3. Signals, Coding and Modulation

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a. Digital signals
b. Digital-to-digital conversion
c. Analog-to-digital conversion
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e. Analog-to-analog conversion

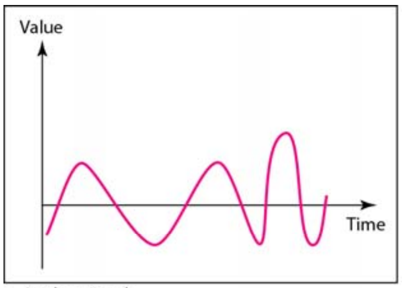
a. Digital signals

To be transmitted, data must be transformed to electromagnetic signals.

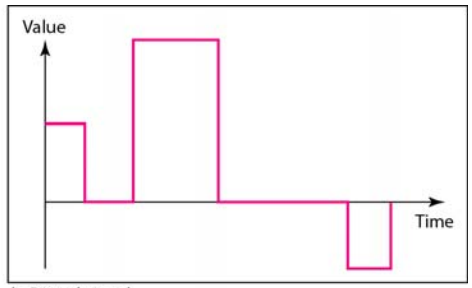
**Data can be analog or digital.
Analog data are continuous and take continuous values.
Digital data have discrete states and take discrete values.**

**Signals can be analog or digital.
Analog signals can have an infinite number of values in a range; digital signals can have only a limited number of values.**

Comparison of analog and digital signals

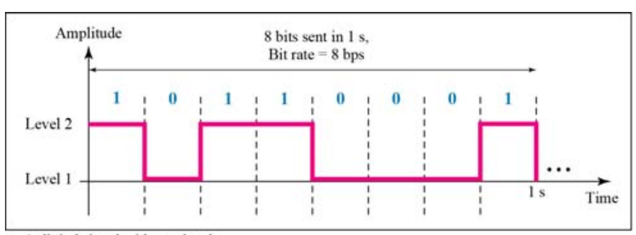


a. Analog signal

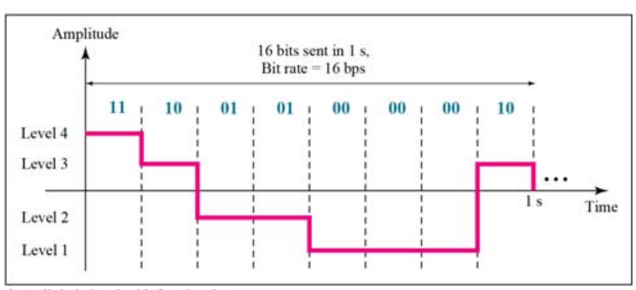


b. Digital signal

Two digital signals: one with two signal levels and the other with four signal levels



a. A digital signal with two levels



b. A digital signal with four levels

Example

A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the formula

$$\text{Number of bits per level} = \log_2 8 = 3$$

Each signal level is represented by 3 bits.

Example

A digitized voice channel, is made by digitizing a 4 KHz bandwidth analog voice signal. We need to sample the signal at twice the highest frequency (two samples per hertz).
We assume that each sample requires 8 bits. What is the required bit rate?

Solution
The bit rate can be calculated as

$$2 \times 4000 \times 8 = 64{,}000 \text{ bps} = 64 \text{ kbps}$$

Example

What is the bit rate for high-definition TV (HDTV)?

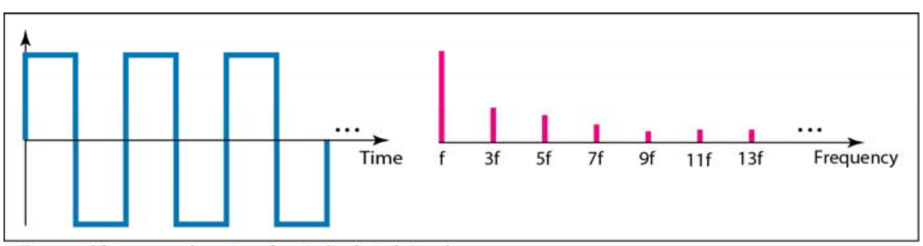
Solution

HDTV uses digital signals to broadcast high quality video signals. The HDTV screen is normally a ratio of 16 : 9. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. Twenty-four bits represents one color pixel.

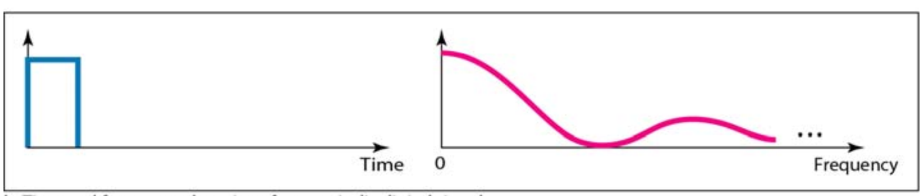
$$1920 \times 1080 \times 30 \times 24 = 1{,}492{,}992{,}000 \text{ or } 1.5 \text{ Gbps}$$

The TV stations reduce this rate to 20 to 40 Mbps through compression.

The time and frequency domains of periodic and nonperiodic digital signals

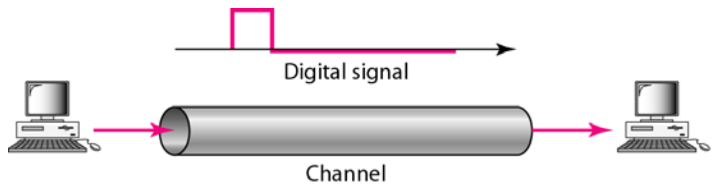


a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

Baseband transmission



Increasing the levels of a signal may reduce the reliability of the system.

Relationship between transmission speed, bandwidth and number of levels

$$Vtx = 2BW \times \log_2 L$$

Donde:

Vtx = bit rate

BW = Bandwidth

L = number of signal levels used to represent data

Example

Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels.

The maximum bit rate can be calculated as

$$\boxed{\text{BitRate} = 2 \times 3000 \times \log_2 2 = 6000 \text{ bps}}$$

Example

Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The maximum bit rate can be calculated as

$$\text{BitRate} = 2 \times 3000 \times \log_2 4 = 12{,}000 \text{ bps}$$

Example

We need to send 265 kbps over a noiseless channel with a bandwidth of 20 kHz. How many signal levels do we need?

Solution

We can use the Nyquist formula as shown:

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L$$

$$\log_2 L = 6.625 \qquad L = 2^{6.625} = 98.7 \text{ levels}$$

Since this result is not a power of 2, we need to either increase the number of levels or reduce the bit rate. If we have 128 levels, the bit rate is 280 kbps. If we have 64 levels, the bit rate is 240 kbps.

Shannon capacity

$$C = BW \times \log_2 \left[\frac{S}{N} + 1 \right]$$

Where:

C = capacity of channel in bits/second

BW = Bandwidth

S/N = signal-to-noise ratio

Example

We can calculate the theoretical highest bit rate of a regular telephone channel (not a metalic line). A telephone line normally has a bandwidth of 3000. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

$$C = B \log_2 (1 + \text{SNR}) = 3000 \log_2 (1 + 3162) = 3000 \log_2 3163$$
$$= 3000 \times 11.62 = 34{,}860 \text{ bps}$$

This means that the highest bit rate for a telephone line is 34.860 kbps. If we want to send data faster than this, we can either increase the bandwidth of the line or improve the signal-to-noise ratio.

Example

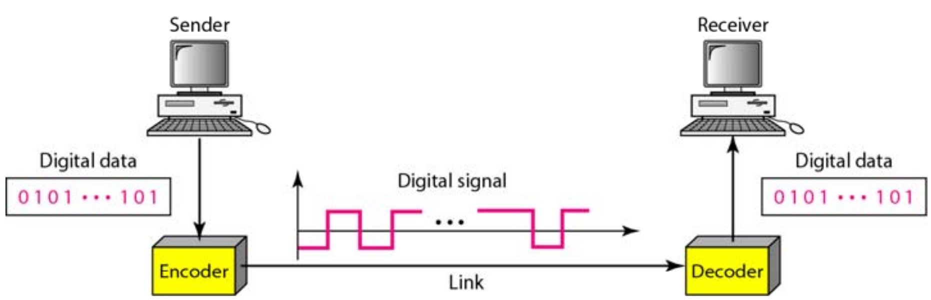
The signal-to-noise ratio is often given in decibels.
Assume that SNR (dB) = 36 and channel bandwidth is 2 MHz.
The theoretical channel capacity can be calculated as

$$SNR_{dB} = 10 \log_{10} SNR \;\rightarrow\; SNR = 10^{SNR_{dB}/10} \;\rightarrow\; SNR = 10^{3.6} = 3981$$
$$C = B \log_2 (1 + SNR) = 2 \times 10^6 \times \log_2 3982 = 24 \text{ Mbps}$$

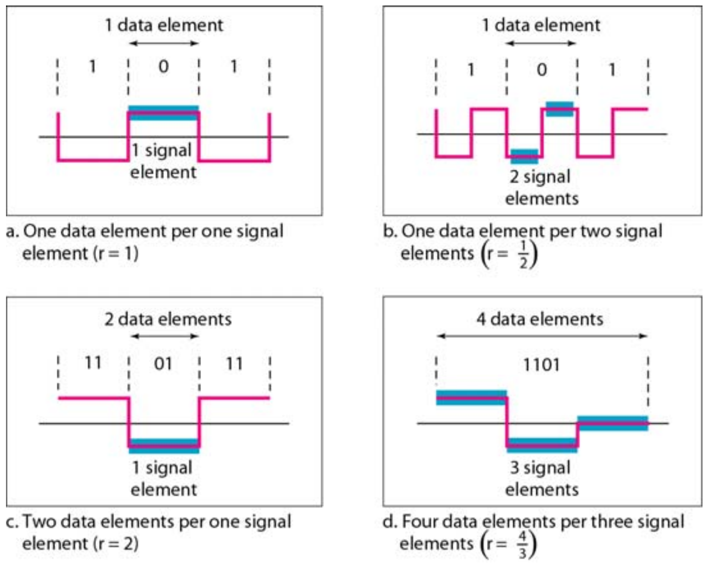
The Shannon capacity gives us the upper limit; the Nyquist formula tells us how many signal levels we need.

b. Digital-to-digital conversion

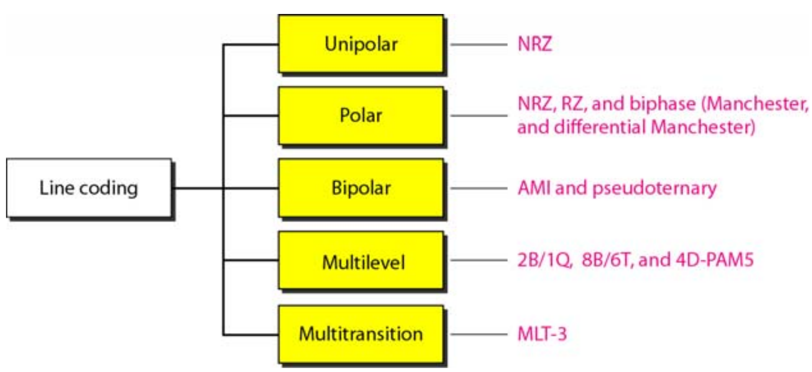
Line coding and decoding



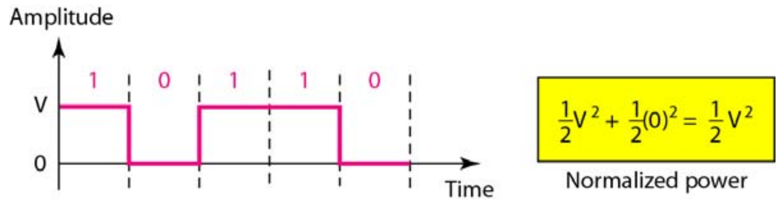
Signal element versus data element



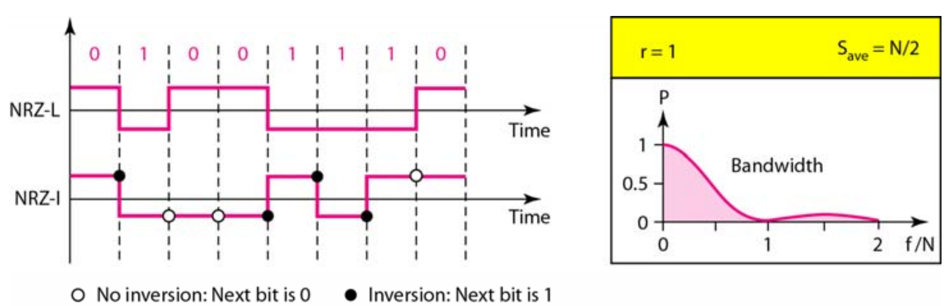
Line coding schemes



Unipolar NRZ scheme

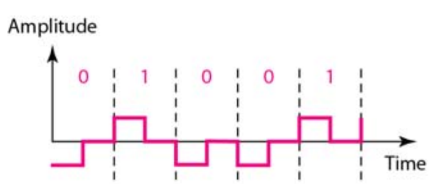


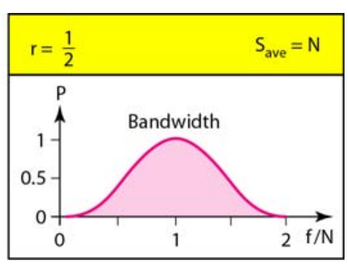
Polar NRZ-L and NRZ-I schemes



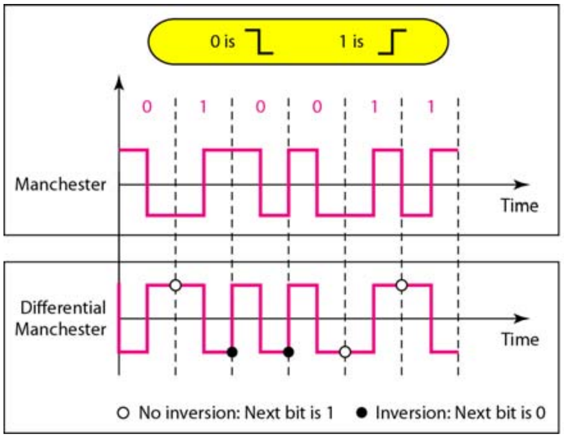
NRZ-L and NRZ-I both have a DC component problem.

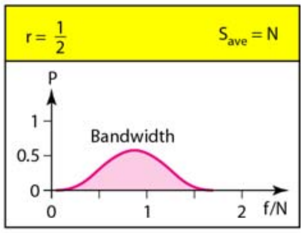
Polar RZ scheme





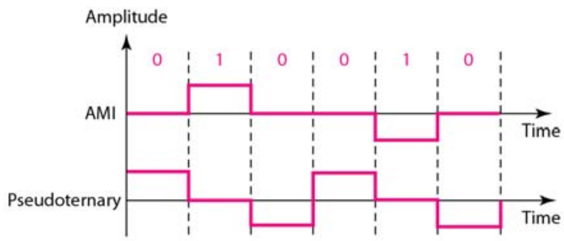
Polar biphase: Manchester and differential Manchester

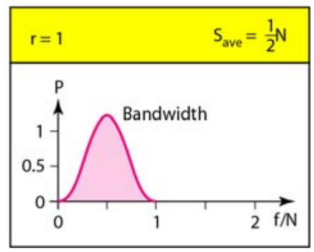




In Manchester and differential Manchester encoding, the transition at the middle of the bit is used for synchronization.

Bipolar schemes: AMI and pseudoternary



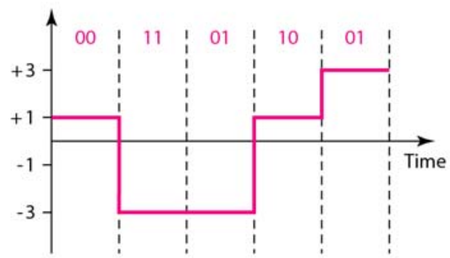


In *m*B*n*L schemes, a pattern of *m* data elements is encoded as a pattern of *n* signal elements in which $2^m \leq L^n$.

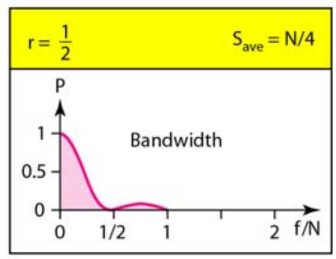
Multilevel: 2B1Q scheme

	Previous level: positive	Previous level: negative
Next bits	Next level	Next level
00	+1	-1
01	+3	-3
10	-1	+1
11	-3	+3

Transition table



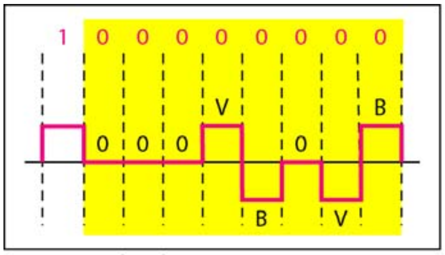
Assuming positive original level



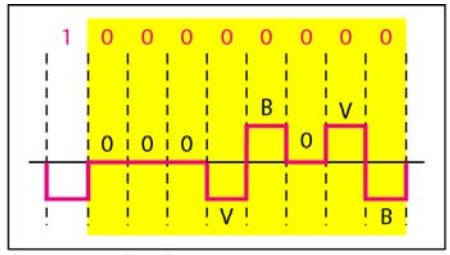
Summary of line coding schemes

Category	*Scheme*	*Bandwidth (average)*	*Characteristics*
Unipolar	NRZ	$B = N/2$	Costly, no self-synchronization if long 0s or 1s, DC
Unipolar	NRZ-L	$B = N/2$	No self-synchronization if long 0s or 1s, DC
	NRZ-I	$B = N/2$	No self-synchronization for long 0s, DC
	Biphase	$B = N$	Self-synchronization, no DC, high bandwidth
Bipolar	AMI	$B = N/2$	No self-synchronization for long 0s, DC
Multilevel	2B1Q	$B = N/4$	No self-synchronization for long same double bits
	8B6T	$B = 3N/4$	Self-synchronization, no DC
	4D-PAM5	$B = N/8$	Self-synchronization, no DC
Multiline	MLT-3	$B = N/3$	No self-synchronization for long 0s

Two cases of B8ZS scrambling technique



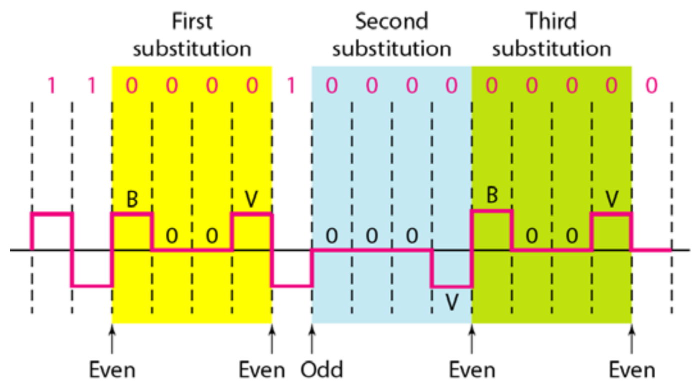
a. Previous level is positive.



b. Previous level is negative.

B8ZS substitutes eight consecutive zeros with 000VB0VB.

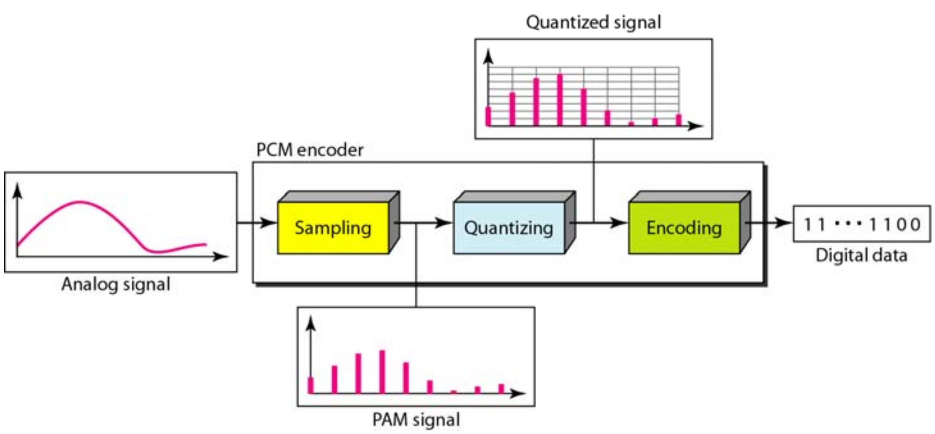
Different situations in HDB3 scrambling technique



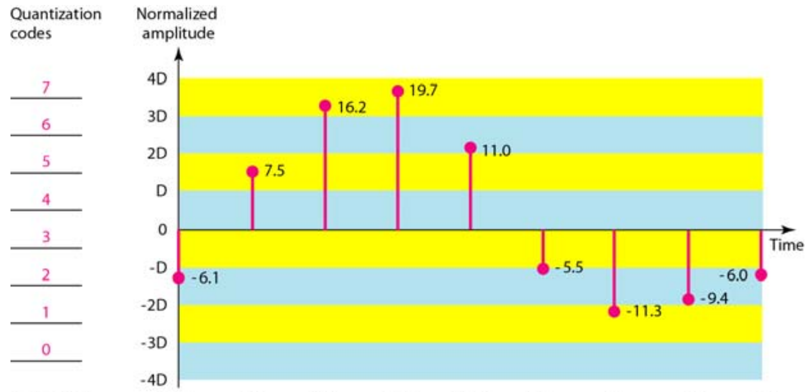
HDB3 substitutes four consecutive zeros with 000V or B00V depending on the number of nonzero pulses after the last substitution.

c. Analog-to-digital conversion

Components of PCM encoder

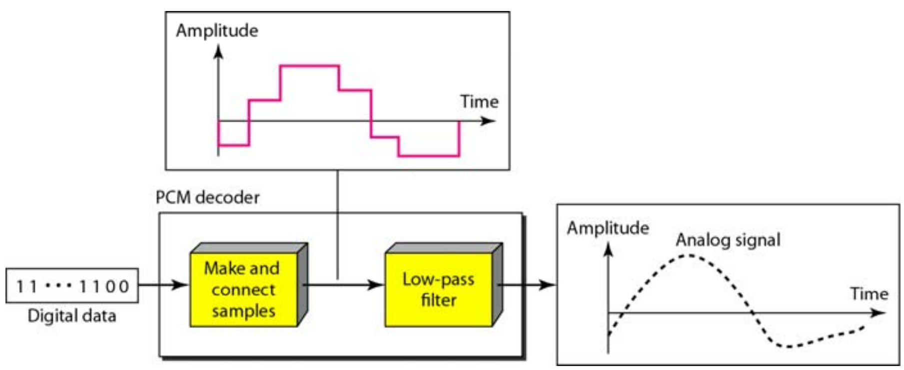


Quantization and encoding of a sampled signal

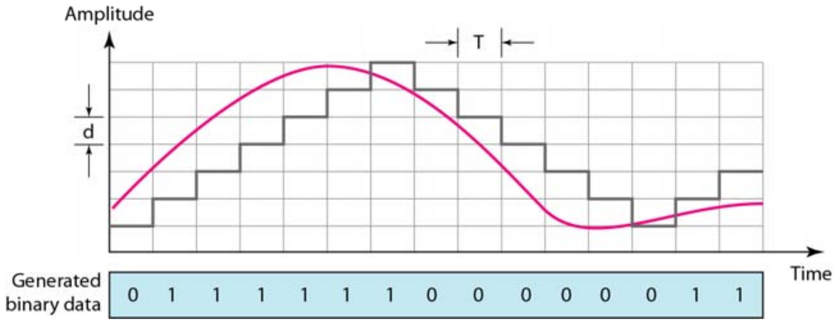


Normalized PAM values	-1.22	1.50	3.24	3.94	2.20	-1.10	-2.26	-1.88	-1.20
Normalized quantized values	-1.50	1.50	3.50	3.50	2.50	-1.50	-2.50	-1.50	-1.50
Normalized error	-0.38	0	+0.26	-0.44	+0.30	-0.40	-0.24	+0.38	-0.30
Quantization code	2	5	7	7	6	2	1	2	2
Encoded words	010	101	111	111	110	010	001	010	010

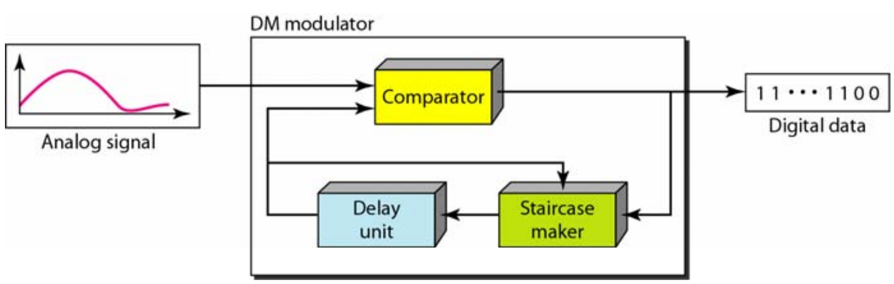
Components of a PCM decoder



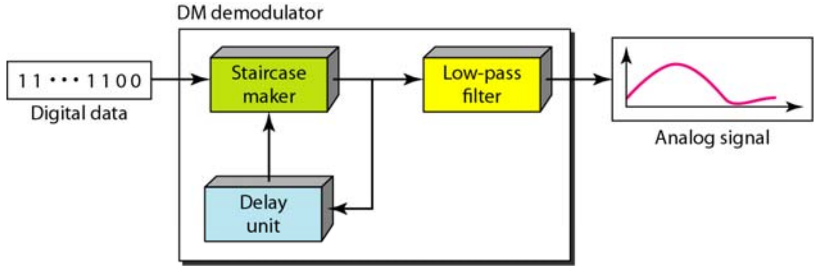
The process of delta modulation



Delta modulation components

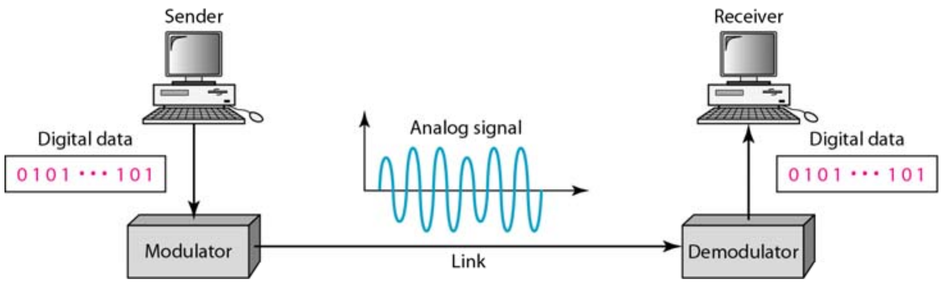


Delta demodulation components

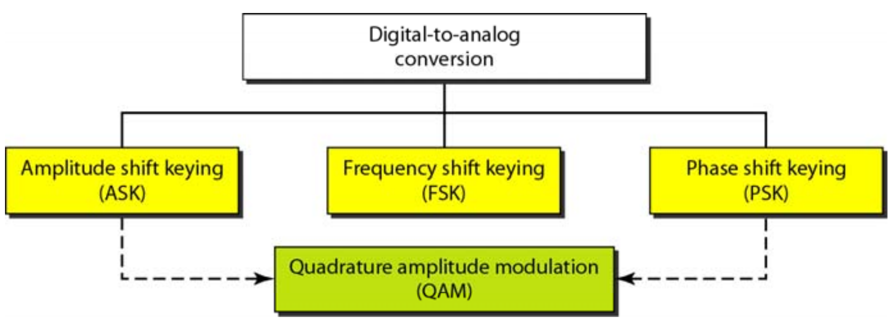


d. Digital-to-analog conversion

Digital-to-analog conversion



Types of digital-to-analog conversion



Bit rate is the number of bits per second. Baud rate or Symbol rate is the number of signal elements per second.

In the analog transmission of digital data, the baud rate is less than or equal to the bit rate.

Relationship between Vtx and Vm

The relationship between data rate (N) and baud (symbol) rate (S) is the following:

$$S = \frac{1}{T} \qquad N = S \log_2 L \qquad r = \log_2 L$$

Where:

T = period of the transmitted digital signal
S = Baud (symbol) rate in symbols/seg
N = bit rate in bps
r = number of data elements carried in one signal element
L = number of significative changes in the line

Example

An analog signal has a bit rate of 8000 bps and a baud rate (Vm) of 1000 baud. How many data elements are carried by each signal element? How many signal elements do we need?

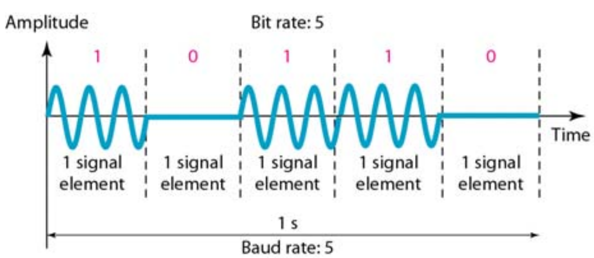
Solution

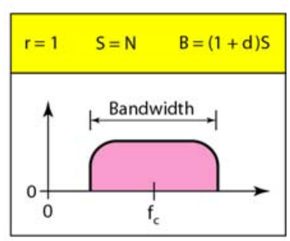
In this example, Vm = 1000, Vtx = 8000, and r and L are unknown. We find first the value of r and then the value of L.

$$S = N \times \frac{1}{r} \quad \Rightarrow \quad r = \frac{N}{S} = \frac{8000}{1000} = 8 \text{ bits/baud}$$

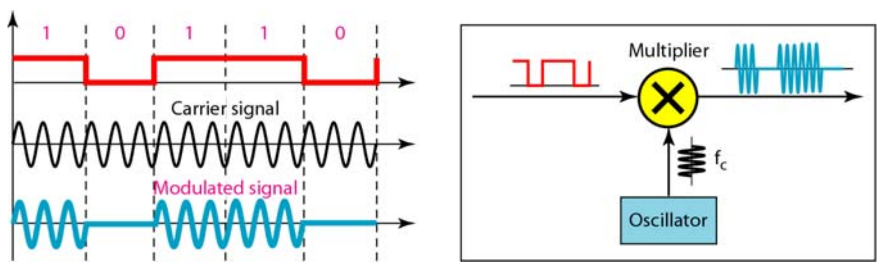
$$r = \log_2 L \quad \Rightarrow \quad L = 2^r = 2^8 = 256$$

Binary amplitude shift keying

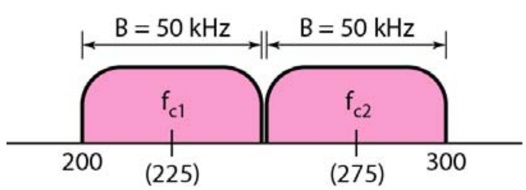




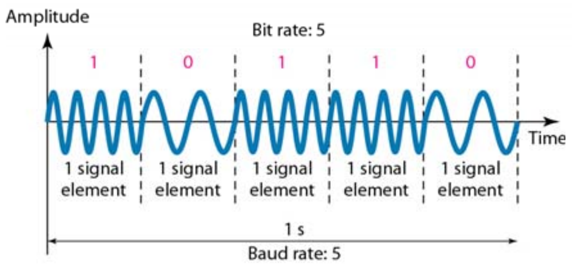
Implementation of binary ASK

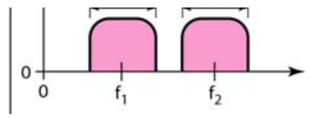


Bandwidth of full-duplex ASK

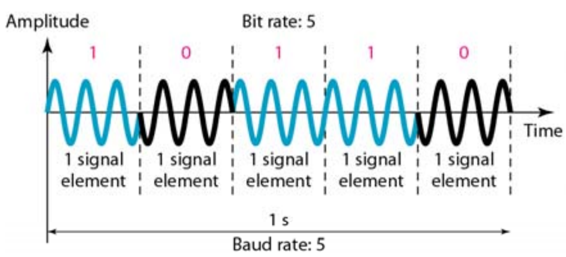


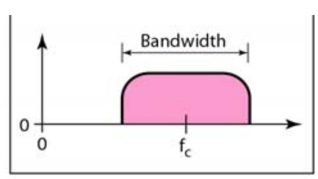
Binary frequency shift keying



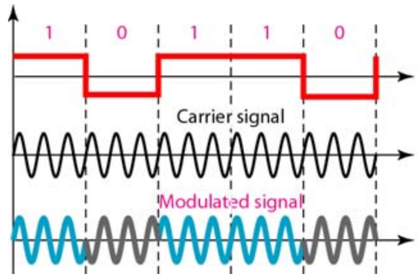


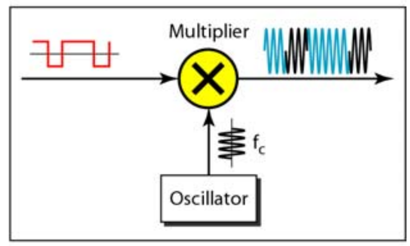
Binary phase shift keying



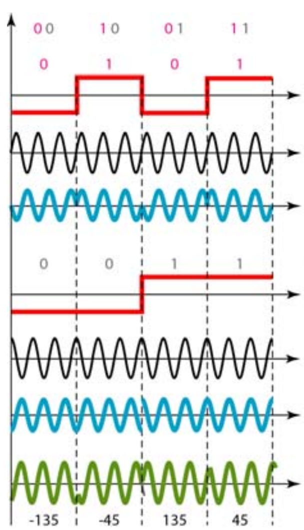


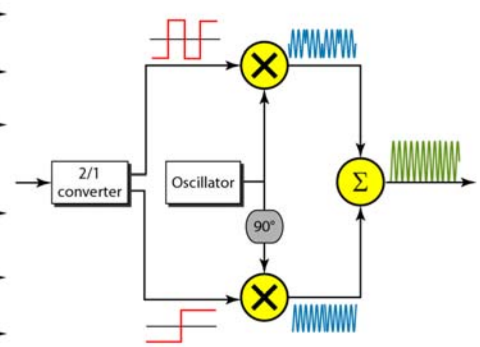
Implementation of BPSK



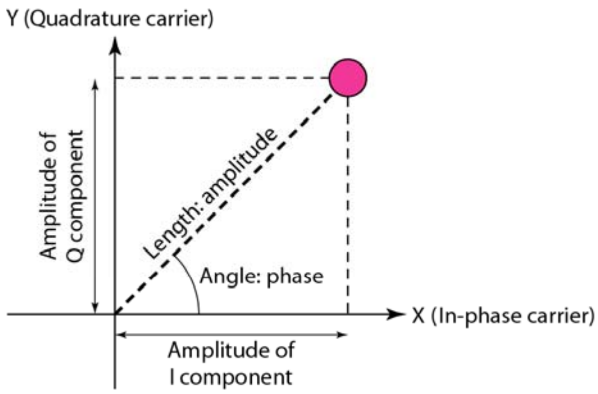


QPSK and its implementation

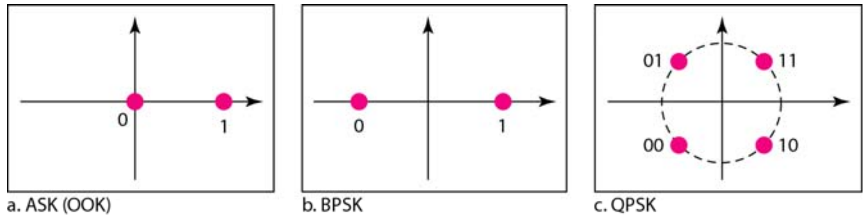




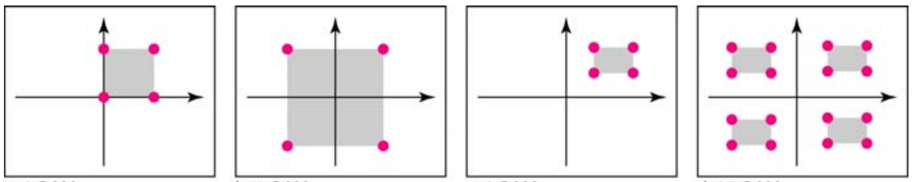
Concept of a constellation diagram



Three constellation diagrams: ASK, BPSK, QPSK



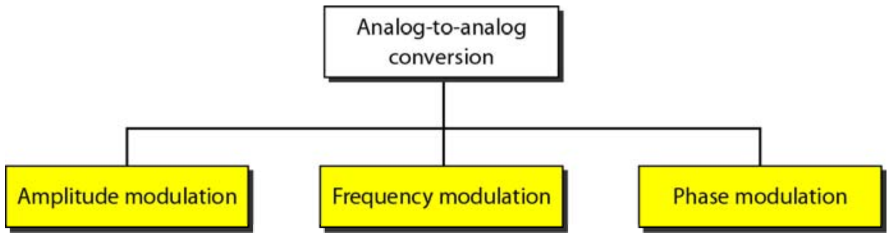
Constellation diagrams for some QAMs



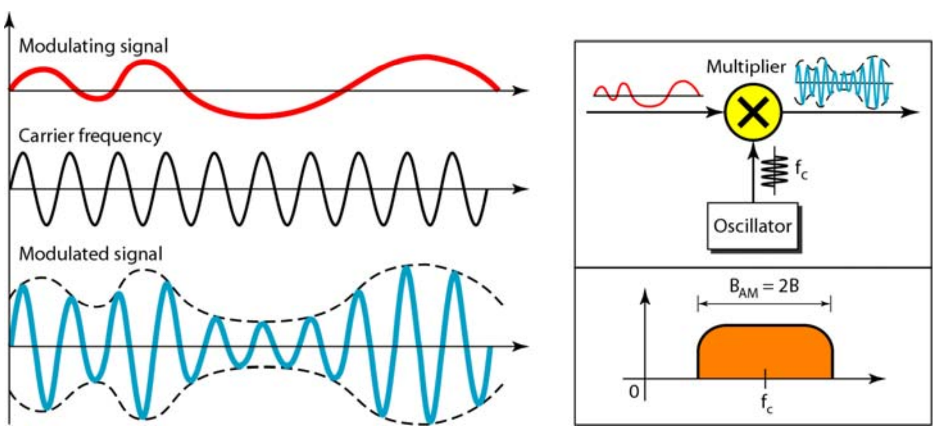
a. 4-QAM b. 4-QAM c. 4-QAM d. 16-QAM

e. Analog-to-analog conversion

Types of analog-to-analog modulation

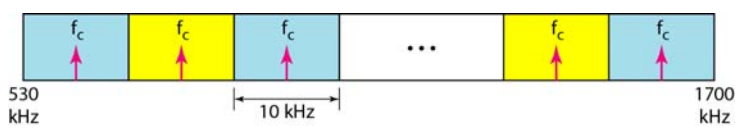


Amplitude modulation



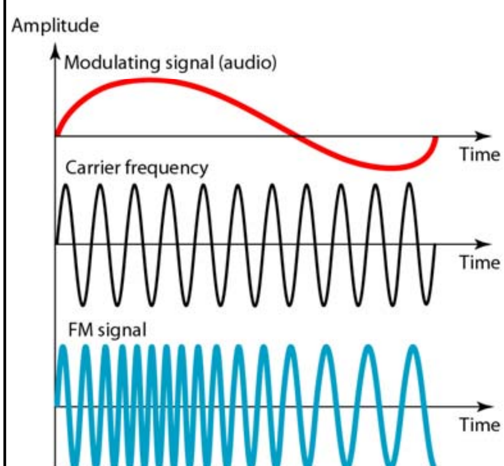
The total bandwidth required for AM can be determined from the bandwidth of the audio signal: $B_{AM} = 2B$.

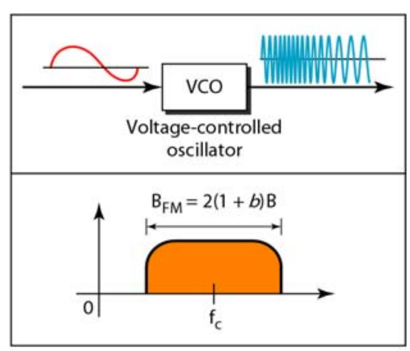
AM band allocation



The total bandwidth required for FM can be determined from the bandwidth of the audio signal: $B_{FM} = 2(1 + \beta)B$.

Frequency modulation





FM band allocation

Phase modulation