Introduction to Communications Engineering

IT4593E

Đỗ Công Thuần, Ph.D.

Dept. of CE, SoICT, HUST

Email: thuandc@soict.hust.edu.vn

ONE LOVE. ONE FUTURE.

Thông tin chung

- Tên học phần: **Nhập môn kỹ thuật truyền thông**
- Mã học phần: **IT4593E**
- Khối lượng: **2 TC (2-1-0-4)**
- Lý thuyết và bài tập: **10 buổi lý thuyết, 5 buổi bài tập**
- Đánh giá học phần:

  30% QT (kiểm tra + bài tập/project + chuyên cần-quiz)

  70% CK (trắc nghiệm + tự luận)
- Tài liệu tham khảo:
  - Lecture slides
  - Lecture notes
  - Textbooks, ví dụ ***Communication Systems Engineering***, 2nd Edition, by John G. Proakis Masoud Salehi
  - Internet

Lec 03: Digital Communication Systems

1. Basic Concepts of Digital Communication Systems

Introduction to digital communications systems

Digital communication systems transmit sequences of symbols belonging to a discrete "alphabet.".

Examples:

- **Human writing**
- **Morse code telegraphy**
- **GSM**
- **CD/DVD**

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Introduction to digital communications systems

We will focus on systems characterized by two features:

1. **Discrete alphabet = binary alphabet {0,1}**
→ binary data sequences

2. **Transmission channel = wired or wireless**

Introduction to digital communications systems

If analog information needs to be transmitted (e.g., voice, video),

↓

it must go through sampling and quantization (source coding),

↓

resulting in binary data sequences.

Introduction to digital communications systems

Examples of digital communication systems:

- GSM/UMTS
- Telephone Modem
- Optical Fibers
- Wired and Wireless LAN
- GPS/Galileo
- ...

Key parameters of digital communications systems

- **Bit-rate**
- **Bandwidth**
- **Power**
- **Error probability**
- **Complexity**

Bit-rate

Binary data sequences are characterized by their bit-rates.

BIT-RATE R_b [bps]

= number of bits transmitted per second

Bandwidth

Binary data sequences

in order to be transmitted through either a wired or wireless channel, must be converted into a waveform *s(t)*.

Bandwidth

The waveform $s(t)$ is characterized by its power spectral density (PSD) – $G_s(f)$.

BANDWIDTH B **[Hz]** = frequency range containing the essential part of $G_s(f)$

Power

The received signal power S [W] [dBm]

depends on the transmitted signal power

characterized by the
Signal-to-Noise Ratio (SNR)
at the receiver side.

Error probability

The transmitted binary data sequences $u_T = (u_T[i])$

The transmitted waveform $s(t)$

The received waveform $r(t) \neq s(t)$ (in practical, non-ideal channels)

The received binary data sequences

$u_R=(u_R[i])$

Error probability

The transmitted binary data sequences $u_T=(u_T[i])$

The received binary data sequences $u_R=(u_R[i])$

Bit error probability

$$P(u_R[i] \neq u_T[i])$$

Complexity

COMPLEXITY = implementation difficulty and cost

Delay

Delay D [s]

difference between transmission and reception times

Input (transmitter - TX) → **Output** (receiver, RX)

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Example of System Design

- **Design a digital communication system under the following conditions:**
  - **BIT-RATE R_b = 34 Mbps**
  - **BANDWIDTH B = 20MHz, centered at f_0 = 18GHz**
  - **Minimum BER = 10^{-7} with received POWER S = -40dBm**
  - **Maximum DELAY D = 500 ms**
  - **Minimum COMPLEXITY (cost)**

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2. Signal Sets, Labeling, and Transmitted Waveforms

Binary data sequences: Concept

Binary alphabet $Z_2 = \{0,1\}$

A binary data sequence:

$$\underline{\mathrm{u}}_{\mathrm{T}} = (u_T[0], u_T[1], \ldots, u_T[i], \ldots) \qquad i \in N \qquad u_T[i] \in Z_2$$

Example: $\underline{\mathrm{u}}_{\mathrm{T}}$ = (1101001...)

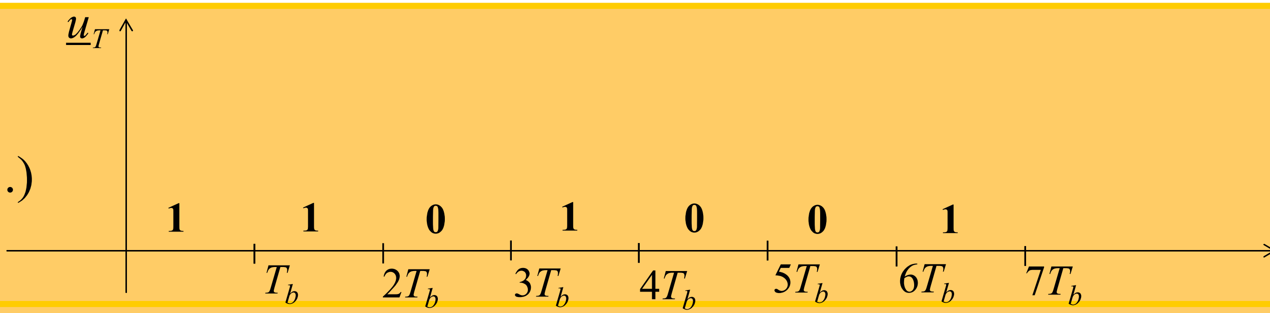
$$\underline{u}_T = (u_T[0], u_T[1], \ldots, u_T[i], \ldots)$$

Bit rate R_b [bps]

Bit duration: $T_b = 1/R_b$ *seconds*. Each bit $u_T[i]$ exists in the interval ($iT_b \leq t < (i+1)T_b$)

Example:

$\underline{u}_T = (1101001\ldots)$



A binary data sequence $\underline{u}_T$ is characterized as follows::

- Its data bits $u_T[i]$
- The transmission clock pulse, with frequency R_b

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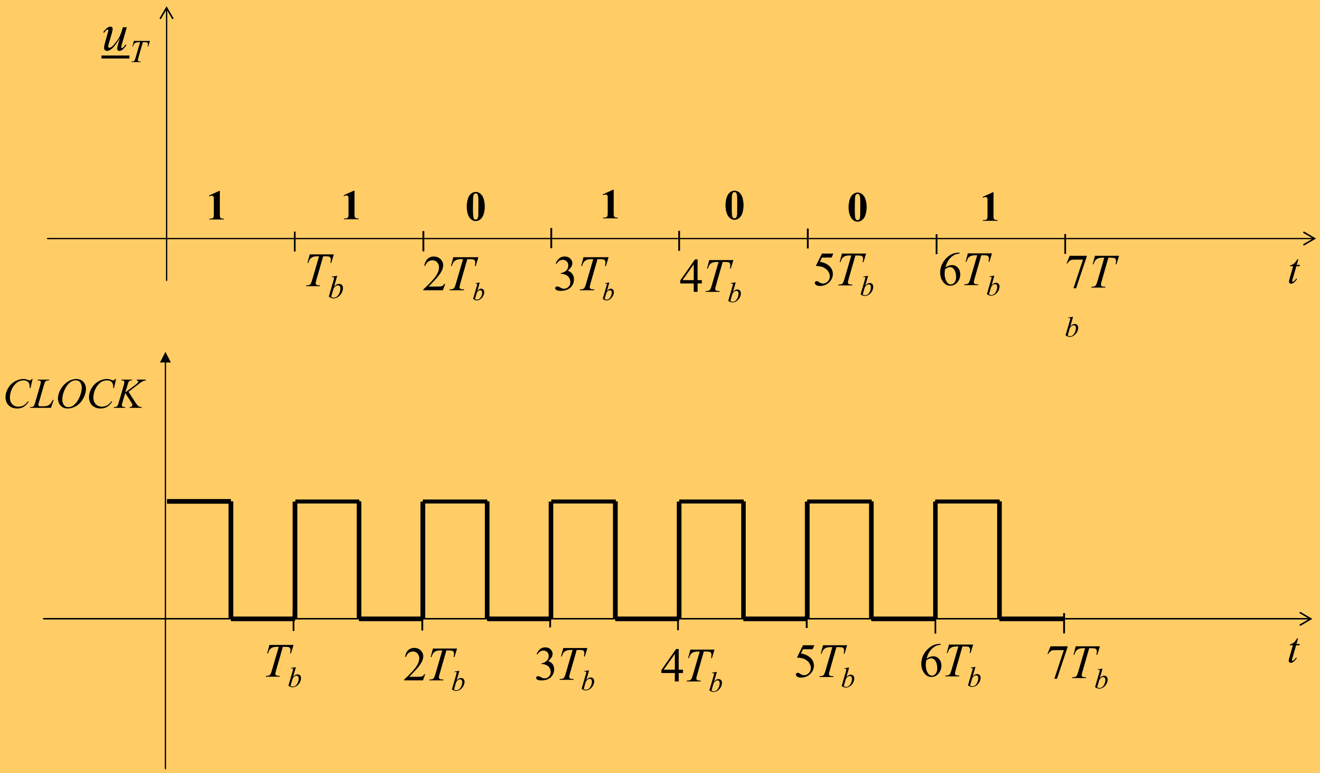
Example:

$\underline{u}_T = (1101001...)$



$$\underline{u}_T = (u_T[0], u_T[1], \ldots, u_T[i], \ldots)$$

Random binary data sequences are assumed statistically independent with equal probability of 0s and 1s.

- **P($u_T[i]$ |($u_T[j]$) = P($u_T[i]$)**
- **P($u_T[i]$ = 0) = P($u_T[i]$ = 1) $\forall i$**

Transmitted Waveforms

Binary data sequence: $\underline{u}_T$

The transmitted signal *s(t)*

is a real-valued function of time derived from the binary data sequence.

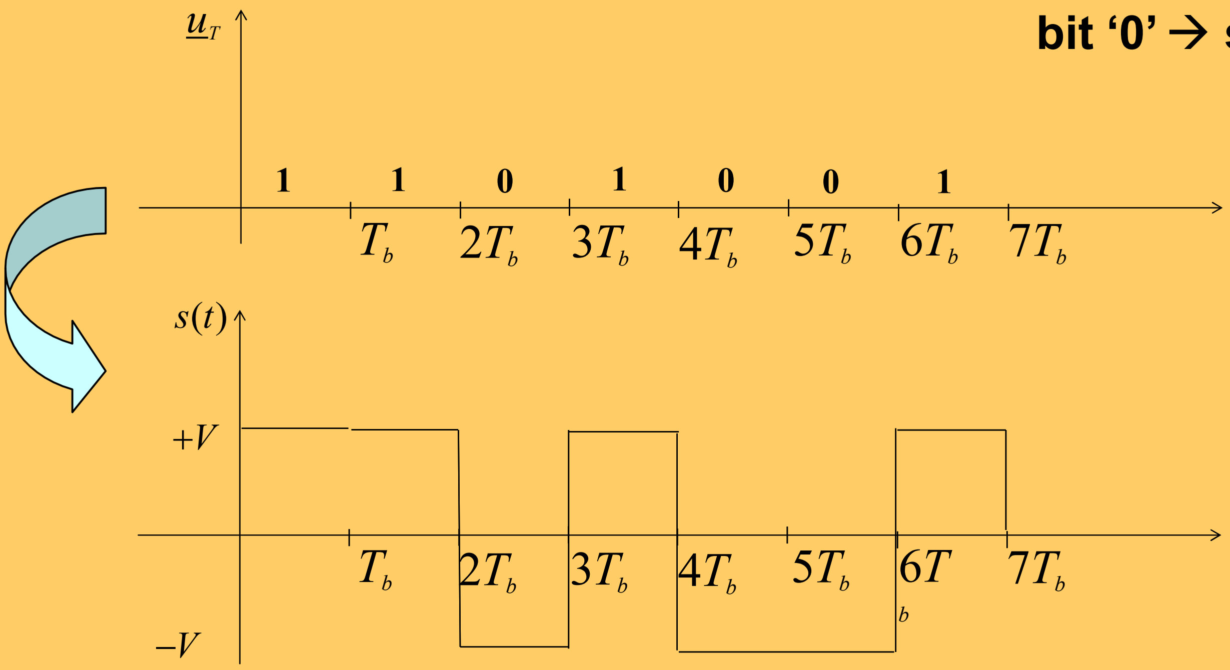
Example:

$\underline{u}_T = (1101001...)$

Bipolar NRZ representation

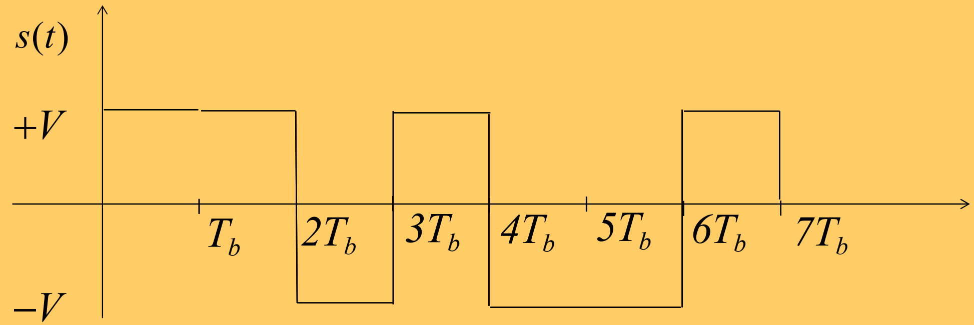
bit '1' → signal +V

bit '0' → signal -V

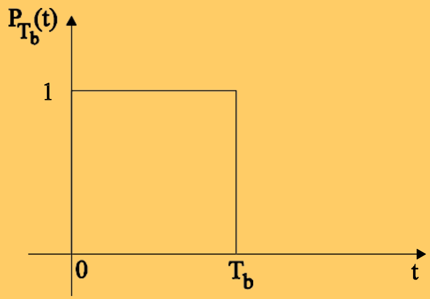


Example:

$$\underline{u}_T = (1101001...)$$



A rectangular pulse within the time interval T_b



Two signals exist:

$$u_T[i] = 1 \rightarrow +VP_{T_b}(t - iT_b)$$

$$u_T[i] = 0 \rightarrow -VP_{T_b}(t - iT_b)$$

Signal Sets

A signal set *M*

$$M = \{s_1(t),\ \ldots,\ s_i(t),\ \ldots,\ s_m(t)\}$$

contains: $|M| = m = 2^k$ waveforms

$$M = \{s_1(t),\ \ldots,\ s_i(t),\ \ldots,\ s_m(t)\}$$

<u>**Assume**</u>: Each signal $s_i(t)$ has finite duration

$$0 \le t < T = kT_b$$

Example:

$$M = \{s_1(t) = +VP_T(t), s_2(t) = -VP_T(t)\} \qquad m = 2$$

$$M = \{s_1(t) = VP_T(t)\cos(2\pi f_0 t), s_2(t) = VP_T(t)\sin(2\pi f_0 t),$$
$$s_3(t) = -VP_T(t)\cos(2\pi f_0 t), s_4(t) = -VP_T(t)\sin(2\pi f_0 t)\}$$
$$m = 4$$

Hamming Space

A k-bit binary vector

$$\underline{v} = (u_0, \ldots, u_i, \ldots u_{k-1}) \;\; u_i \in Z_2$$

Hamming Space

$$H_k = \{\underline{v} = (u_0, \ldots, u_i, \ldots, u_{k-1}) \quad u_i \in Z_2\}$$

contains: $|H_k| = 2^k$ vectors

Example:

$$H_1 = \{ (0)\ (1) \} = Z_2$$

$$H_2 = \{ (00)\ (01)\ (10)\ (11) \}$$

$$H_3 = \{ (000)\ (001)\ (010)\ (011)\ (100)\ (101)\ (110)\ (111) \}$$

Binary Labeling

A signal set M contains 2^k signals.

A Hamming space H_k contains 2^k vectors.

1-1 mapping

Binary Labeling

$$
\boxed{
\begin{aligned}
e: \quad & H_k \leftrightarrow M \\
& \underline{v} \in H_k \leftrightarrow s(t) = e(\underline{v}) \in M
\end{aligned}
}
$$

Example:

$$M = \{s_1(t) = +VP_T(t), s_2(t) = -VP_T(t)\}$$

$m=2 \rightarrow k=1$

$H_1 = \{(0), (1)\}$

$$e : H_1 \leftrightarrow M$$

$$(0) \leftrightarrow s_1(t)$$

$$(1) \leftrightarrow s_2(t)$$

Example:

$$M = \{s_1(t) = VP_T(t)\cos(2\pi f_0 t), s_2(t) = VP_T(t)\sin(2\pi f_0 t),$$
$$s_3(t) = -VP_T(t)\cos(2\pi f_0 t), s_4(t) = -VP_T(t)\sin(2\pi f_0 t)\}$$

$m=4 \rightarrow k=2$

$$H_2 = \{(00), (01), (11), (10)\}$$

$$e : H_2 \leftrightarrow M$$

$$(00) \leftrightarrow s_1(t)$$
$$(01) \leftrightarrow s_2(t)$$
$$(10) \leftrightarrow s_3(t)$$
$$(11) \leftrightarrow s_4(t)$$

Transmitted Waveforms

Assume:

- Binary data sequence: $\underline{u}_T$
- Signal set: M
- Binary labeling: e

Constructing the transmitted waveform ***s(t)*** is a fairly straightforward task.

M contains 2^k vectors $\Rightarrow$ $e : H_k \leftrightarrow M$

Split $\underline{u}_T$ into *k*-bit vectors

$$\underline{\boldsymbol{u}}_T = (u_T[0], u_T[1], \ldots, u_T[i], \ldots)$$

$$\underline{\boldsymbol{u}}_T = \left(\underline{v_T[0]}, \underline{v_T[1]}, \ldots, \underline{v_T[n]}, \ldots\right)$$

Vector [0] $\Rightarrow$ $\underline{v}_T[0]=(u_T[0] ,\ldots, u_T[k\text{-}1])$

Vector [*n*] $\Rightarrow$ $\underline{v}_T[n]=(u_T[nk] ,\ldots, u_T[(n+1)k\text{-}1])$

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Each bit exists in T_b seconds

Each k-bit vector exists in $kT_b = T$ seconds

$$\underline{\boldsymbol{u}}_T = (\underbrace{\underline{v_T[0]}}_{T}, \underbrace{\underline{v_T[1]}}_{T}, \ldots, \underbrace{\underline{v_T[n]}}_{T}, \ldots)$$

Each signal $s_i(t) \in M$ exists in T seconds

$$\boxed{0 \leq t < T = kT_b}$$

Transmitted waveform

Binary labeling $\boxed{e : H_k \leftrightarrow M}$

$$\underline{\boldsymbol{u}}_T = (\underbrace{\underline{v_T[0]}}_{T} , \underbrace{\underline{v_T[1]}}_{T} , \ldots , \underbrace{\underline{v_T[n]}}_{T} , \ldots)$$

$$e \qquad e \qquad e$$

$$s(t) = (\overbrace{s[0](t)}^{T} , \overbrace{s[1](t)}^{T} , \ldots , \overbrace{s[n](t)}^{T} , \ldots)$$

Correct alignment: $s[n](t) = e(\underline{v}_T[n])???$

<u>Problem</u>: The signal set

$$M = \{\, s_1(t) \,,\ \ldots \,,\ s_i(t),\ \ldots,\ s_m(t) \,\}$$

is defined in the interval

$$0 \le t < T = kT_b$$

but only the first binary vector is represented (mapped) during this interval.

$$\begin{array}{ccccccccc}
\underline{\boldsymbol{u}}_T & = & (& \underline{v_T[0]} & , & \underline{v_T[1]} & ,\ ..\ , & \underline{v_T[n]} & ,\ ..\ ) \\
 & & & e \big\downarrow T & & e \big\downarrow T & & e \big\downarrow T & \\
s(t) & = & (& s[0](t) & , & s[1](t) & ,\ ..\ , & s[n](t) & ,\ ..\ )
\end{array}$$

Correct alignment is achieved: $s[n](t) = T_n(e(\underline{v}_T[n]))$

if

$$T_n(y(t)) = y(t - nT)$$

Binary labeling $\boxed{e : H_k \leftrightarrow M}$

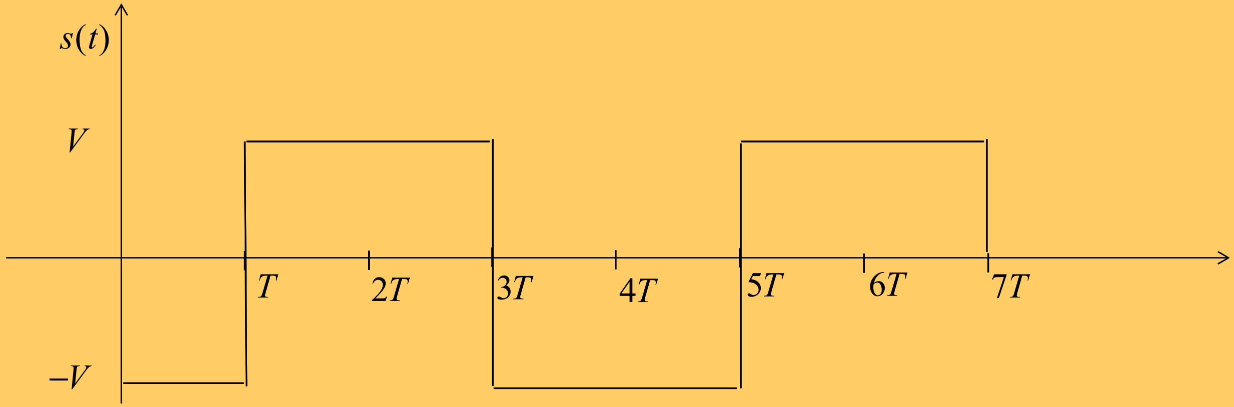
$$\begin{array}{ccccccccccc}
\underline{\boldsymbol{u}}_T & = & (& \underline{v_T[0]} & , & \underline{v_T[1]} & , & .. & , & \underline{v_T[n]} & , \; .. \;) \\
 & & & e \quad T & & e \quad T & & & & e \quad T & \\
s(t) & = & (& s[0](t) & , & s[1](t) & , & .. & , & s[n](t) & , \; .. \;)
\end{array}$$

$\boxed{\text{Correct alignment: } s[n](t) = T_n(e(\underline{v}_T[n]))}$

Example:

$\underline{\boldsymbol{u}}_T$=(0110011...) R_b=1 Mbps

$$M = \{s_1(t) = -VP_T(t)\ ,\ s_2(t) = +VP_T(t)\}$$



$$\boxed{T = T_b = 1\,\mu s}$$

Exercise

$\underline{\boldsymbol{u}}_{\mathrm{T}}$=(10011100…) R_b=1 Mbps

$$M = \{s_1(t) = VP_T(t)\cos(2\pi f_0 t), s_2(t) = VP_T(t)\sin(2\pi f_0 t),$$
$$s_3(t) = -VP_T(t)\cos(2\pi f_0 t), s_4(t) = -VP_T(t)\sin(2\pi f_0 t)\}$$

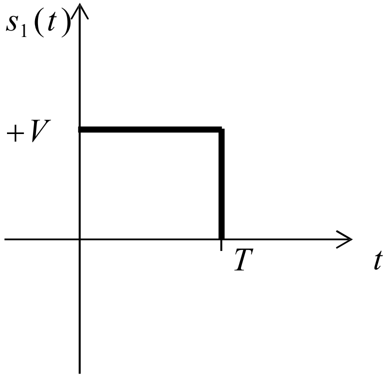
(f_0 = 1MHz)

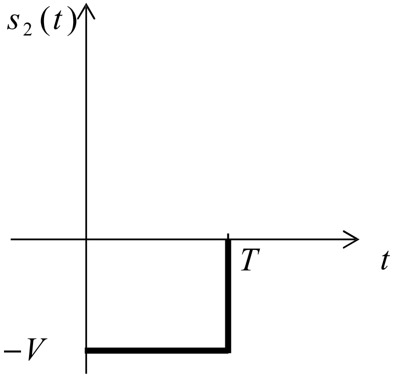
Draw the transmitted waveform s(t).

Examples of signal sets in practice

Bipolar Non Return to Zero

$$M = \{s_1(t) = +VP_T(t), s_2(t) = -VP_T(t)\}$$

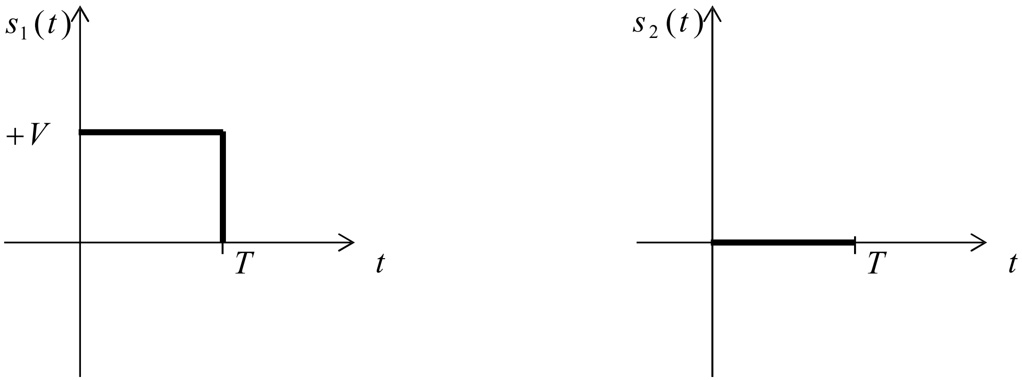




$$m = 2 \rightarrow k = 1 \rightarrow T = T_b$$

Unipolar Non Return to Zero

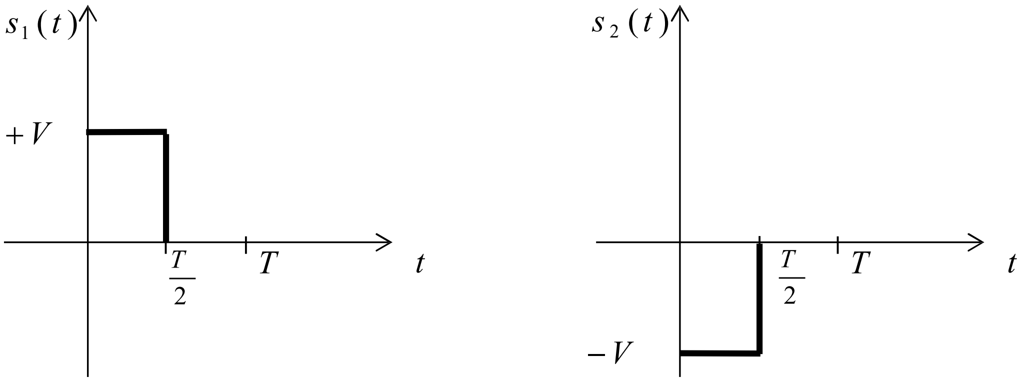
$$M = \{s_1(t) = +VP_T(t), s_2(t) = 0\}$$



$$m = 2 \rightarrow k = 1 \rightarrow T = T_b$$

Bipolar Return to Zero

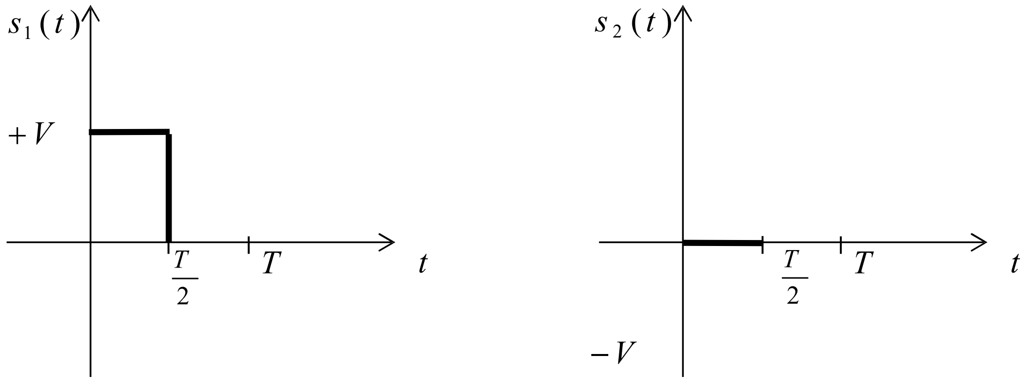
$$M = \{s_1(t) = +VP_{T/2}(t), s_2(t) = -VP_{T/2}(t)\}$$



$$m = 2 \rightarrow k = 1 \rightarrow T = T_b$$

Unipolar Return to Zero

$$M = \{s_1(t) = +VP_{T/2}(t),\ s_2(t) = 0\}$$

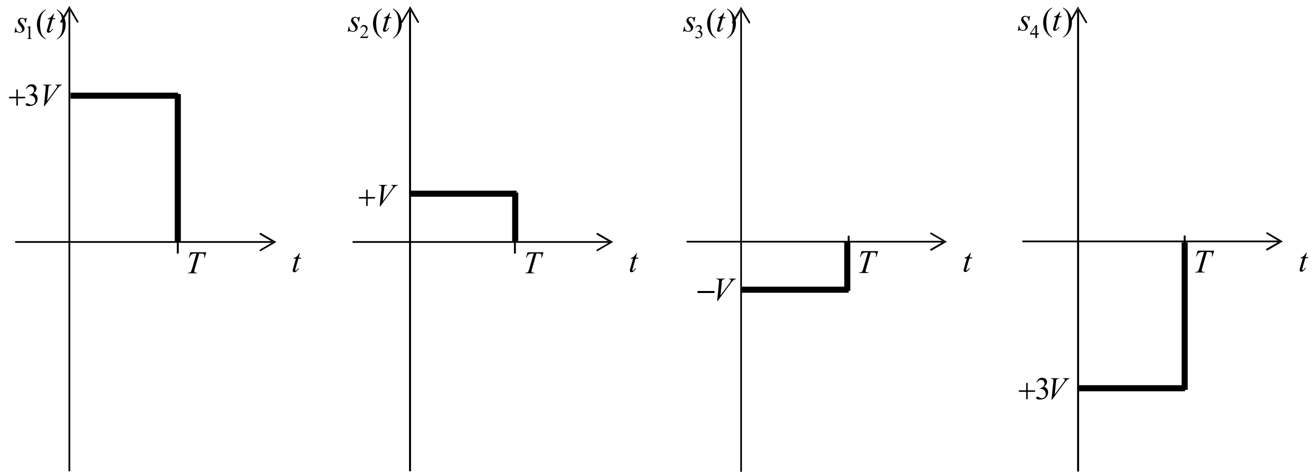


$$m = 2 \rightarrow k = 1 \rightarrow T = T_b$$

m-PAM (Pulse Amplitude Modulation)

Example: 4-PAM

$$M = \left\{ s_1(t) = +3VP_T(t), s_2(t) = +VP_T(t), s_3(t) = -VP_T(t), s_4(t) = -3VP_T(t) \right\}$$



$$m = 4 \rightarrow k = 2 \rightarrow T = 2T_b$$

m-ASK (Amplitude Shift Keying)

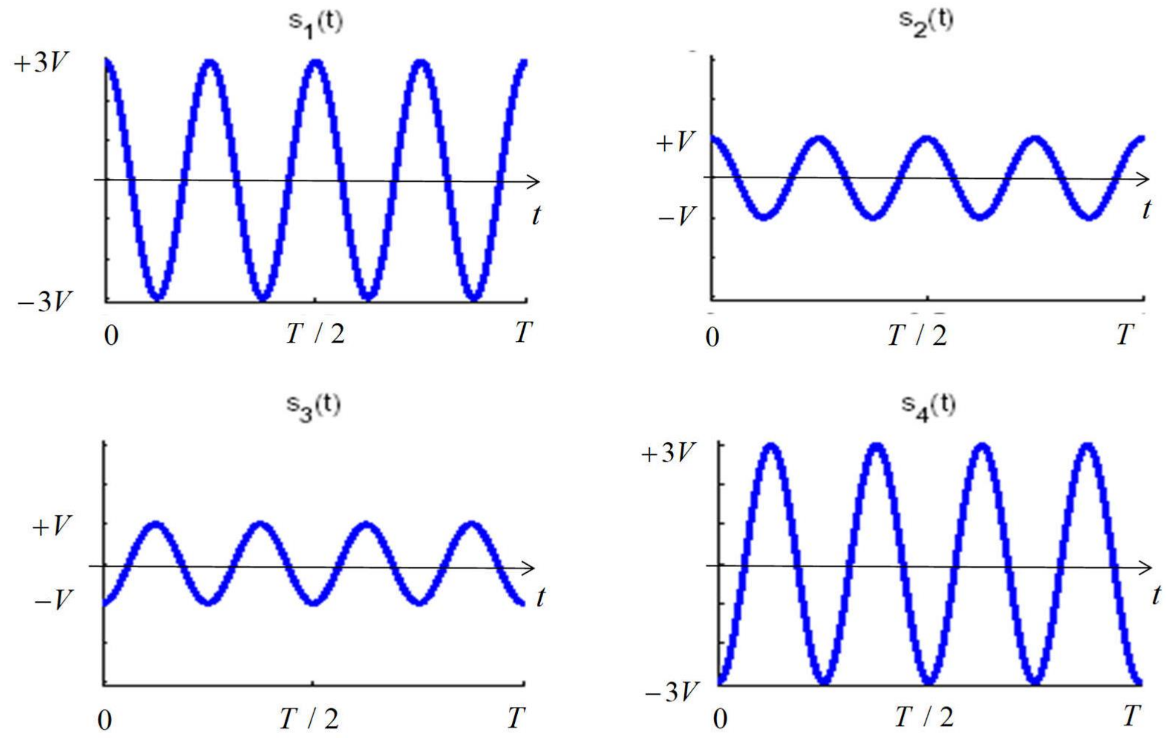
Example: 4-ASK

$$M = \{s_1(t) = +3VP_T(t)\cos(2\pi f_0 t), s_2(t) = +VP_T(t)\cos(2\pi f_0 t),$$
$$s_3(t) = -VP_T(t)\cos(2\pi f_0 t), s_4(t) = -3VP_T(t)\cos(2\pi f_0 t)\}$$

$$m = 4 \rightarrow k = 2 \rightarrow T = 2T_b$$

4-ASK

$$f_0 = 2R_b$$



m-PSK (Phase Shift Keying)

Example: 2-PSK

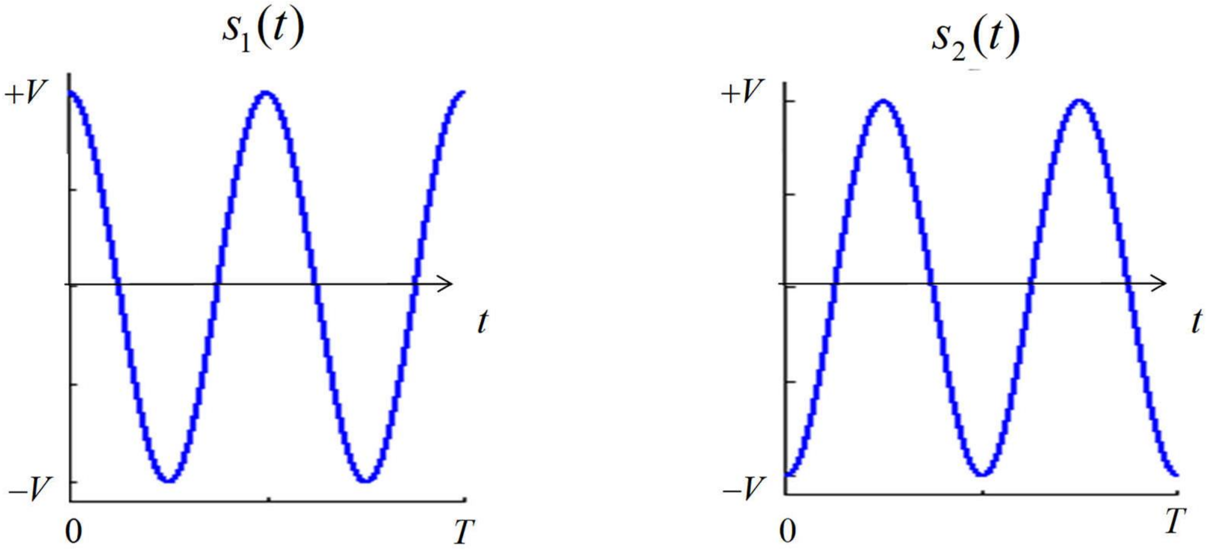
$$M = \{s_1(t) = +VP_T(t)\cos\left(2\pi f_0 t\right), s_2(t) = -VP_T(t)\cos\left(2\pi f_0 t\right)\} =$$

$$= \{s_1(t) = +VP_T(t)\cos\left(2\pi f_0 t\right), s_2(t) = +VP_T(t)\cos\left(2\pi f_0 t - \pi\right)\}$$

$$m = 2 \rightarrow k = 1 \rightarrow T = T_b$$

2-PSK

$$f_0 = 2R_b$$



Example: 4-PSK

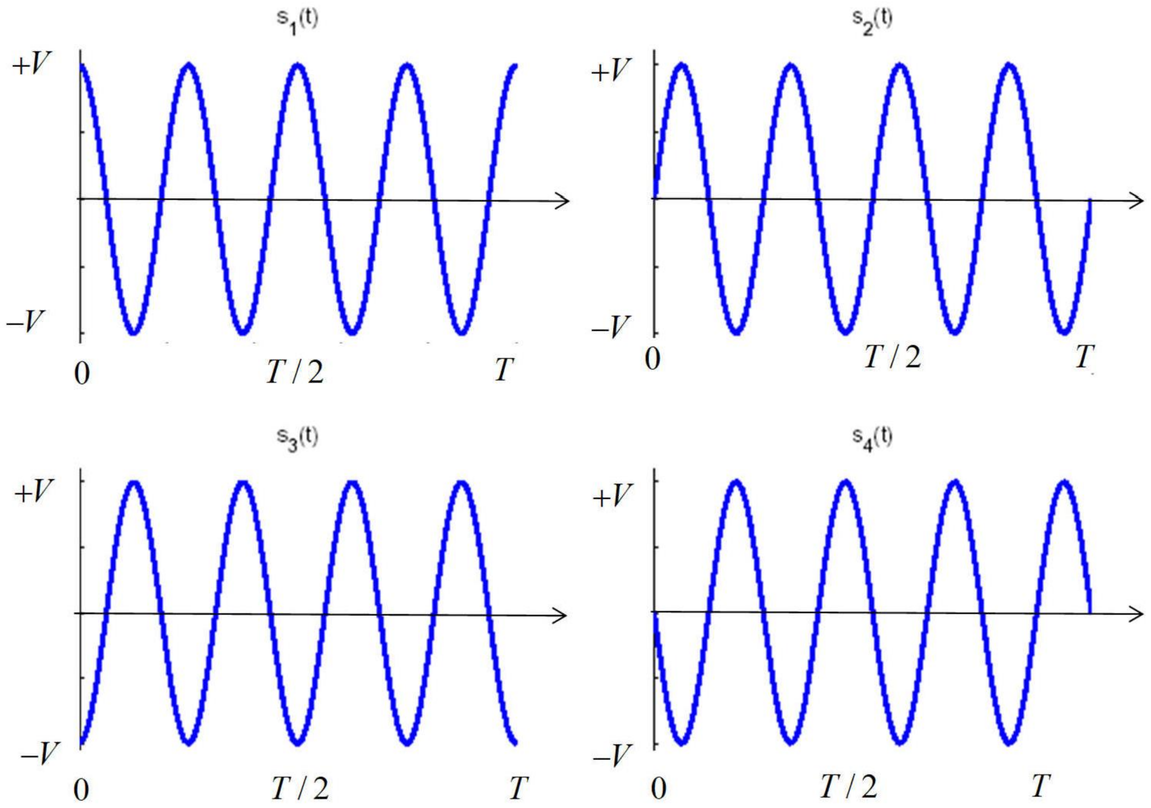
$$M = \begin{Bmatrix} s_1(t) = +VP_T(t)\cos\left(2\pi f_0 t\right), s_2(t) = +VP_T(t)\sin\left(2\pi f_0 t\right), \\ s_3(t) = -VP_T(t)\cos\left(2\pi f_0 t\right), s_4(t) = -VP_T(t)\sin\left(2\pi f_0 t\right) \end{Bmatrix} =$$

$$= \begin{Bmatrix} s_1(t) = +VP_T(t)\cos\left(2\pi f_0 t\right), s_2(t) = +VP_T(t)\cos\left(2\pi f_0 t - \frac{\pi}{2}\right), \\ s_3(t) = +VP_T(t)\cos\left(2\pi f_0 t - \pi\right), s_4(t) = VP_T(t)\cos\left(2\pi f_0 t - \frac{3\pi}{2}\right) \end{Bmatrix}$$

$$m = 4 \rightarrow k = 2 \rightarrow T = 2T_b$$

4-PSK

$$f_0 = 2R_b$$



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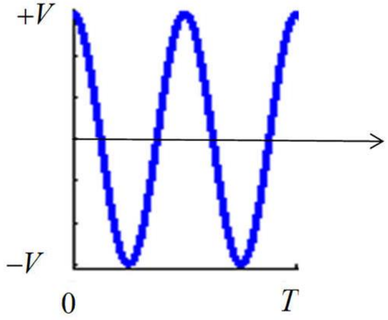
m-FSK (Frequency Shift Keying)

Example: 2-FSK

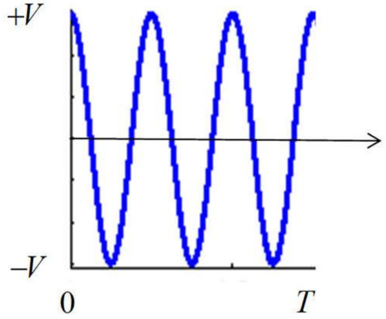
$$M = \{s_1(t) = +VP_T(t)\cos(2\pi f_1 t), s_2(t) = +VP_T(t)\cos(2\pi f_2 t)\}$$

$$m = 2 \rightarrow k = 1 \rightarrow T = T_b$$

2-FSK



$$f_1 = 2R_b$$



$$f_2 = 3R_b$$

Exercise

$\underline{\boldsymbol{u}}_{\mathrm{T}}$=(10011100…) R_b=1 Mbps

Draw the waveform of all the signal sets listed above.