Chapter 2
Baseband and Passband Data Transmissions

2.1 Synchronous and asynchronous transmission. Signaling speed and data transmission rate

- ***Data*** = encoded alphabetic and numeric characters being exchanged between two devices (Data Terminal Equipment – DTE).
- The alphabetic, numeric and punctuation characters, generally referred to as *printable characters*, as well as a range of additional *control characters*, also known as non-printable characters, are represented by using binary codes (usually a 7-bit or 8-bit code).
- Data are transmitted between two DTEs in multiples of a fixed unit, typically of eight bits. Each character or byte is transmitted *serially*.
- ***Serial*** **vs.** ***parallel*** transmission.
- **Transmission circuit**:
    - Simplex;
    - Half-duplex;
    - Full-duplex.
- **Transmission modes**:
    - Characters;
    - Octets (bytes).
- For the receiving device to decode and interpret the bit string, it must be able to determine:

1) the start of each bit cell – in order to sample the incoming signal in the middle of the bit cell and to determine what kind of bit it is: 0 or 1 → **bit (clock) synchronization**;
2) the start and end of each element (character or byte) → **character (byte) synchronization**;
3) the start and end of each complete message block (called also frame) → **frame (block) synchronization**.

- There are two methods to accomplish these tasks, each one determined by whether the transmitter and receiver clocks are independent (**asynchronous transmission**) or synchronized (**synchronous transmission**).

Asynchronous transmission

- Data to be transmitted are generated at random intervals (from the keyboard, for example).
- The receiver must be able to detect the beginning of each new character received → each transmitted character or byte is encapsulated (framed) between two additional elements with different electrical representation: a **start** bit and a **stop** element (figure 2.1).

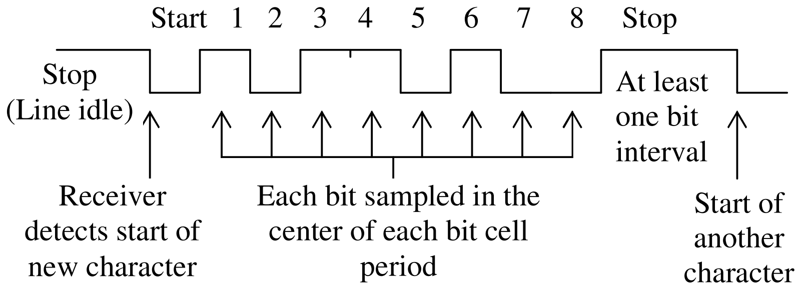


Figure 2.1 Asynchronous transmission.

Synchronous transmission

- Having breaks between characters for the transmission of large blocks of data at higher bit rates is not efficient → to transmit the code combinations that correspond to these characters one at a time *without breaks*.
- The receiver must have a clock synchronized with the transmitter clock. If it is not synchronized there will be errors in the recovered data (figure 2.2) → need for *timing information* (in the transitions of the data signal, because the intervals between the data signal transitions are multiples of the bit intervals).

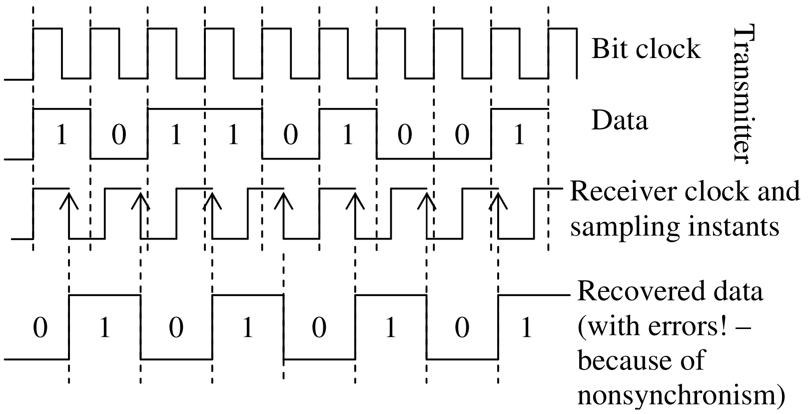


Figure 2.2 Errors due to the nonsynchronized receiver clock.

Signalling rate

- At each instant the transmitted signal can be in one state from a finite set of states (ex. In the binary transmission, one of two states);
- The duration of the shortest state is named *elementary interval* (*T*) → the signaling rate is defined as:

$$v_s = \frac{1}{T}[\text{Bd}], \qquad \text{(baud)} \qquad (2.1)$$

Data transmission rate

- Number of binary elements (bits) transmitted per second → bits/s.
- The signaling rate (in bauds) and the data transmission rate (in bits/s) are often numerically equal, but in some cases differ → example of signal with four levels, having 2 bits per level:

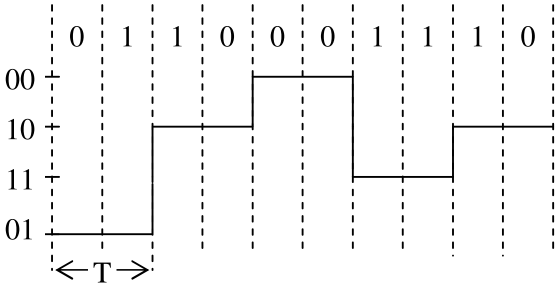


Fig. 2.3 Four states signal.

- In this case $D = v_s * 2$.

2.2 Baseband data signals

- ***Baseband*** = the band of frequencies occupied by the (data) signal before it modulates a carrier (or subcarrier) frequency in order to form the transmitted line or radio signal → The baseband, therefore, has a frequency content extending into direct current region.
- Baseband data can be transmitted hundreds or even thousands of meters (the transmission distance is limited by several factors) and this is commonly done on wire pair, which has a low-pass frequency transfer characteristic so that it permits data to be transmitted directly without need for frequency translating.
- However, there is need for some line coding to ensure that the transmitted signal has the following features:
    - **no d.c. component and low frequency components**, because the transmission equipment is connected to the transmission line by transformers and these transformers have large attenuation at small frequencies;
    - **small bandwidth**, in order to use efficiently the useful bandwidth of the transmission line and to avoid the large attenuation of the line at high frequencies;
    - a **good protection against noise**;
    - **presence of timing information** (transitions), necessary to synchronize the receiver clock with the transmitter clock;
    - **no necessity for the receiving device to determine the absolute polarity** of the data signal.

Figure 2.4 gives some examples of data electrical representations:

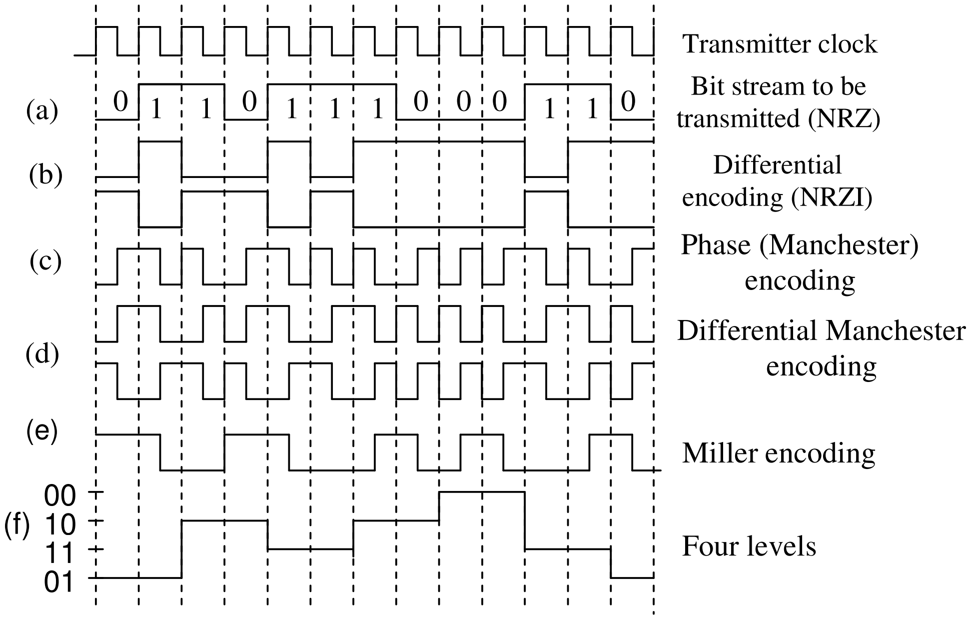


Figure 2.4 Line codes.

- NRZ (Non Return to Zero, figure 2.4.a);
- Phase (Manchester) encoding - representing "1" symbols using the clock signal and "0" symbols using the inverted clock signal;
- Differential encoding (figure 2.3.b) - the symbols "1" are represented by the signal transition at the beginning of the bit interval and the symbols "0" by no transition;
- The Miller encoding, obtained from differential Manchester encoding by suppressing one transition from two;
- The multilevel representation (in figure 2.3.f a four level signal is presented), using $M=2^m$ levels;
- The power spectral densities for some of these signals are represented in figure 2.5.

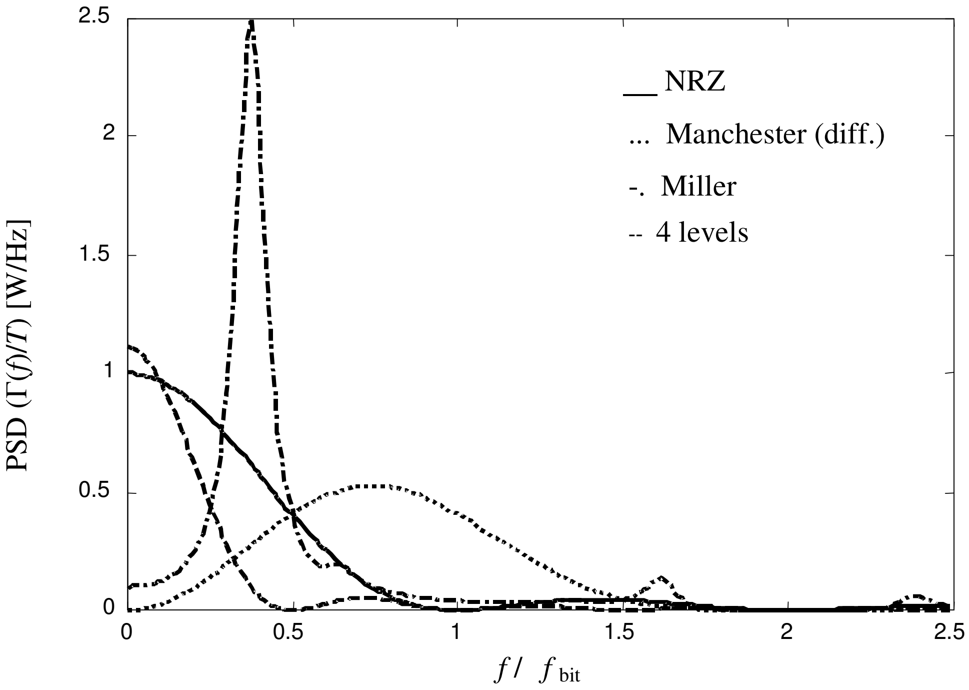


Fig. 2.5 Power Spectral Density.

- Each representation has advantages but also disadvantages, so that choosing between them depends on the application.

2.3 Effects of restricted bandwidth in baseband data transmission

- The baseband data signal $d(t)$ is generally composed of rectangular pulses with different amplitudes a_n (Figure 2.6):

$$d(t) = \sum_n a_n g(t - nT) \tag{2.2}$$

, $g(t)$ being a rectangular pulse with amplitude equal with unity (Figure 2.7).

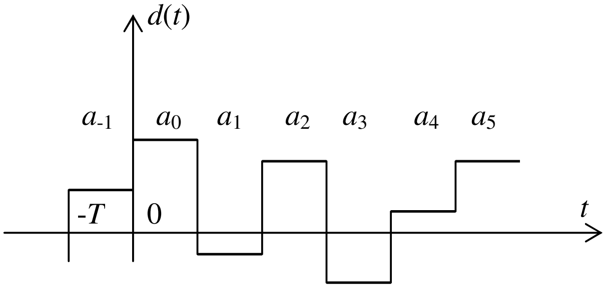


Fig. 2.6 Baseband data signal.

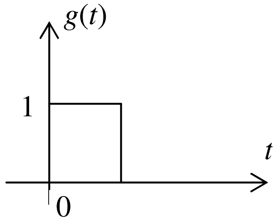


Fig. 2.7 Rectangular pulse.

- The number of levels M of these values is a power of 2, $M=2^m$, and the spacing between levels is uniform: $\pm d; \pm 3d;...; \pm(M-1)d$. Each level can represent m binary symbols.
- The frequency spectrum of the rectangular data signal $d(t)$ is extended over an unlimited frequency band → even if the data transmission system doesn't limit the signal spectrum the transmission line will limit it → different shape of the received signal compared to the transmitted signal;
- The simplified block diagram of a baseband data transmission system is shown in figure 2.8;

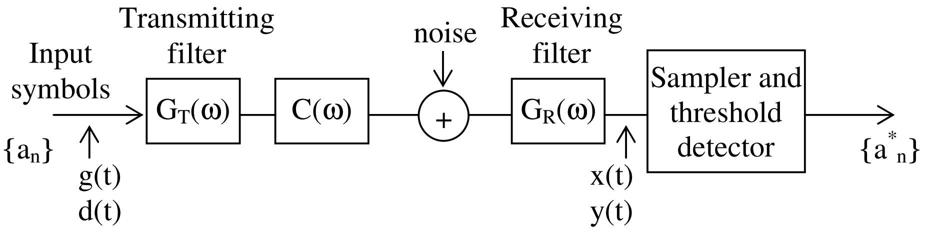


Fig. 2.8 Baseband data transmission system.

- Denoting by $x(t)$ the system response, to a transmitted pulse $g(t)$, the system response to a data sequence $\{a_n\}$, represented by the data signal $d(t)$ is:

$$y(t) = \sum_n a_n x(t-nT) + \eta(t) \qquad (2.3)$$

where $\eta(t)$ is the additive noise.

- The effect of the restricted bandwidth is a time extension of the response $x(t)$ over many symbol intervals (Figure 2.9).

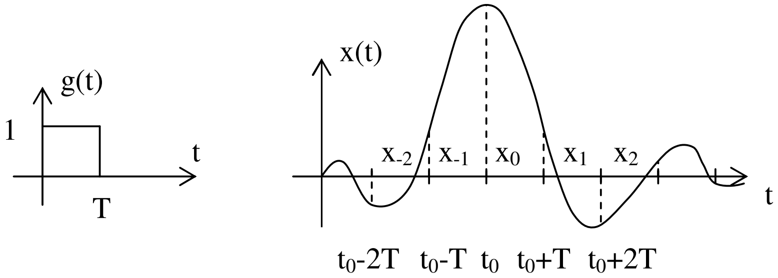


Fig. 2.9 The response *x(t)* to a pulse *g(t)*.

- At time t_0+kT the desired output voltage is a_k; however the actual value is

$$y(t_0+kT)=\sum_n a_n x(kT-nT+t_0)+\eta(t_0+kT) \tag{2.4}$$

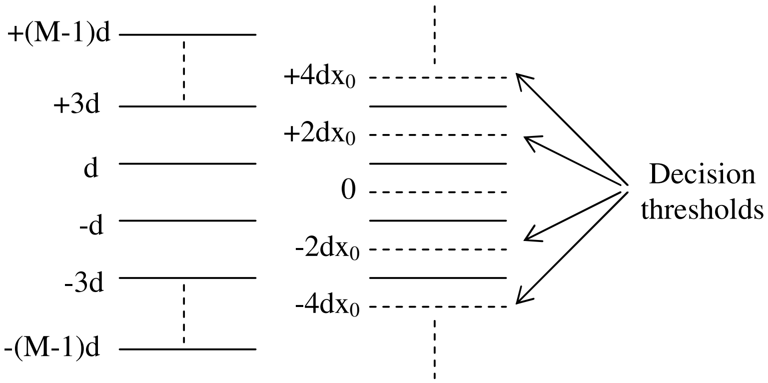
or in a concise form

$$y_k=\sum_n a_n x_{k-n}+\eta_k \tag{2.5}$$

- Isolating the desired amplitude a_k we have

$$y_k=x_0(a_k+\frac{1}{x_0}\sum_n a_n x_{k-n}+\frac{\eta_k}{x_0}) \tag{2.6}$$

- Decision by threshold comparison:



(a) (b)

Figure 2.10 – a) Allowed transmitter level
b) Decision thresholds (indicated by dashed lines)

- An error occurs whenever:

$$\left|\sum_{n\neq k} a_n x_{k-n}+\eta_k\right| \triangleright x_0 d \tag{2.7}$$

2.4 Pulse shaping for no intersymbol interference. Nyquist crterion

- Intersymbol interference (ISI) can only be eliminated by making $x_n = 0$ for all $n \neq 0$.
- An example of a pulse having no ISI is shown in figure 2.11.

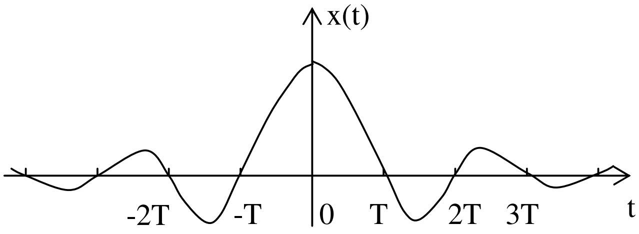


Fig. 2.11 Response (pulse) corresponding to no intersymbol interference.

- Necessity to specify in the frequency domain the requirements for no intersymbol interference → $X(\omega)$, the Fourier transform of $x(t)$;
- Sampling theorem → $x(t)$ and the frequency response $X(\omega)$ for a function band-limited to $[-f_{Max}, f_{Max}]$ → samples taken at $1/2f_{Max}$ - sec (**Nyquist interval**) intervals → $f_N = 1/2T$ Hz (**Nyquist frequency**):
  - $f_{Max} = f_N$ → these samples uniquely determine the function $x(t)$;
  - $f_{Max} < f_N$ → no solutions;
  - $f_{Max} > f_N$ → infinite number of solutions.
- The characteristic band-limited to the Nyquist band and corresponding to the samples sequence $\{x_n\}$ is called the **equivalent Nyquist characteristic**. For no interference, that means to have $x_n = 0$ for $n \neq 0$, the equivalent Nyquist characteristic (Figure 2.12) is

$$x(t) = \mathrm{sinc}(\pi t/T); \qquad X(\omega) = T \text{ for } |\omega| \leq \omega_N; \; X(\omega) = 0 \text{ for } |\omega| > \omega_N \tag{2.8}$$

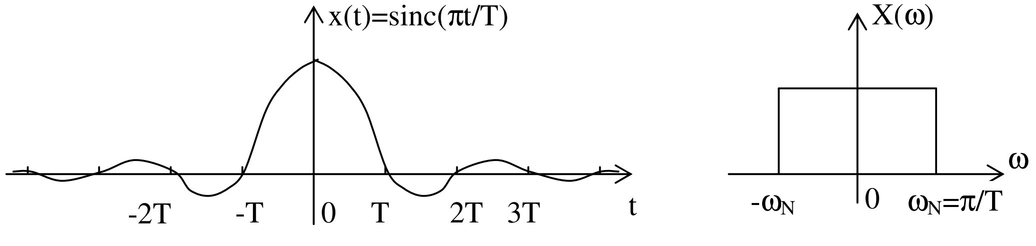


Fig. 2.12 Equivalent Nyquist characteristic for no intersymbol interference.

- Physical implementation → possibilities;
  - Causality;
  - actual bandwidth available is larger than the minimum-required Nyquist bandwidth for the desired symbol rate *1/T*, but it does not exceed twice this bandwidth.

$$X(\omega)=0 \text{ for } |\omega|>2\pi/T \tag{2.9}$$

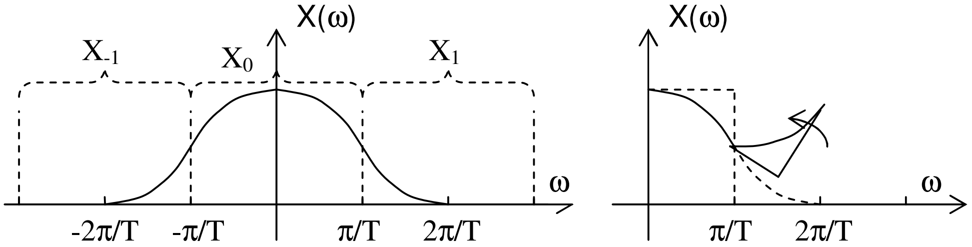


Fig. 2.13 a) Equivalent Nyquist characteristic is superposition of X_{-1}, X_0, X_1;
b) Folding of the portion of characteristic in excess of Nyquist bandwidth.

- The characteristic *X(ω)*, when it is a real one, must have an *odd symmetry* about $\omega=\omega_N$;
- **Raised cosine characteristic**. A raised cosine characteristic consists of a flat amplitude portion and a roll-off portion that has a sinusoidal form (Figure 2.14):

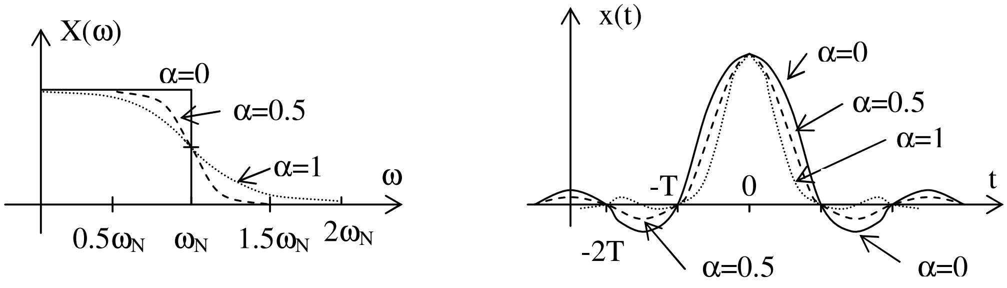


Fig. 2.14 Raised cosine characteristics.

- **Raised cosine characteristic**:

$$X(\omega)=T \quad \text{for } 0\leq\omega\leq\omega_N(1-\alpha)$$

$$X(\omega)=\frac{T}{2}\left\{1-\sin\left[\frac{T}{2\alpha}(\omega-\omega_N)\right]\right\} \quad \text{for } \omega_N(1-\alpha)\leq\omega\leq\omega_N(1+\alpha) \tag{2.10}$$

The response *x(t)* is given by:

$$x(t)=\frac{\sin \pi t/T}{\pi t/T}\frac{\cos \alpha\pi t/T}{1-4\alpha^2t^2/T^2} \tag{2.11}$$

α is a parameter, called *roll-off factor*, which indicates the ratio between the supplementary bandwidth used in excess of the minimum Nyquist bandwidth and the Nyquist bandwidth.

2.5 Performance of baseband data transmission systems

2.5.1 Performance of ideal systems

- The principal causes for errors in data transmission are noise, intersymbol interference and timing jitter;
- An *ideal system*, having neither intersymbol interference nor timing jitter, but only noise from the transmission line;
- For such an ideal system the probability of error due to the noise can be computed and for the real system this probability can be measured;
- The error probability P_e due to a white Gaussian noise:

$$P_e=(1-\frac{1}{M})P(\eta>dx_0)=(1-\frac{1}{M})\left\{1-2F\left[\left(\frac{3}{M^2-1}\frac{S}{N}\right)^{1/2}\right]\right\} \tag{2.12}$$

where *M* is the number of levels used to represent the data symbols, *S* is the signal power, *N* is the noise power in the Nqyuist bandwidth at the input of the receiving filter, and *F(v)* is a function given by

$$F(v)=\frac{1}{2\pi}\int_0^v e^{-\frac{u^2}{2}}du \tag{2.13}$$

- A sequence of curves for the error probability P_e as a function of signal-to-noise ratio is shown in Figure 2.15.

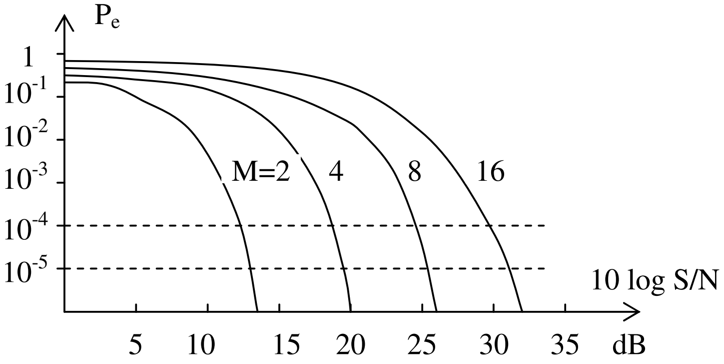


Fig. 2.15 – Probability of error for M level baseband transmission system

2.5.2 Performance of real systems

- BER estimation as function of ISI, noise, etc. = too complex, and not specifying the source of errors;
- A more useful method to appreciate the quality of a data transmission system is called "*eye pattern*";
- Eye pattern representations for the undistorted and distorted signals in figure 2.16; horizontal sweep rate 1/*T* or 1/(*nT*);

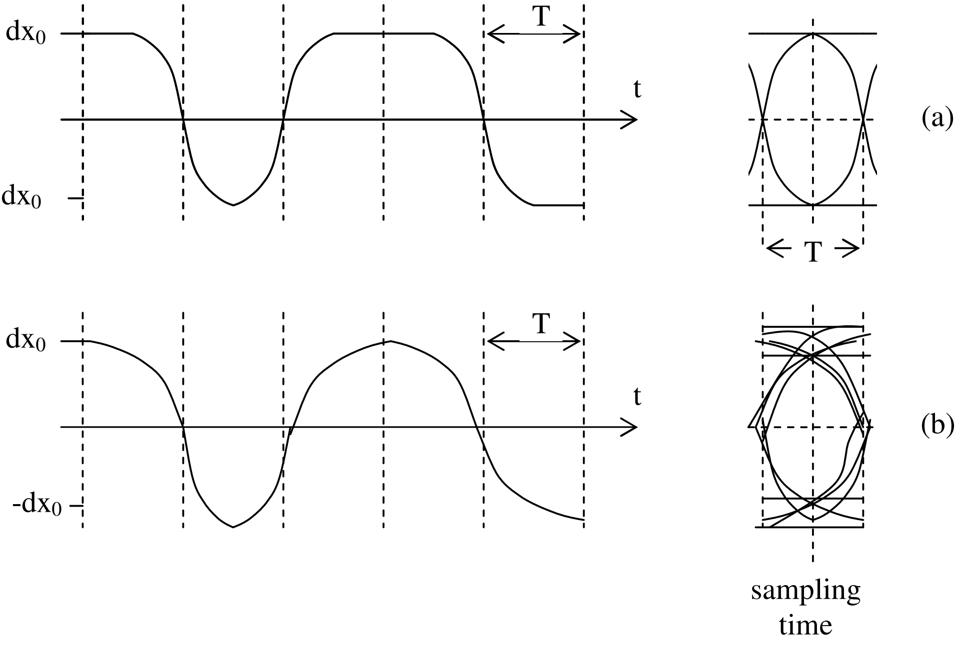


Fig. 2.16 – Binary signals and corresponding eye patterns for undistorted (a) and distorted (b) signals

- For a well-defined eye pattern, schematised like in figure 2.17, some performance parameters can be determined.

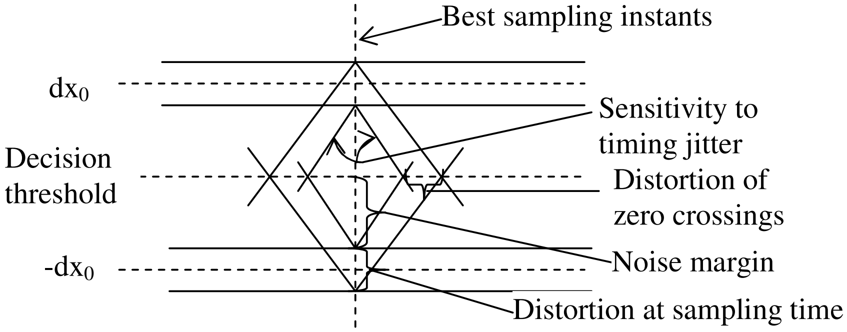


Fig. 2.17 – Eye pattern parameters

- A **relative evaluation** of data systems can be realized using two criterions related to eye pattern: eye closure (peak distortion) and mean square distortion;

- Peak distortion criterion -

- The maximum value of (ISI) is:

$$(ISI)_{Max} = (M-1)d\sum_{n\neq 0}|x_n| \tag{2.14}$$

- The peak eye closure (PEC), normalized, is

The peak eye closure (PEC), normalized, is

$$PEC = \frac{(M-1)d\sum\limits_{n\neq 0}|x_n|}{dx_0} = (M-1)D_p \tag{2.15}$$

where

$$D_p = \frac{\sum\limits_{n\neq 0}|x_n|}{x_0} \tag{2.16}$$

is called the **peak distortion** and it depends only on the data system, x_n being the samples of the system impulse response.

- Mean square distortion -

- Mean - square eye closure (*MSEC*):

$$MSEC = \frac{\langle (ISI)^2 \rangle}{(dx_0)^2} \tag{2.17}$$

- Assuming the symbols a_n are independent and equiprobable results:

$$\langle (ISI)^2 \rangle = \overline{a^2} \sum_{n \neq 0} x_n^2 \tag{2.18}$$

where $\overline{a^2}$ is the mean - square value of the amplitudes. Using (2.18) and (2.17) we obtain:

$$MSEC = \frac{\overline{a^2}}{d^2} D_{MS} \tag{2.19}$$

where

$$D_{MS} = \frac{\sum_{n \neq 0} x_n^2}{x_0^2} \tag{2.20}$$

is the mean - square distortion of the system impulse response.

2.6 The block diagram of a baseband data modem

- A simplified conventional block diagram of a baseband data modem is presented in Figure 2.18.

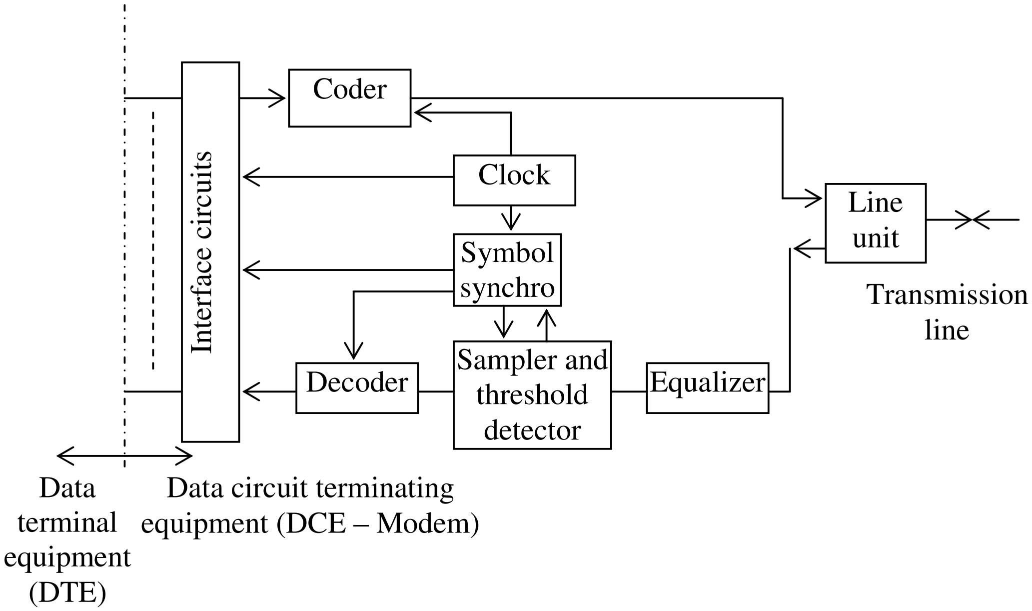


Fig. 2.18 – Block diagram of a baseband data modem