbody>
</table>

- **Property:**
  1. real, non-negative, even
  2. distribution of signal power/energy in the frequency domain
  3. Average power: $P_x = \int_{-\infty}^{\infty} G_x(f) df = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} x(t) \overline{x(t)} dt$
  4. Average energy: $E_x = \int_{-\infty}^{\infty} \Psi_x(f) df$

- **Example:** Find the spectral density of $x(t) = \sin(2\pi ft)$

3. **Applications.**

- $R_x(t)$: correlator receiver
- $G_x(f)$: noise power

\[ (6) \]
1.5 Random signals

1.5.1 Random variable \( X(A) \)

- **Probability density function (pdf)**
  \[
P_X(x) : \quad P(x_1 \leq X \leq x_2) = \int_{x_1}^{x_2} P_X(x) \, dx
\]

- **Property:**
  i) \( P_X(x) \geq 0 \)
  ii) \( \int_{-\infty}^{\infty} P_X(x) \, dx = 1 \)

- **Average parameters**
  i) **Mean:** \( M_X = E[X] = \int_{-\infty}^{\infty} x \, P_X(x) \, dx \)
  ii) **Variance:** \( \sigma_X^2 = E[(X-M_X)^2] = E[X^2] - M_X^2 \)

- **Two important random variables**
  i) **Gaussian distribution**
  ii) **Uniform distribution**
1.5.2 Random Process:

- \( X(A, t) \)
  - event \( \uparrow \uparrow \) time \( \{ \text{Compare:} \)
  - \( X(A, 0) \)
  - \( X(0, t) \)

- Stationary

- Average parameters
  1) Mean: \( M_X(t) = E[X(t)] = \int_{-\infty}^{\infty} x(t) p_X(x) dx \)
  2) Auto-correlation:
     \( R_X(t) = R_X(t_1 - t_2) = E[X(t)X(t+t_2)] \)
     
     \( = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t) \, dt \)

  3) Power spectral density (PSD)
     \( G_X(f) \)

- Important random processes
  1) AWGN (additive white Gaussian noise)
     \( G_n(f) = \frac{N_0}{2}, \quad P_n(t) \): Gaussian
  2) Received noisy signal
     \( x(t) \xrightarrow{\oplus} y(t) \)
     \( \oplus \)
     \( n(t) \)
1.6 Signal transmission through linear systems

- **Model**: deterministic signals

  \[
  x(t) \xrightarrow{H(t)} y(t) \xrightarrow{Y(f)}
  \]

  \[
  y(t) = x(t) \ast h(t)
  \]

  \[
  y(f) = X(f)H(f)
  \]

- **Model**: random process signals

  \[
  \begin{aligned}
  G_y(f) &= G_x(f) |H(f)|^2 \\
  y(t) &= x(t) \ast h(t)
  \end{aligned}
  \]

- **Ideal filter**: no distortion, with constant magnitude response and linear phase shift

  \[
  H(f) = |H(f)|e^{-j\Theta(f)}
  \]

  where

  \[
  \begin{aligned}
  H(f) &= \{ 0 \text{ \quad stop band} \\
  \Theta(f) &= 2\pi f \text{ to}
  \end{aligned}
  \]

  \[
  h(t) = ?
  \]

- **Example**: input: white noise with PSD: \( G_n(f) = \frac{N_0}{2} \)

  system: ideal lowpass filter

  What are output? (9)
Chapter 2. Baseband Modulation

• Terminology
  i) Format
  ii) Transmit formatting
  iii) Source coding
  iv) Line coding
  v) Baseband
  vi) Baseband signaling (waveform)

• Compare:

  \[ \text{PAM} \xrightarrow{\text{Format}} \text{PCM} \xrightarrow{\text{Baseband}} \text{baseband waveform} \]

  \[ \text{Source coding} \xrightarrow{\text{Line coding}} \]
2.5 Sources of corruption

- Error & noise in sampling/quantizing
- Noise (AWGN)

- Channel effect: ISI
  (intersymbol interference)
  (due to: limited bandwidth
   Multipath propagation

- Methods to reduce corruption
  i) Compressing
  ii) Optimal detector (matched filter)
  iii) Equalization
• M-way pulse modulation waveform

1) binary PCM bit sequence \[ \Rightarrow \] K-bit tuple \[ \Rightarrow \] symbol sequence \[ \Rightarrow \] M-way pulse waveform

2) Three ways:
   \[
   \begin{align*}
   \text{PAM: amplitude} \\
   \text{PPM: position} \\
   \text{PDM: width}
   \end{align*}
   \]

3) PAM: multi-level signaling:
   \[ M = 2^R : \# \text{of levels} \]
   \[ \text{Symbol rate } R_s = \frac{R_b}{R} \]

• Example: Speech signal with 4kHz bandwidth, 8kHz sampling, represented by 8-bit PCM. If transmit in an M=256 any PAM waveform, bandwidth efficiency = ?
CHAPTER 3  Baseband Demodulation
            Baseband Detection

- Definitions:
  - Demodulator
  - Detector

- Objective:
  - Obtain best SNR
  - Eliminate ISI

- Equivalence theorem
  - Baseband processing - passband processing
  - Baseband channel - passband systems
3.1 Systems, Signals and Noise

- Systems:
  i) Transmitter + channel
    \[
    s_i(t) \xrightarrow{\text{AWGN}} n(t) \rightarrow r(t)
    \]
  ii) Receiver (demodulator + detector)
    \[
    r(t) \xrightarrow{\text{Filter}} z(t) \xrightarrow{\text{Sample at } t=T} m_i
    \]

- Signals:
  i) Sent: \( s(t) = \begin{cases} s_1(t), & 0 \leq t \leq T, \text{ for binary "1" } \\ s_2(t), & 0 \leq t \leq T, \text{ for binary "0" } \end{cases} \)
  ii) Received: \( r(t) = s(t) + n(t), \quad i=1, 2, \quad 0 \leq t \leq T \)
  iii) Noise: \( n(t) \): AWGN
    with PSD: \( G_n(f) = \frac{N_0}{2} \frac{1}{f_0 \sqrt{2\pi f}} - \frac{m_0^2}{2 \sigma_n^2} \)
    pdf: \( f(n_0) = \frac{1}{\sigma_n \sqrt{2\pi}} - \frac{m_0^2}{2 \sigma_n^2} \)
    where \( \sigma_n^2 = N_0/2 \).

\[(19)\]
• Signal processing procedure

i) Receiving filter \( h(t) \)

\[ y(t) = h(t) * r(t) \]

ii) Sampling at time \( t = T \),

\[ z(T) = y(T) + n_0(T) \]

which is simplified to

\[ z = y + n_0 \]

where \( y = \pm A \), (corresponding to "1", "0")

\( n_0 \): Gaussian, relative to \( n(t), h(t) \).

iii) Detection: use threshold \( \beta \).

\[ \frac{z}{\sqrt{\frac{H_1}{H_2}}} \]

where hypothesis:

\( H_1 \): in favor of binary "1"

\( H_2 \): in favor of binary "0"

• Key points:

i) Demodulated by a linear filter \( h(t) \)

ii) Detected by the value at \( t = T \) only,

not by all the values in \( y(t) \).

(20)
• **Properties of matched filter**

  i) In noiseless case, MF & sampler's output is the energy of the received signal
  \[ y(t) = \int_0^T s^2(t) \, dt \]

  ii) In AWGN case, MF maximize the output (SNR)
  - If \( r(t) = s(t) + n(t) \),
    \[ h(t) = s(T-t) \]
  then \( (SNR)_0 \leq \frac{2}{N_0} \int_0^T s^2(t) \, dt = \frac{E_s}{N_0/2} \]
  and \( (SNR)_0 = \frac{E_s}{N_0/2} \) when \( h(t) = h_s(T-t) \).

  iii) **Frequency response:**
  - **MF:** \( H(f) = S^*(f) \, e^{-j \cdot 2\pi f T} \)
  - **Output:** \( Y(f) = |S(f)|^2 e^{-j \cdot 2\pi f T} \)

  • **Example:** If \( s(t) = \frac{A}{T} \cdot u(t) \), what's \( h(t) \) MF?
    output \( y(t) \)?

(24)
Signal space (vector) representation of MF

When dimension $N \geq 2$, vector MF is required.

(i) Time-domain Signal

\[ S(t) = \sum_{j=1}^{N} a_j y_j(t) \]
\[ R(t) = S(t) + n(t) \]

Vector Representation

\[ \vec{s} = [a_1, \ldots, a_N] \]
\[ \vec{r} = [a_1, \ldots, a_N] + [n_1, \ldots, n_N] = \vec{s} + \vec{n} \]

(ii) Use the orthonormal basis \{y_j(t)\} as MF

\[ r(t) \rightarrow \begin{bmatrix} y_1(T-t) \\ \vdots \\ y_N(T-t) \end{bmatrix} \rightarrow \begin{bmatrix} r_1 = a_1 + n_1 \\ \vdots \\ r_N = a_N + n_N \end{bmatrix} \rightarrow \vec{r} \]

**Key point:** the output is directly the vector representation of the received signal.

- **Example:** For two signal waveforms, find MF and output.
Three Common Signal-Space Representation

1. Binary PAM.

<table>
<thead>
<tr>
<th>Signal Waveform</th>
<th>Basis</th>
<th>Vector</th>
<th>Constellation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1(t) = A ), ( S_2(t) = -A ), ( 0 \leq t \leq T )</td>
<td>( y(t) = \sqrt{\frac{T}{T}} )</td>
<td>( S_1 = \sqrt{E_b} ), ( S_2 = -\sqrt{E_b} ), ( E_b = 2^{1/T} )</td>
<td>( S_2(t) \rightarrow \frac{S_1(t)}{\sqrt{E_b}} )</td>
</tr>
</tbody>
</table>

2. M-ary PAM. (\( M = 4 \)) (\( E_b = A^2 T \))

<table>
<thead>
<tr>
<th>Signal Waveform</th>
<th>Basis</th>
<th>Vector</th>
<th>Constellation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1(t) = 3A ), ( S_2(t) = A ), ( S_3(t) = -A ), ( S_4(t) = -3A ), ( 0 \leq t \leq T )</td>
<td>( y(t) = \sqrt{\frac{T}{T}} )</td>
<td>( S_1 = 3\sqrt{E_b} ), ( S_2 = \sqrt{E_b} ), ( S_3 = -\sqrt{E_b} ), ( S_4 = -3\sqrt{E_b} )</td>
<td>( \rightarrow \frac{S_2(t)}{3\sqrt{E_b}} )</td>
</tr>
</tbody>
</table>

3. PSK (\( E_b = A^2 T/2 \))

<table>
<thead>
<tr>
<th>Signal Waveform</th>
<th>Basis</th>
<th>Vector</th>
<th>Constellation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1(t) = A \cos(2\pi f_0 t) ), ( S_2(t) = -A \cos(2\pi f_0 t) ), ( S_3(t) = A \sin(2\pi f_0 t) ), ( S_4(t) = -A \sin(2\pi f_0 t) ), ( 0 \leq t \leq T )</td>
<td>( y(t) = \sqrt{\frac{T}{T}} \cos(2\pi f_0 t) ), ( y_2(t) = \sqrt{\frac{T}{T}} \sin(2\pi f_0 t) )</td>
<td>( S_1 = [\sqrt{E_b}, 0] ), ( S_2 = [-\sqrt{E_b}, 0] ), ( S_3 = [0, \sqrt{E_b}] ), ( S_4 = [0, -\sqrt{E_b}] )</td>
<td>( \rightarrow y_i(t) )</td>
</tr>
</tbody>
</table>
3.3 Baseband System Design
(Transmitting Filter Design)

3.3.1 Inter_symbol interference (ISI)

* happens when channel impulse response longer than 1 symbol interval, due to:
  * limited bandwidth of channel,
  * transmitting/receiving filters
  * multipath propagation

* Result: symbol detection errors

* System design objective:

zero-ISI with limited bandwidth (of transmitted signal)

* Method:
  i) Ideally: Nyquist filter
  ii) Practical: raised-cosine filter
  iii) If channel unknown: equalizer.
3.3.2 Ideal Nyquist filter

- System:

\[
\begin{align*}
\text{Transmitting filter } H_t(f) \rightarrow \text{Channel } H_c(f) \rightarrow \text{Receiving filter } H_r(f)
\end{align*}
\]

\[
\begin{align*}
H(f) &= H_t(f) H_c(f) H_r(f) \\
h(t) &= h_t(t) * h_c(f) * h_r(t)
\end{align*}
\]

- Design \(H_t(f)\) & \(H_r(f)\) such that \(H(f)\) is Nyquist filter:

\[
\begin{align*}
H(f) &= \begin{cases} 
T, & \frac{-1}{2T} \leq f \leq \frac{1}{2T} \\
0, & \text{else}
\end{cases} \\
h(t) &= \text{sinc} \left( \frac{t}{T} \right)
\end{align*}
\]

i) Key point: \(h(t) = 0\) at all \(t = kT\).

ii) Bandwidth of transmitted signal:

\[
W = \frac{1}{2T} = \frac{Rs}{2}
\]

(36)
3.3.3. Pulse-shaping with Raised-Cosine Filter

- Raised-cosine spectrum and impulse response

\[ H(f) = \begin{cases} 
1, & |f| < 2W_0 - W \\
\cos^2\left(\frac{\pi}{W} \left| f + W - 2W_0 \right| \right), & 2W_0 - W < |f| < W \\
0, & |f| > W.
\end{cases} \]

- Bandwidth of signal:

\[ W = \frac{1 + r}{2T} \]

where \( r \) is raised-cosine roll-off factor:

\[ r = \frac{W - W_0}{W_0} = \frac{W - \frac{1}{2T}}{\frac{1}{2T}}, \quad 0 \leq r \leq 1 \]

- In practice: use the truncated version, e.g., \( h(t), -3T \leq t \leq 3T \)
3.3.4 System Response (why zero ISI)

* System:

\[ a_i \rightarrow h(t) \rightarrow s(t) \rightarrow h(t) \rightarrow r(t) \rightarrow h_r(t) \rightarrow \varepsilon(t) \rightarrow ML \text{ detector} \rightarrow \hat{a}_i \]

\[ \text{Channel} \]

\[ h(t) \]

* Signal analysis:

\[ S(t) = \sum_{i=-\infty}^{\infty} a_i h(t-iT) \]

\[ r(t) = \sum_{i=-\infty}^{\infty} a_i h'(t-iT) + n(t) \]

where \( h'(t) = h(t) * h_c(t) \)

\[ z(t) = \sum_{i=-\infty}^{\infty} a_i h(t-iT) + \nu(t) \]

where \( h(t) = h_cc(t) + h_c(t) \times h_r(t) \)

\[ \varepsilon(t) = \sum_{i=-\infty}^{\infty} a_i h((k-i)T) + \nu((k-i)T) \]

\[ = a_k r(0) + \sum_{i \neq k} a_i h((k-i)T) + \nu((k-i)T) \]

\[ = a_k r(0) + \nu(mT) \]

where \( m \) is the desired signal part and \( \nu \) is the AWGN part.

* Zero-ISI

(38)
3.4 Eye-pattern and equalization

- Eye-pattern: measure ISI, or the reliability of symbol detection
  i) eye-open: small ISI, low BER, reliable
  ii) eye-closed: large ISI, high BER, unreliable

- How to generate eye-patterns?
  plot the received signal r(t) periodically (with period progress of T) on the same time scale.
• Equalization:

i) When channel is unknown, or \( h(t) \ast h(t) \ast h(t) \) has large ISI, use an equalizer to reduce ISI

ii) Equalizer can be implemented as a linear FIR/IIR filter, or non-linear filter (decision feedback)

iii) Linear FIR/IIR filter
   - Zero-forcing equalizer
   - MMSE equalizer

iv) Adaptive equalizer
ADAPTIVE EQUALIZATION using the LMS ALGORITHM

Equalizer output:

\[ v_k = w_k^* r_k = w_{-1}^* r_{k+1} + w_0^* r_k + w_1^* r_{k-1} = [w_{-1} \ w_0 \ w_1]^T r_k. \]

Error:

\[ e_k = z_k - a_k. \]

LMS algorithm:

\[ w(k+1) = w(k) - \mu e_k r_k^*. \]
Parameters:

4-ary PAM

\[ H(z) = 1 - 0.5z^{-1} \]

\[ \sigma = 0.1 \]

\[ \mu = 0.005 \]
Chapter 4. Bandpass Modulation/ Demodulation

4.1. Introduction

- Why use band pass?
  - transmission efficiency, frequency reuse

- System block:

  \[ \text{B.B.M.} \rightarrow \text{P.B.M.} \rightarrow \text{Channel (P.B)} \rightarrow \text{P.B.D.M} \rightarrow \text{B.B.D.M} \]

- Modulation methods
  - AM \rightarrow ASK
  - PM \rightarrow PSK
  - AM+PM \rightarrow QAM
  - FM \rightarrow FSK

- Key points:
  i) Signal waveforms (modulator)
  ii) Signal-space representation
  iii) Optimal demodulator (coherent, non-coherent)
  iv) spectral and Pe.

(44)
4.2. General passband waveforms

- Carrier:  \( s(t) = A(t) \cos(\omega t) \).
  \[ = A(t) \cos(\omega t + \phi(t)). \]

<table>
<thead>
<tr>
<th>Modulation types</th>
<th>Varying parameter</th>
<th>Demodulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSK</td>
<td>( \phi(t) )</td>
<td>coherent/ non-coherent (phase estimation) (Differential encoding)</td>
</tr>
<tr>
<td>QAM</td>
<td>{ ( A(t) ), ( \phi(t) ) }</td>
<td>Same</td>
</tr>
<tr>
<td>FSK</td>
<td>( \omega(t) )</td>
<td>coherent: frequency estimation, noncoherent: envelope detector</td>
</tr>
</tbody>
</table>

- Waveform illustration.
4.2.2 PSK

- **Waveform:**
  \[ S_i(t) = \sqrt{\frac{2E}{T}} \cos \left[ \omega_0 t + \phi_i(t) \right], \quad 0 \leq t \leq T, \quad i = 1, \ldots, M \]
  \[ \phi_i(t) = \frac{2\pi i}{M} \]
  (consider pulse shaping \( g(t) \), we have:
  \[ S_i(t) = \sqrt{\frac{2E}{T}} g(t) \cos \left[ \omega_0 t + \phi_i(t) \right] \])

- **BPSK:** \( M = 2 \), \( \phi = \{0, \pi\} \),
  **QPSK:** \( M = 4 \), \( \phi = \{0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}\} \) or others
  **8-PSK:**

- **Symbol energy:** \( E = \int_0^T S_i^2(t) \, dt \)
  **Bandwidth:** \( B_w = 2 \) Baseband Bandwidth

- **Signal space representation:**
  \[ \mathbb{S}_M = \left[ \sqrt{E} \cos \frac{2\pi i}{M}, \sqrt{E} \sin \frac{2\pi i}{M} \right], \quad i = 1, \ldots, M \]
  basis:
  \[ y_1(t) = \sqrt{\frac{2E}{T}} g(t) \cos(\omega_0 t) \]
  \[ y_2(t) = \sqrt{\frac{2E}{T}} g(t) \sin(\omega_0 t) \]

(46)
- **Modulator:**

  BPSK: \( a_k \rightarrow g(t) \rightarrow s(t) \)

  \[ \sqrt{\frac{1}{T}} \cos(\omega_0 t) \]

  M-PSK:

  \[ a_k \rightarrow \text{bit splitter} \rightarrow g(t) \rightarrow \sqrt{\frac{1}{T}} \cos(\omega_0 t) \]

  \[ a_k \rightarrow \sqrt{\frac{1}{T}} \sin(\omega_0 t) \]

  \[ s(t) = a_{k1} g(t) \sqrt{\frac{1}{T}} \cos(\omega_0 t) + a_{k2} g(t) \sqrt{\frac{1}{T}} \sin(\omega_0 t) \]

- Represented in the complex domain?

  \[ s(t) = \text{Re} \{ a_k g(t)e^{j\omega_0 t} \} \]

  \[ a_k = a_{k1} + i a_{k2} \]
4.2.3 8AM (Quadrature Amplitude Modulation)

- **Signal waveform**
  \[ S_i(t) = \sqrt{2E_i} g_i(t) \cos[\omega t + \phi_i(t)] \text{, for } 0 \leq t \leq T, i = 1, \ldots, M \]
  \[ = A_i g_i(t) \sqrt{\frac{E}{M}} \cos(\omega t) + B_i g_i(t) \sqrt{\frac{E}{M}} \sin(\omega t) \]

- **Eq:**
  4QAM,
  16QAM

- **Bandwidth:** 2x Baseband bandwidth

- **Signal space representation**
  \[ \vec{S_i} = \left[ \sqrt{E_i} \cos \frac{2\pi i}{M} \sin \frac{2\pi i}{M} \right] \]
  \[ i = 1, \ldots, M \]

  Back: \[ y_1(t) = \sqrt{\frac{E}{M}} g_i(t) \cos(\omega t) \]
  \[ y_2(t) = \sqrt{\frac{E}{M}} g_i(t) \sin(\omega t) \]

- **Modulator:**
  Similar to M-PSK
  different in magnitude.
4.4. Coherent demodulation/detection

- **General rule:**
  
  Use basis as MF, output samples are signal-space point value.

- **General requirement:**
  
  Carrier frequency and phase synchronization.

- For **PSK:**

  i) \[
  r(t) = s(t) + n(t) \\
  \hat{r} = \hat{s} + \hat{n}
  \]

  \[
  \hat{z} = \left[ \sqrt{E} \cos \frac{2\pi i}{M}, \sqrt{E} \sin \frac{2\pi i}{M} \right] + [n_1, n_2]
  \]

  Where \( n_1, n_2 \) are AWGN, zero mean, variance \( \frac{N_0}{2} \), independent.

  ii) Detection: \[
  \min_{\{s_m\}} \| \hat{z} - \hat{s}_m \|^2
  \]

(51)
iii) Second view of the demodulator

\[
\begin{align*}
\text{r(t)} & \xrightarrow{\cos(\omega t)} \text{LP} \xrightarrow{\mathcal{G}(T-t)} \{ z \} \\
\text{sin}(\omega t) & \xrightarrow{\text{LP}} \mathcal{G}(T-t) \xrightarrow{\text{baseband}} \\
\end{align*}
\]

- **QAM**: similar to PSK
- **FSK**:

\[
\begin{align*}
\text{y}_1(t) & \xrightarrow{\text{LP}} \{ z \} \\
\vdots \\
\text{y}_n(T-t) & \xrightarrow{\text{LP}} \\
\end{align*}
\]