Data Communication

1

SİGNAL ENCODİNG TECHNİQUES

Signal Encoding Techniques

- Digital Communication
  - Digital Data, Digital Signal
  - Analog Data, Digital Signal
- Analog Communication
  - Digital Data, Analog Signal
  - Analog Data, Analog Signal

Signal Encoding Techniques

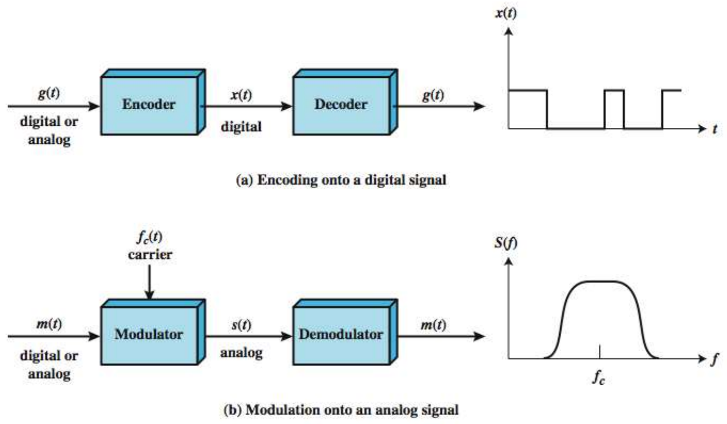
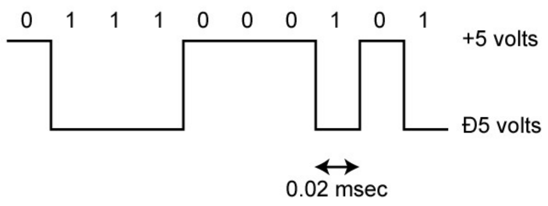


Figure 5.1 Encoding and Modulation Techniques

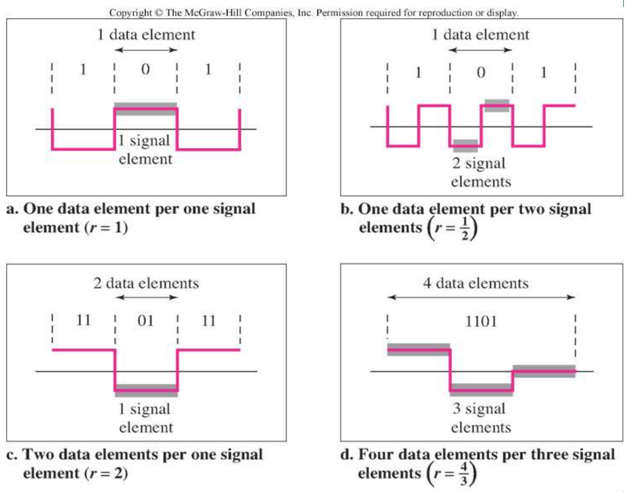
Digital Data, Digital Signal

- Digital signal
  - discrete, discontinuous voltage pulses
  - each pulse is a signal element
  - binary data (digital) encoded into signal elements



Bitrate and Baudrate

- **r,** represents the transmitted data bit counts by one signal
- **Nyquist bitrate**
  - **N = 2B $\log_2$L**
  - **N= 2 x B x r**
- **Baudrate (digital transmission)**
  - **S=1/2 x N x 1/r**



Some Terms

- Unipolar, *All signal elements have the same sign*
- Polar, *One logic state represented by positive voltage the other by negative voltage*
- data rate, (R) *transmission in bits per second*
- duration or length of a bit, *(1/R)*
- modulation rate, *Rate at which the signal level changes, measured in baud = signal elements per second. Depends on type of digital encoding used*
- mark and space

Interpreting Signals

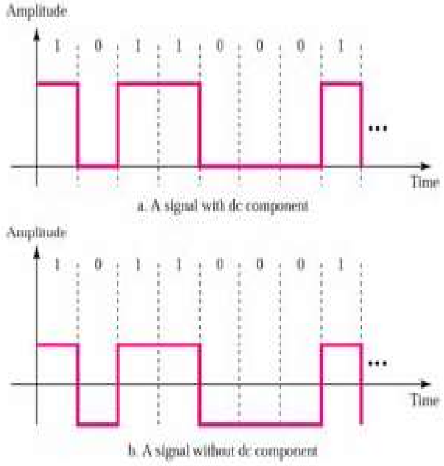
- need to know
  - timing of bits - when they start and end
  - signal levels
- factors affecting signal interpretation
  - signal to noise ratio
  - data rate
  - bandwidth
  - encoding scheme

Comparison of Encoding Schemes

- signal spectrum,
- Clocking, for synchronizing transmitter and receiver.
- error detection, useful if can be built
- signal interference and noise immunity
- cost and complexity

Digital Data Digital Signal Problems

- Long bit string of ones and zeros is a problem for sensing.
- If the duration of a signal is constant for a long time, it causes DC component. It is a problem for systems that don't transmit low frequencies (Ex. Telephone lines don't transmit frequencies below 200 Hz
- Coding Schemes must capable by these problems



a. A signal with dc component

b. A signal without dc component

Digital Data Digital Signal Problems - 2

- Both sides must have same bit interval time (bitrate)
- Synchronization
  - Start and end delimeter problem (11111111)
  - It causes additional bits
    - 1111→11111
  - A new line or entegrated signal coding can solve this problem.

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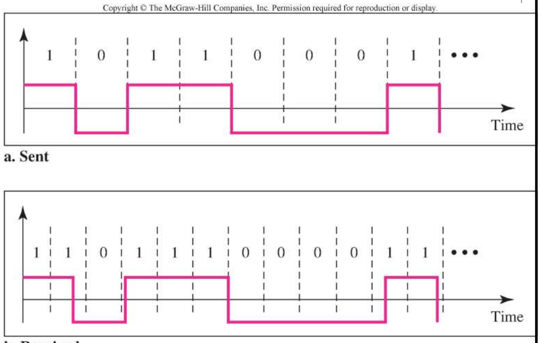
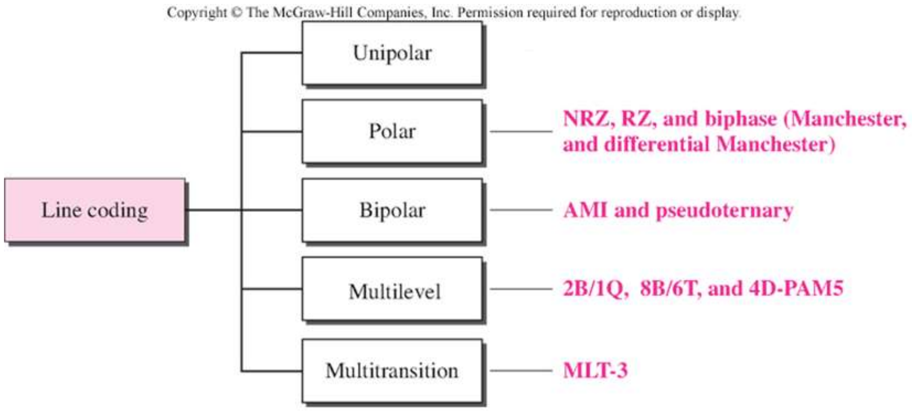


a. Sent

b. Received

Line Coding



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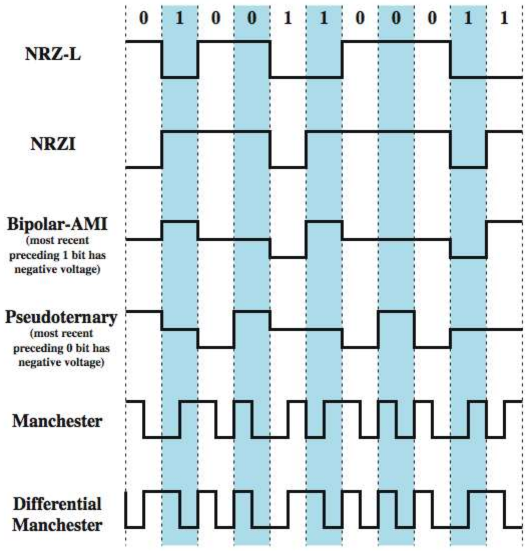
Encoding Schemes



- Nonreturn to Zero-Level (NRZ-L)
- Nonreturn to Zero Inverted (NRZI)
- Bipolar –AMI
- Pseudoternary
- Manchester
- Differential Manchester
- B8ZS
- HDB3

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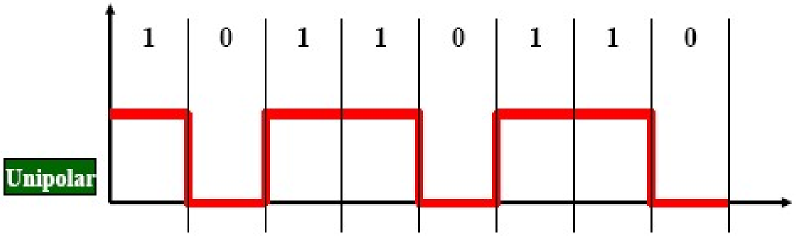
Unipolar Coding

- Single level.
- Bit 1 is positive voltage level
- Bit 0 is no voltage
- Very simpel



NRZ Coding Scheme

- is a level based coding scheme. Data are shown by levels
- has a DC component
- has a problem of synchronization
- NRZ-L and NRZ-I types are present.

Nonreturn to Zero-Level (NRZ-L)

- two different voltages for 0 and 1 bits
- voltage constant during bit interval
  - no transition I.e. no return to zero voltage
  - such as absence of voltage for zero, constant positive voltage for one
  - more often, negative voltage for one value and positive for the other
  - Used for short connections, e.g. PC-Ex.Modem

NRZ-I, Nonreturn to Zero Inverted

- nonreturn to zero inverted on ones
- constant voltage pulse for duration of bit
- data encoded as presence or absence of signal transition at beginning of bit time
  - transition (low to high or high to low) denotes binary 1
  - no transition denotes binary 0
- example of differential encoding since have
  - data represented by changes rather than levels
  - more reliable detection of transition rather than level
  - easy to lose sense of polarity

NRZ-L and NRZ-I

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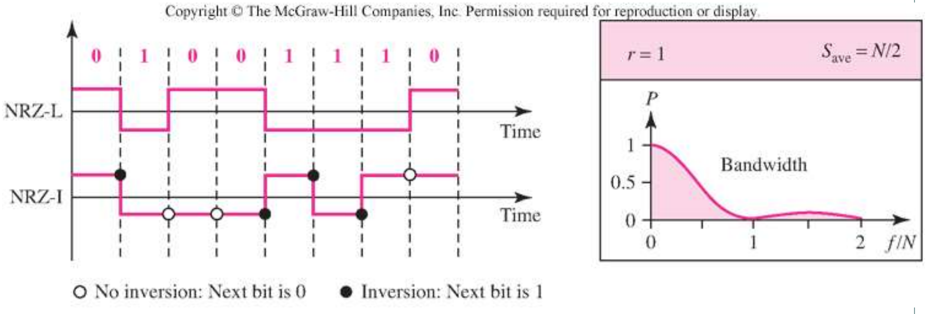

NRZ Pros & Cons

- Pros
  - easy to engineer
  - make good use of bandwidth
- Cons
  - dc component
  - lack of synchronization capability
- used for magnetic recording
- not often used for signal transmission

RZ- Return to Zero

- Three level (+V, -V, 0)
- Two signal per bit

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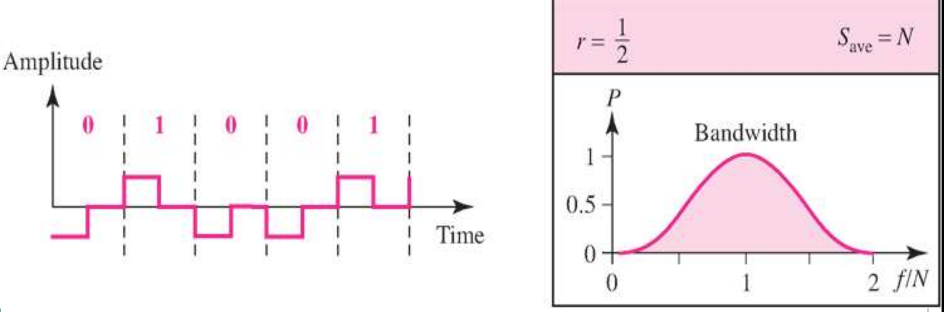
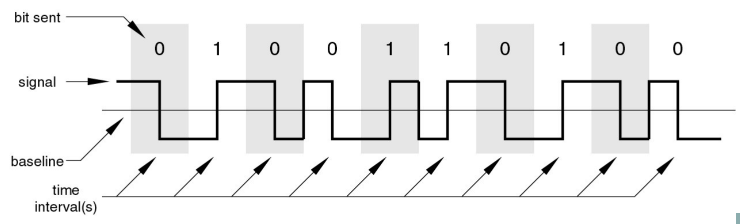
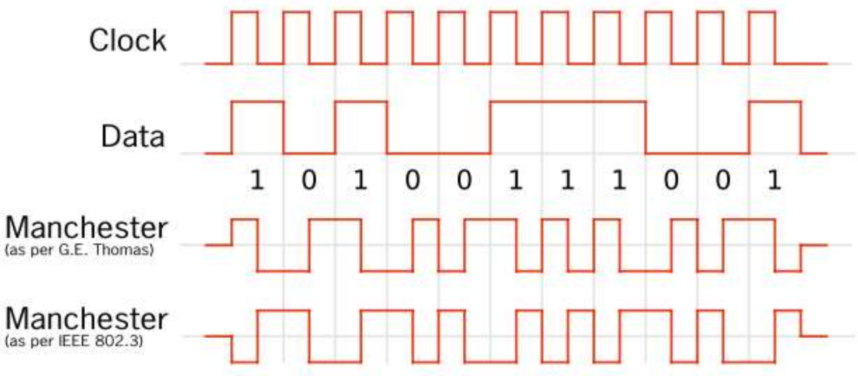


Manchester Encoding

- has transition in middle of each bit period
- transition serves as clock and data
- low to high represents one
- high to low represents zero
- used by IEEE 802.3



Manchester Encoding



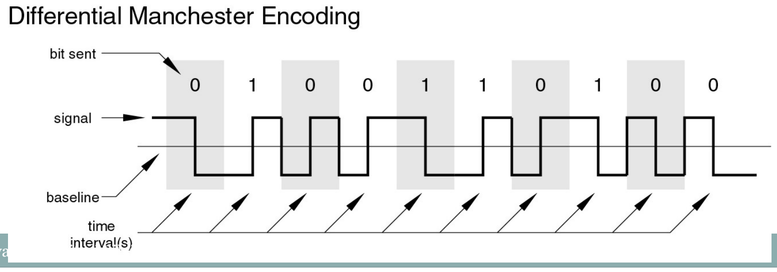
Manchester Encoding

- Extracting the original data from the received encoded bit (from Manchester as per 802.3)

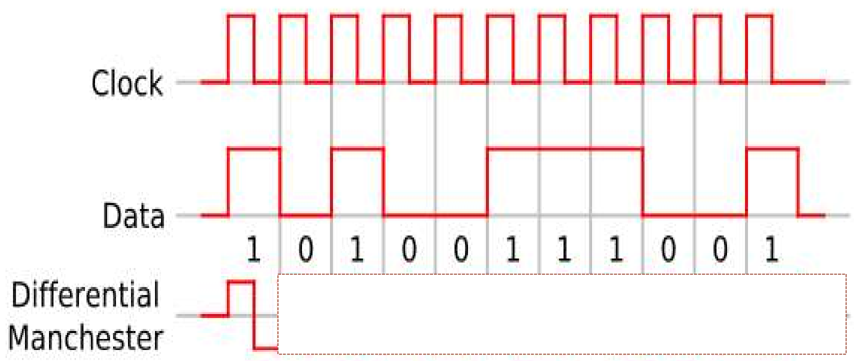
original data	= clock XOR	Manchester value
0	0	0
0	1	1
1	0	1
1	1	0

Differential Manchester Encoding

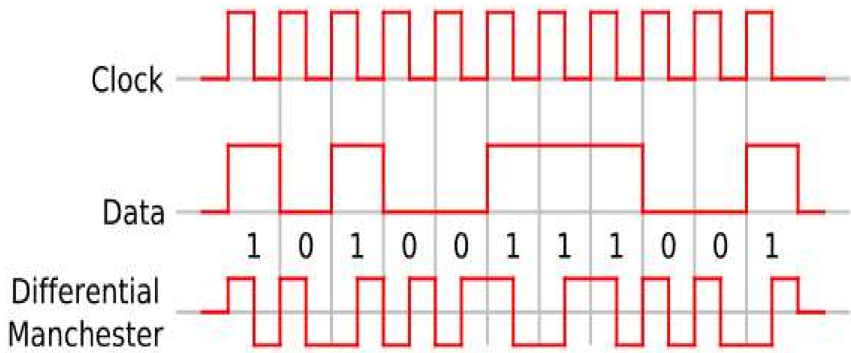
- midbit transition is clocking only
- transition at start of bit period representing 0
- no transition at start of bit period representing 1
  - this is a differential encoding scheme
- used by IEEE 802.5



Differential Manchester Encoding



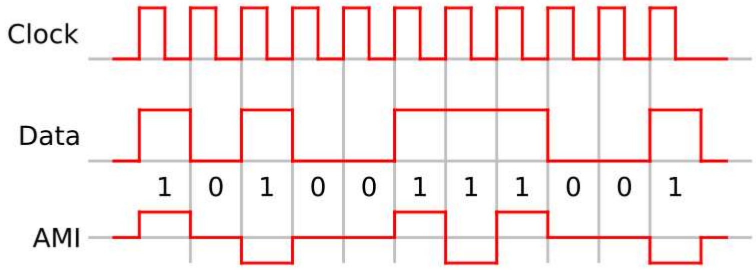
Differential Manchester Encoding



Multilevel Binary Bipolar-AMI

- Alternate Mark Inversion
- Use more than two levels
- Bipolar-AMI
  - zero represented by no line signal
  - one represented by positive or negative pulse
  - one pulses alternate in polarity
  - no loss of sync if a long string of ones
  - long runs of zeros still a problem
  - no net dc component
  - lower bandwidth
  - easy error detection

AMI- Alternate Mark Inversion



Multilevel Binary Pseudoternary

- one represented by absence of line signal
- zero represented by alternating positive and negative
- no advantage or disadvantage over bipolar-AMI
- each used in some applications

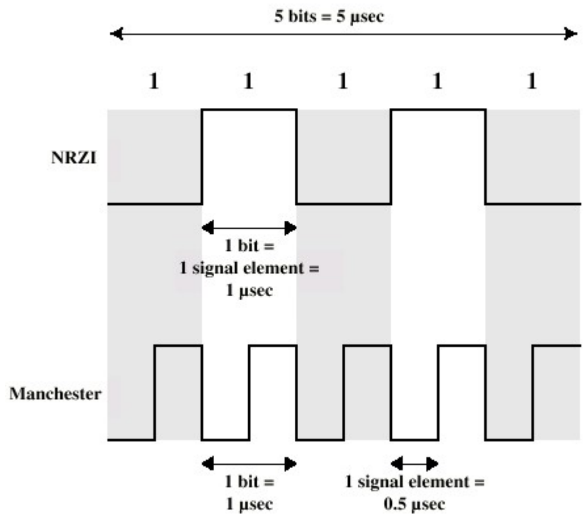
Multilevel Binary Issues

- synchronization with long runs of 0's or 1's
  - can insert additional bits, cf ISDN
  - scramble data (later)
- not as efficient as NRZ
  - each signal element only represents one bit
    - receiver distinguishes between three levels: +A, -A, 0
  - a 3 level system could represent $\log_2 3 = 1.58$ bits
  - requires approx. 3dB more signal power for same probability of bit error

Biphase Pros and Cons

- Con
  - at least one transition per bit time and possibly two
  - maximum modulation rate is twice NRZ
  - requires more bandwidth
- Pros
  - synchronization on mid bit transition (self clocking)
  - has no dc component
  - has error detection

Modulation Rate



Scrambling

- use scrambling to replace sequences that would produce constant voltage
- these filling sequences must
  - produce enough transitions to sync
  - be recognized by receiver & replaced with original
  - be same length as original
- design goals
  - have no dc component
  - have no long sequences of zero level line signal
  - have no reduction in data rate
  - give error detection capability

B8ZS-Bipolar With 8 Zeros Substitution

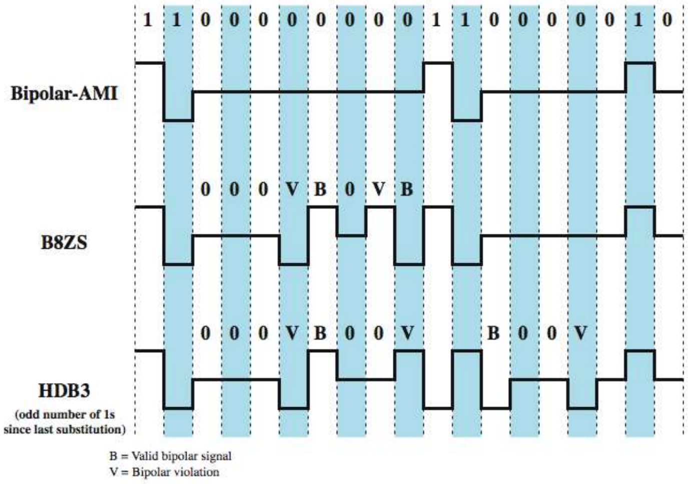
- Based on Bipolar AMI
- A coding scheme that is commonly used in North America
- If an octet of all zeros occurs and the last voltage pulse preceding this octet was positive, then the eight zeros of the octet are encoded as 000+–0–+
- If an octet of all zeros occurs and the last voltage pulse preceding this octet was negative, then the eight zeros of the octet are encoded as 000–+0+–

HDB3 – High Density Bipolar 3 Zeros

- A coding scheme that is commonly used in Europe and Japan
- After last violation (ihlal), we look to number of 1s (odd or even)
- If there is no 1 after last violation (e.g. After 0000 again 0000) the number of 1s is assumed as even
- Odd+ → 000+
- Odd – → 000-
- Even + → -00-
- Even – → +00+

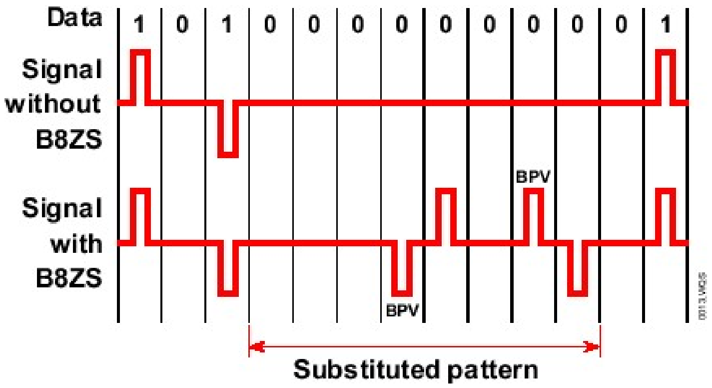
B8ZS and HDB3

B: Valid Bipolar Signal
V: Bipolar Violation

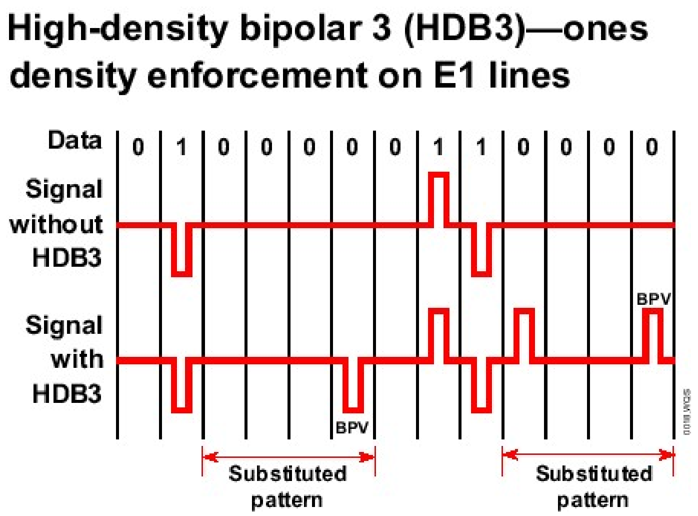


B8ZS-Example

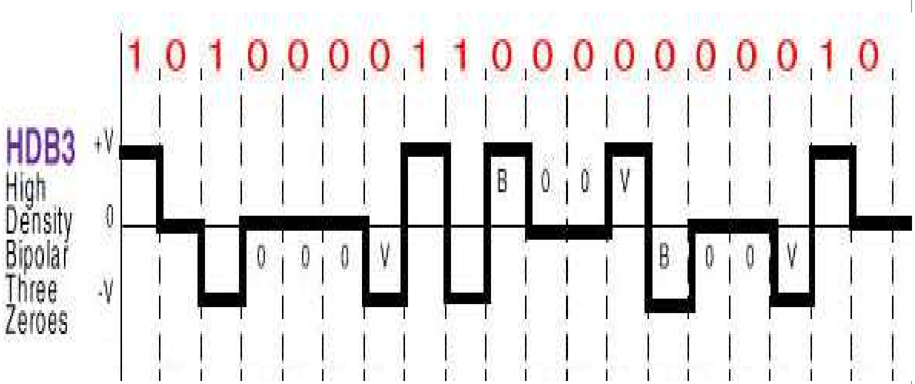
Bipolar 8-zero substitution (B8ZS)—ones density enforcement on T1 lines



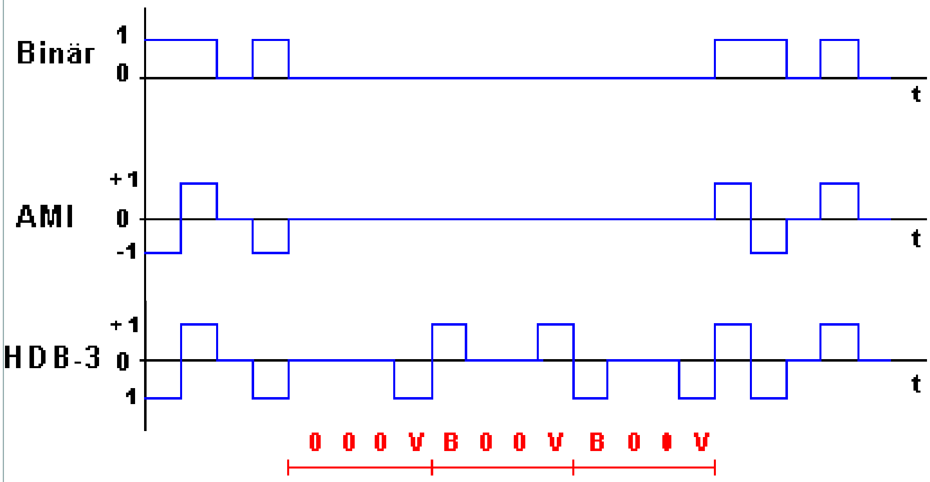
HDB3 - Example



HDB3 -Example



HDB3 - Example



Other Digital Data Digital Signal Codings

- 2B1Q (Two Binary, One Quaternary)
- MLT-3 (Multiline Tx, three Level)

2B1Q – Two Binary One Quaternary

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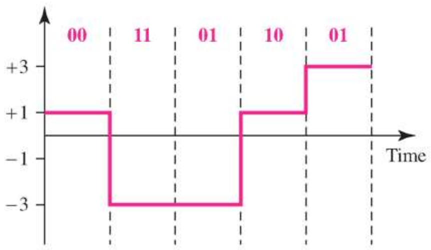
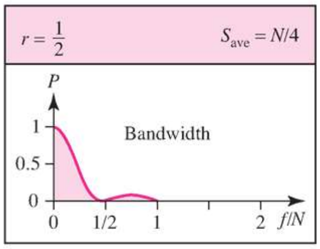
	Previous level: positive	Previous level: negative
Next bits	Next level	Next level
00	+1	−1
01	+3	−3
10	−1	+1
11	−3	+3

Transition table

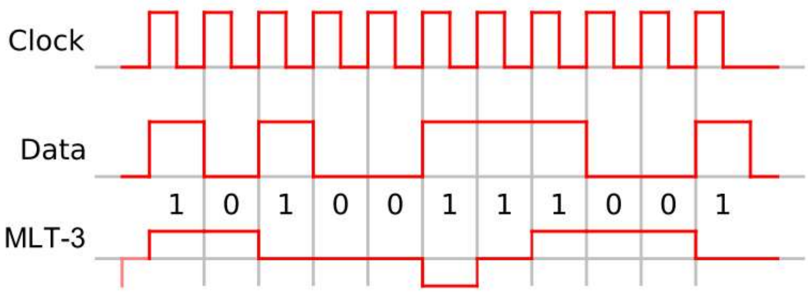


Assuming positive original level



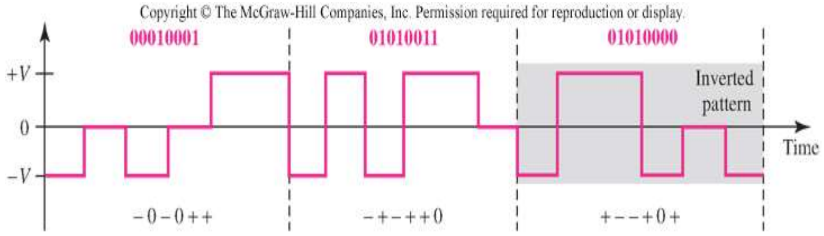
MLT-3

- Like NRZ-I.
- Use 3 signal level (+1, 0, -1)
- Transition at 1 bit, no transition at 0 bit.



8B6T

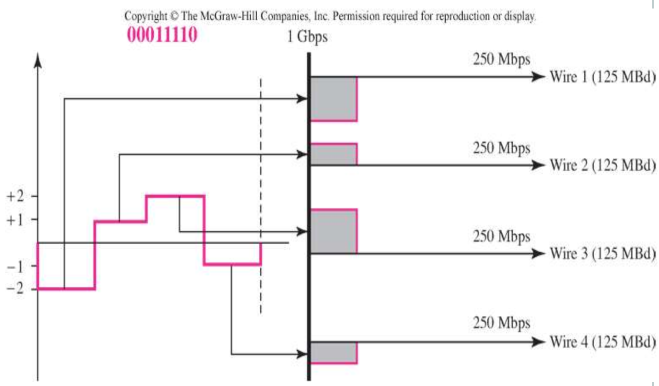
- 8B6T (Eight-binary-six-ternary) kodlamada 8 bit veri (m=8) 3 seviyeli (L=3) sinyalle gösterilir
- 2^8=256 farklı veri ve 3^6=729 farklı sinyal kullanılır
- Sinyallerin bir kısmı senkronizasyon ve hata denetimi için kullanılır
- Her bit grubu için kullanılacak sinyal grubu sabittir
- 100Base-T4 Ethernet çeşidinde 8B6T kodlama yöntemi kullanılır



4D-PAM5

- 4D-PAM5 (Four-dimensional five-level pulse-amplitude-modulation) kodlamada 4D verinin 4 kablo ile iletildiğini gösterir
- 5 farklı sinyal seviyesi (-2, -1, 0, 1, 2) bulunur.

- Sinyal 4 parça ile gösterilir her parçası bir kablo üzerinden iletilir
- Gigabit-LAN ağlarında kullanılır



Multiline Kodlama - MLT-3

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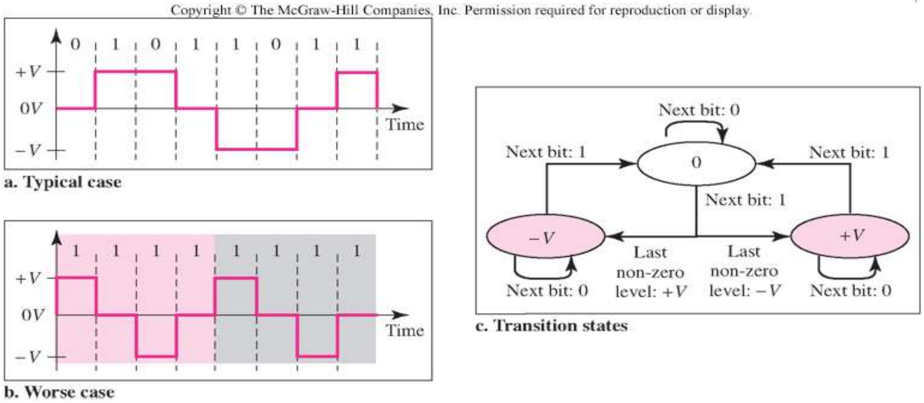

- NRZ-I ve farksal manchester veriyi kodlarken iki geçiş yapar
- MLT-3 (Multiline Transmission, Three Level) kodlama 3 seviyeli geçiş yapar, yani 3 sinyal seviyesi kullanır (+V, 0, -V).

Blok Kodlama

- Senkronizasyonu ve hata sezimini sağlamak için ek bitlere ihtiyaç duyulur
- Blok kodlamada m adet bit n adet bit haline getirilir (mB/nB, n>m). Diğer bir deyişle m bit grubu n bit grubu yerine yerleştirilir. Örnek olarak 4B/5B'de orijinal bitler 4-bit gruplara ayrılır ve her 4 bitin yerine 5 bitlik karşılıkları yazılır
- "/" işareti blok kodlamayı multilevel kodlamadan ayırır

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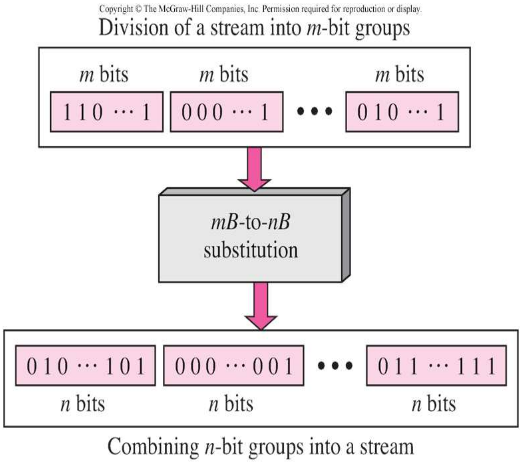

4B/5B Blok Kodlama

- 4B/5B (four binary/five binary) blok kodlama yöntemi NRZ-I ile birlikte kullanılır
- NRZ-I kodlama ardarda gelen uzun 0'larda senkronizasyon problemi oluşturur. Bundan dolayı kodlamadan önce uzun 0 olmayacak şekilde değişiklik gerekir.

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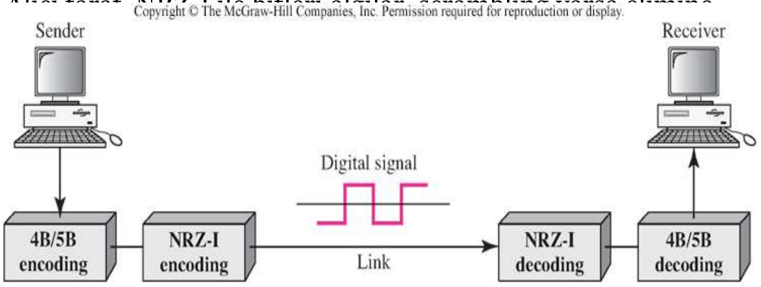

4B/5B Blok Kodlama

- Örnek: 1 Mbps hızında veri göndermek istiyoruz. 4B/5B + NRZ-I ve Manchester kodlama kullanıldığında gereken minimum bant genişliği nedir?
  - 4B/5B bit hızını 1.25 Mbps olarak aktarır
  - NRZ-I kodlama N/2 bantgenişliği gerektirdiğinden 625 KHz gerekir

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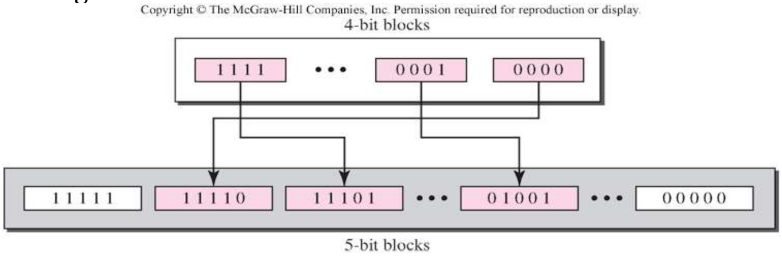

4B/5B Blok Kodlama

Data Sequence	Encoded Sequence	Control Sequence	Encoded Sequence
0000	11110	Q (Quiet)	00000
0001	01001	I (Idle)	11111
0010	10100	H (Halt)	00100
0011	10101	J (Start delimiter)	11000
0100	01010	K (Start delimiter)	10001
0101	01011	T (End delimiter)	01101
0110	01110	S (Set)	11001
0111	01111	R (Reset)	00111
1000	10010		
1001	10011		
1010	10110		
1011	10111		
1100	11010		
1101	11011		
1110	11100		
1111	11101		

- 4B/5B blok kodlama yöntemi FDDI ve 100BaseTx Ethernet çeşidinde kullanılır
- 4B/5B haricinde 6B/8B, 8B/10B ve 64B/66B blok kodlama yöntemleri bulunmaktadır

Hat Kodlama Yöntemleri – Özet Tablo

Kategori	Şema	Bant genişliği	Karakteristik
Unipolar	NRZ	BW = N/2	• Uzun 1 ve 0 larda senkronizasyon yoktur • DC bileşen vardır
Polar	NRZ-L	BW = N/2	• Uzun 1 ve 0 larda senkronizasyon yoktur • DC bileşen vardır
	NRZ-I	BW = N/2	• Uzun 0 larda senkronizasyon yoktur • DC bileşen vardır
	Biphase	BW = N	• Yüksek bant genişliği gerektirir • Senkronizasyon vardır • DC bileşen yoktur
Bipolar	AMI	BW = N/2	• Uzun 0 lar için senkronizasyon yoktur • DC bileşen yoktur
Multilevel	2B1Q	BW = N/4	• Uzun aynı bit çiftleri için senkronizasyon yoktur
	8B6T	BW = 3N/4	• Senkronizasyon vardır • DC bileşen yoktur
	4D-PAM5	BW = N/8	• Senkronizasyon vardır • DC bileşen yoktur
Multiline	MLT-3	BW = N/3	• Uzun 0 lar için senkronizasyon yoktur

- Bu tablo, Doç.Dr. M. Ali Akçayol'un Veri İletişimi ders notlarından alınmıştır

Analog Data, Digital Signal

- digitization is conversion of analog data into digital data which can then:
  - be transmitted using NRZ-L
  - be transmitted using code other than NRZ-L
  - be converted to analog signal
- analog to digital conversion done using a codec
  - pulse code modulation
  - delta modulation

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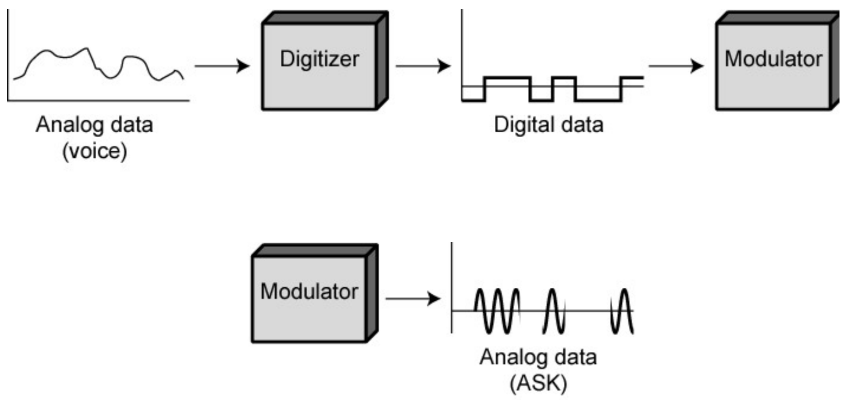
Digitizing Analog Data



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Block Diagram of PCM

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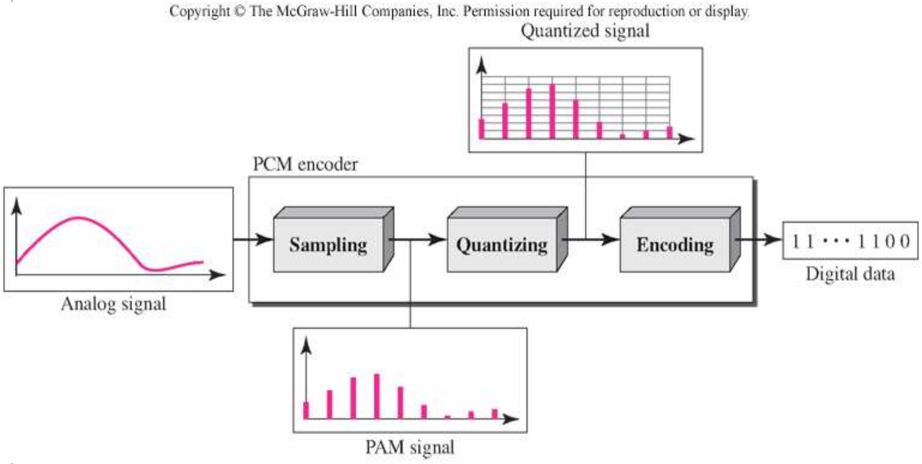

Pulse Code Modulation (PCM)

- sampling theorem:
  - "If a signal is sampled at regular intervals at a rate higher than twice the highest signal frequency, the samples contain all information in original signal"
  - eg. 4000Hz voice data, requires 8000 sample per sec
- strictly have analog samples
  - Pulse Amplitude Modulation (PAM)
- so assign each a digital value

Sampling

- First stage of PCM
- Take a sample for each T_s period. And also this taken sample has a digital value
- Three types of sampling

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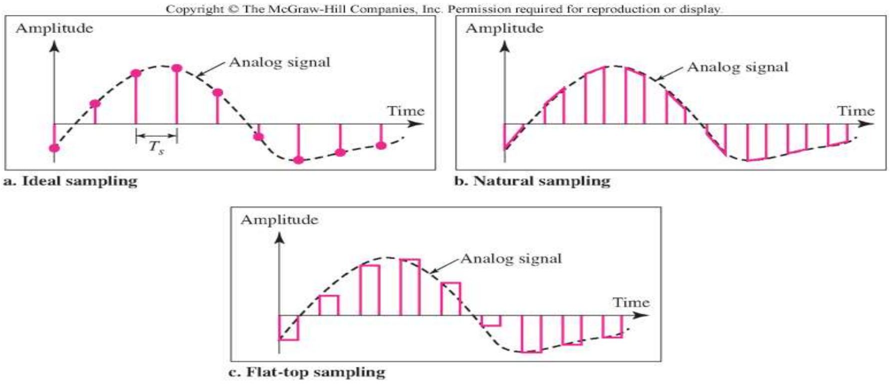

a. Ideal sampling
b. Natural sampling
c. Flat-top sampling

Sampling – Nyquist Teorem

- If a signal is sampled with the twiced frequency of maximum frequency of signal, the samples hold all of the data.

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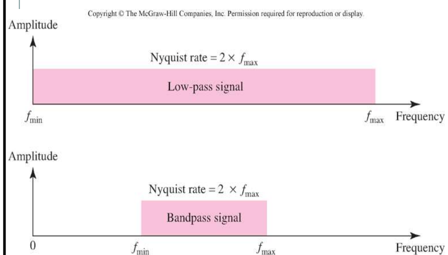

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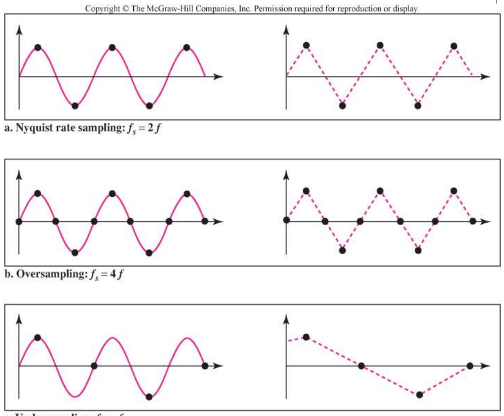

a. Nyquist rate sampling: $f_s = 2f$
b. Oversampling: $f_s = 4f$
c. Undersampling: $f_s = f$

Sampling Rate

- Let's digitize human voice. What is the bitrate if we encode each sample with 8 bit?
- Ans: Human voice has a frequency of 0-4000 Hz (for telephone line)
  - Sampling rate:
  - 4000 x 2 = 8000 sample/sec
  - Bitrate = sampling rate x encoding bit numbers per sample = 8000 x 8 = 64000 bps = 64 kbps

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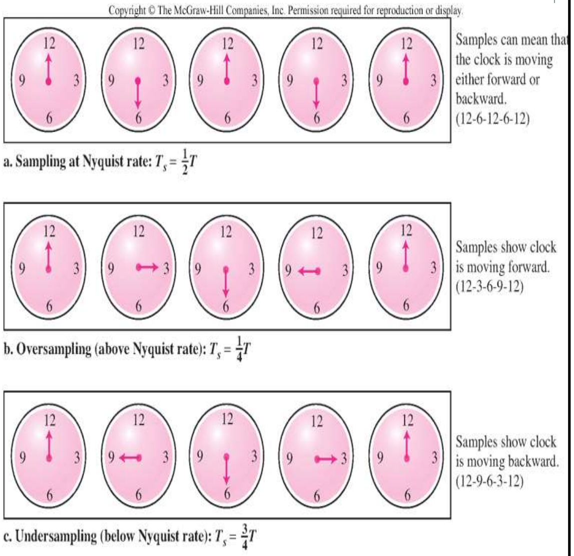
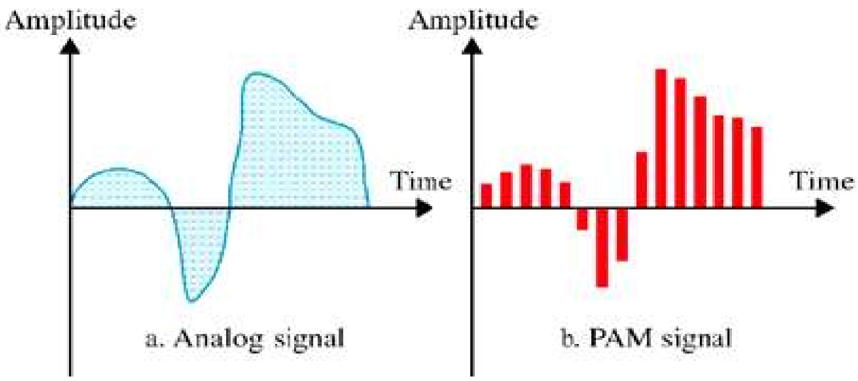
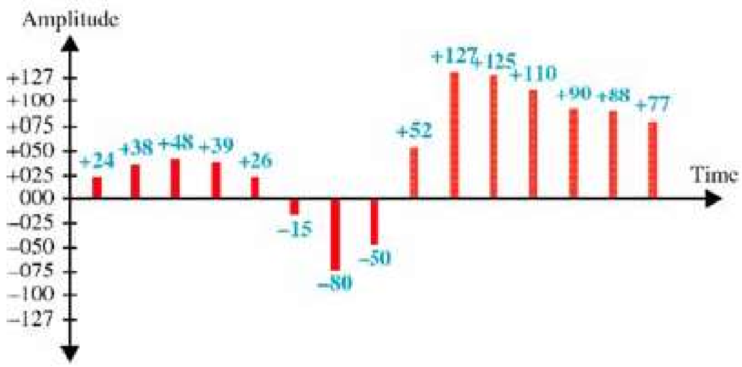


Quantizing



Quantized Signal

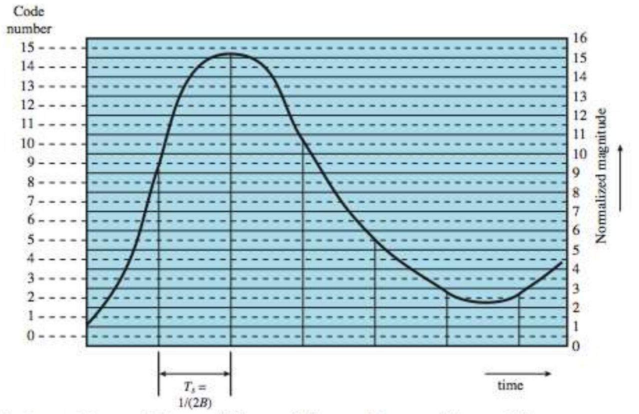


Encoding

+024	00011000	−015	10001111	+125	01111101
+038	00100110	−080	11010000	+110	01101110
+048	00110000	−050	10110010	+090	01011010
+039	00100111	+052	00110110	+088	01011000
+026	00011010	+127	01111111	+077	01001101

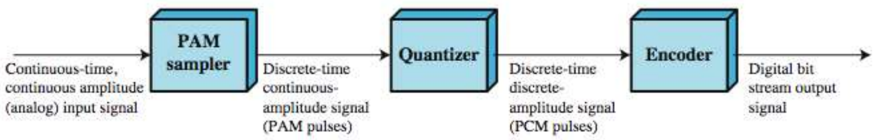
Sign bit
+ is 0 − is 1

PCM Example

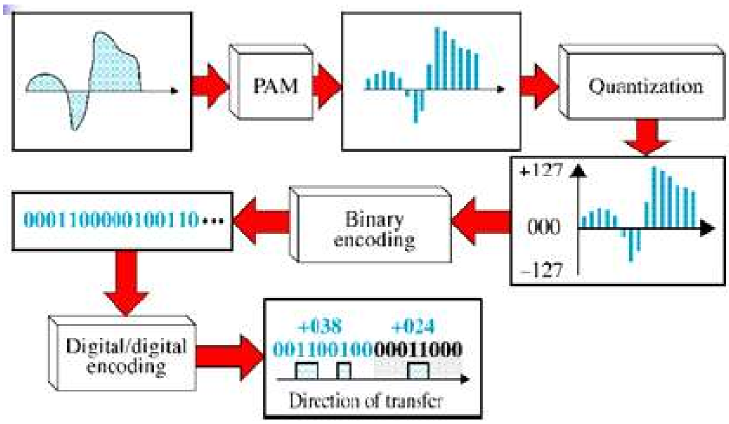


PAM value	1.1	9.2	15.2	10.8	5.6	2.8	2.7
quantized code number	1	9	15	10	5	2	2
PCM code	0001	1001	1111	1010	0101	0010	0010

PCM Block Diagram

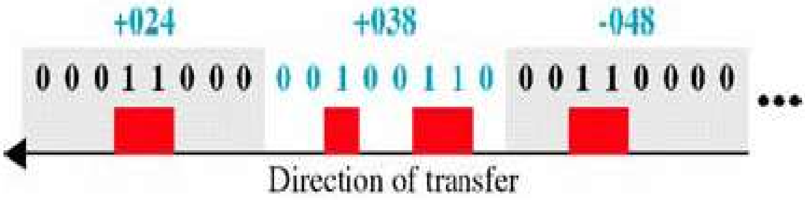


Darbe Kod Modülasyonu - Özet



Sayısal Verinin Kodlanması

- Analog sinyal sayısal bir veri haline dönüştürüldükten sonra;
  - Sayısal veriden sayısal sinyale dönüşüm tekniklerinden herhangi biri kullanılarak sayısal bir iletim ortamı üzerinden gönderilebilir
  - Sayısal veriden analog sinyale dönüşüm teknikleri kullanılarak analog bir iletim ortamı üzerinden gönderilebilir



İletişim Teknikleri

- Sayısal verin, bir iletim ortamı üzerinden ya seri ya da paralel modda aktarılabilir

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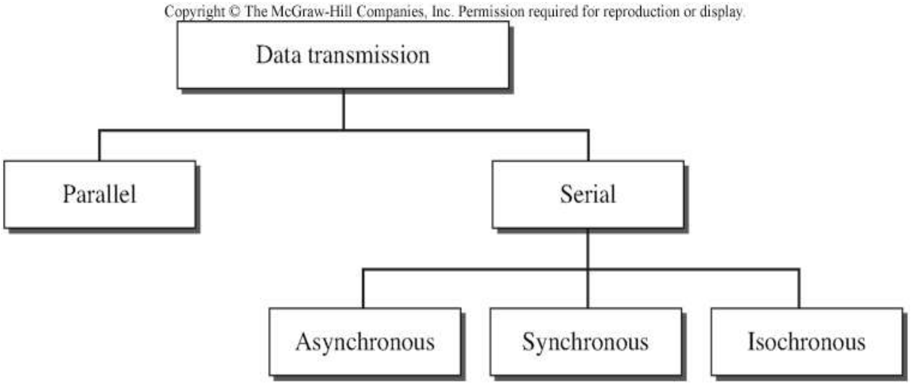

Seri İletişim Tekniği

- Gönderilecek bilginin tek bir iletim yolu üzerinden sıra ile aktarıldığı iletim şeklidir
- Sayısal formattaki bilginin aktarım hızı, 'baud' birimiyle ölçülür.
- PC'lerdeki seri portlar, seri iletişim tekniği kullanırlar.
  - Seri iletişim kendi arasında; Asenkron, Senkron, Isenkron olmak üzere üçe ayrılır:

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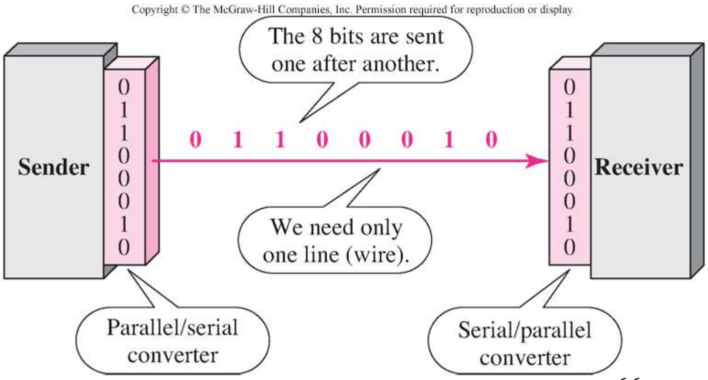

Asenkron Seri İletişim Tekniği

- Gönderici ve alıcının birbirinden bağımsız hareket ettikleri bir iletişim şeklidir.
- Gönderilecek bilgi, 'karakter' adı verilen bloklara ayrılır. Sonra iletim ortamına seri olarak verilir.
- Bir blokta genellikle 7 yada 8 bit bulunur
- Her veri bloğu başla bitiyle başlar ve dur biti ile sonlanır. Alıcı bu bitler vasıtasıyla gelen veriyi anlar/yakalar

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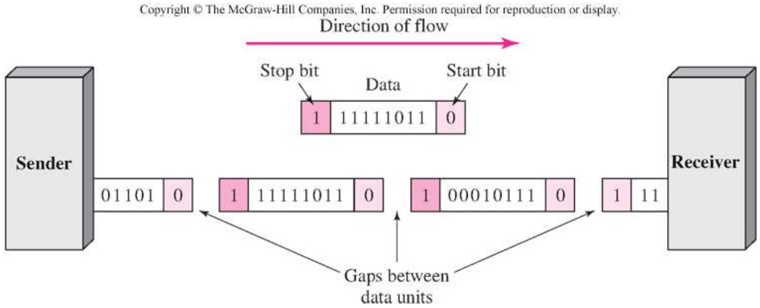


Senkron Seri İletişim Tekniği

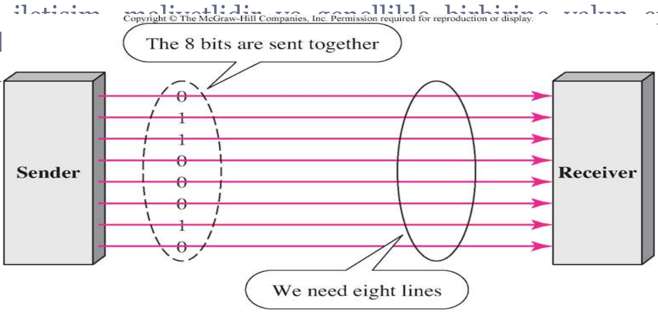
- Gönderici, saat işaretini bilgi ile modüle ederek alıcıya gönderir. Alıcı, vericinin gönderdiği işaret dizisini kullanarak (uygun devreler yardımı ile) vericinin frekansı ile eşit frekanslı bir senkronizasyon işareti elde eder.
- Senkronizasyon işlemi için modülasyon gerektirmeyen ikinci bir yol, verici ve alıcı arasında bulunan bir hat üzerinden saat işaretinin gönderilmesidir.
- Uzunluğu kullanılan protokole göre değişen bilgi bit katarına ön ve son ekler konularak alıcının bilginin başlangıç ve sonunu belirlemesi sağlanır. Eklenen ön ve son eklerin uzunlukları, kullanılan protokole bağımlı olarak belirlenir.

Isenkron Seri İletişim Tekniği

- Senkron iletişimin bir çeşidi (türevi) olarak düşünülebilir.
- Isenkron bilgi iletiminde, uç sistemlerin birbirleri ile olan haberleşme gereksinimi periyodik olarak karşılanır.
- Sabit hızda verinin iletimi sağlanır
- Örneğin; her 125 µs'de 193 bit aktarılacak gibi bir gereksinim belirtilir ve bu garanti olarak sağlanır.
- Bu tür iletişim özellikle gerçek zamanlı ses video aktarım uygulamalarında yada kritik veri transferi gerektiren endüstriyel otomasyon/kontrol sistemlerinde kullanılır.

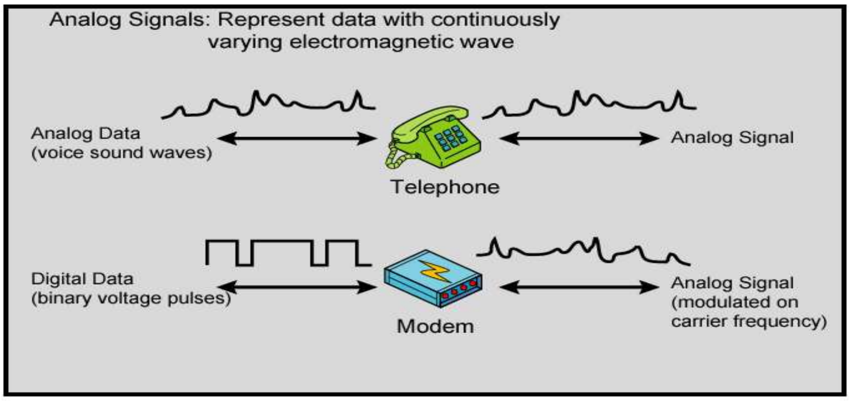
Paralel İletişim Tekniği

- Gönderilecek bilginin her bir bitinin ayrı bir iletim yolundan aktarıldığı iletim şeklidir
- Aktarma anında, vericinin yola bilgi bitleri çıkardığını belirtmek için vericiden alıcıya veri hazır (data ready) ve alıcıdan vericiye veri alabileceğini belirten istek belirtme (request) hatlarına gereksinim vardır.
- Paralel ... cihazlar arasınd
- PC'lerd



ANALOG TRANSMISSION

- Digital Data, Analog Signal
- Analog Data, Analog Signal
- Analog and Digital Data carried by Analog Signals



Analog Transmission's Terms

- Bitrate
  - Bits transmitted per second
  - Transmit time
- Baudrate : signal per second
  - **Digital transmission → 1/2 x N x 1/r**
  - **Analog transmission → N x 1/r**
- Transmission System (Carrier)
- Carrier Signal (Carrier Frequency)
  - Use higher frequency to transmit data
  - Transmitter and Receiver angree on same frequency
  - Digital data is modulated by changing the carrier characterics over carrier (shift registers)
- Characterics are
  - Amplitude
  - Frequency
  - Phase

Analog Transmission

- **Digital Data, Analog Signal**
- main use is public telephone system
  - has freq range of 300Hz to 3400Hz
  - use modem (modulator-demodulator)
- encoding techniques
  - Amplitude shift keying (ASK)
  - Frequency shift keying (FSK)
  - Phase shift keying (PSK)

Types of Modulations

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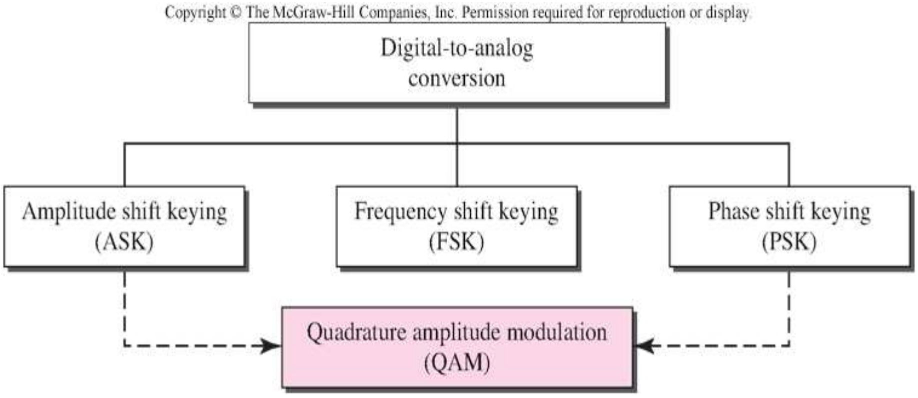
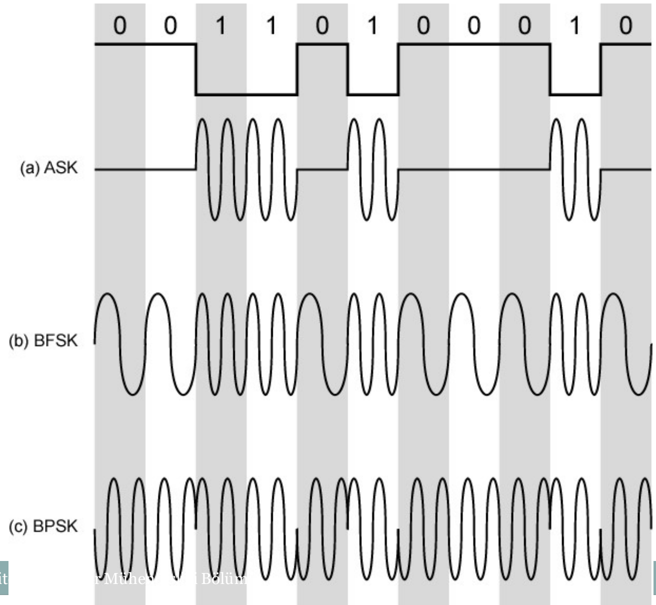
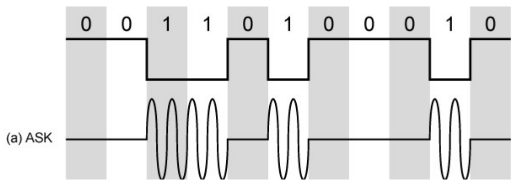


Modulation Techniques

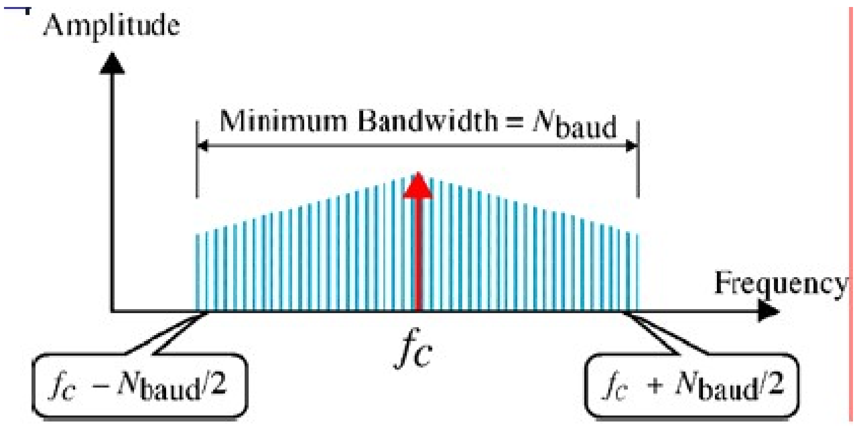


Amplitude Shift Keying

- encode 0/1 by different carrier amplitudes
  - usually have one amplitude zero
- susceptible to sudden gain changes
- inefficient
- used for
  - up to 1200bps on voice grade lines
  - very high speeds over optical fiber



Bandwidth for ASK



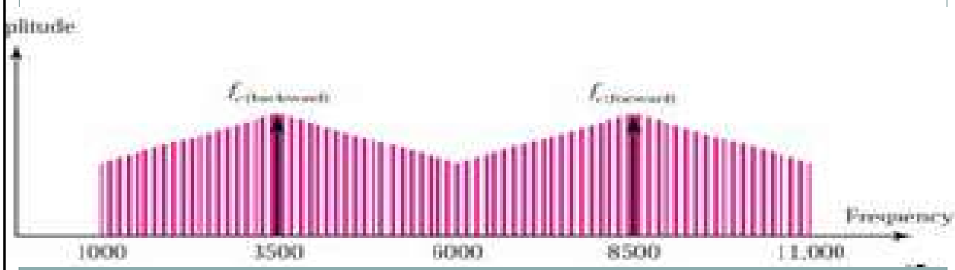
ASK Example

- For an ASK signal that has a 2000 bps transfer speed, what is the minimum bandwidth?
- Baudrate=Bitrate (for ASK)
- So minimum BW=2000 Hz

ASK Example-2

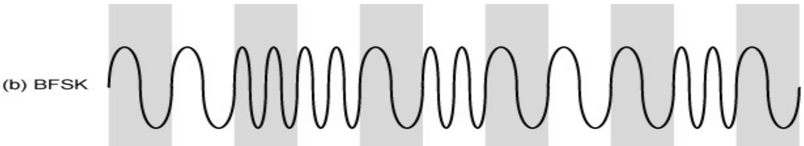
- For a 10000 Hz bandwidth (between 1000 Hz and 11000 Hz) draw the full-dublex ASK diagram. Find the carrier and bandwidth at both of two sides. Suppose that there is no gap.

- For full-dublex BW=10000/2 = 5000 Hz
- Carrier frequencies are at the center of each band, so
- fc (forward) =1000+5000/2 =3500 Hz
- fc (backward)= 11000-5000/2=8500 Hz



Binary Frequency Shift Keying

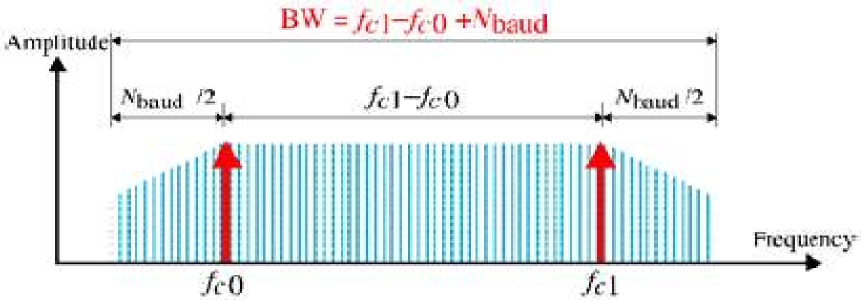
- most common is binary FSK (BFSK)
- two binary values represented by two different frequencies (near carrier)
- less susceptible to error than ASK
- used for
  - up to 1200bps on voice grade lines
  - high frequency radio
  - even higher frequency on LANs using co-ax



FSK Example

- For a FSK signal that transfer data at 1000 bps, what is the minimum bandwidth? Suppose that communication is half-dublex and carriers are seperated with 2000 Hz.

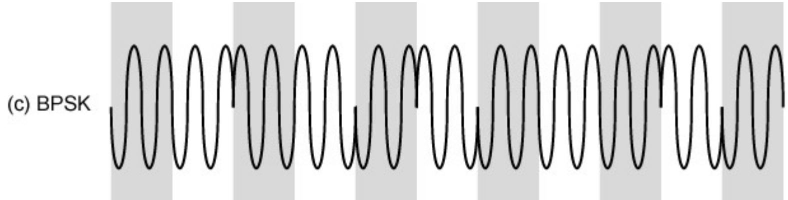
- BW=baudrate +fc1-fc0
- BW= bitrate+fc1-fc0= 1000+2000
- BW=3000 Hz



Sakarya Üniversitesi Bilgisayar Mühendisliği Bölümü

Phase Shift Keying

- phase of carrier signal is shifted to represent data
- binary PSK
  - two phases represent two binary digits
- differential PSK
  - phase shifted relative to previous transmission rather than some reference signal



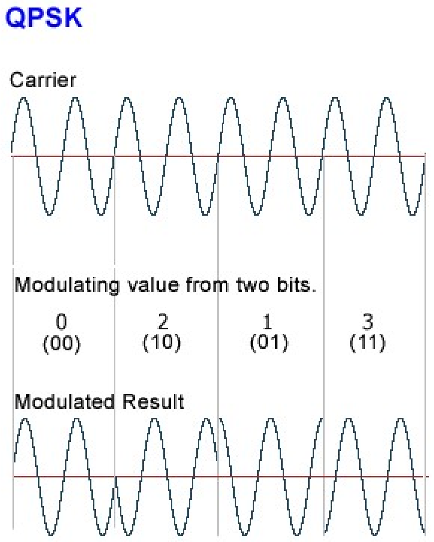
Sakarya Üniversitesi Bilgisayar Mühendisliği Bölümü

Quadrature PSK

- get more efficient use if each signal element represents more than one bit
  - eg. shifts of $\pi/2$ (90^o)
  - each element represents two bits
  - split input data stream in two & modulate onto carrier & phase shifted carrier
- can use 8 phase angles & more than one amplitude
  - 9600bps modem uses 12 angles, four of which have two amplitudes

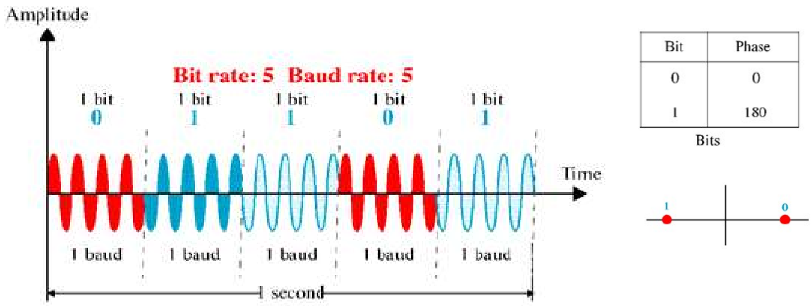
QPSK

- Quadrature PSK (QPSK) is like 4QAM without amplitude modulation. QPSK uses four phase angles to represent each two bits of input; however, the amplitude remains constant.

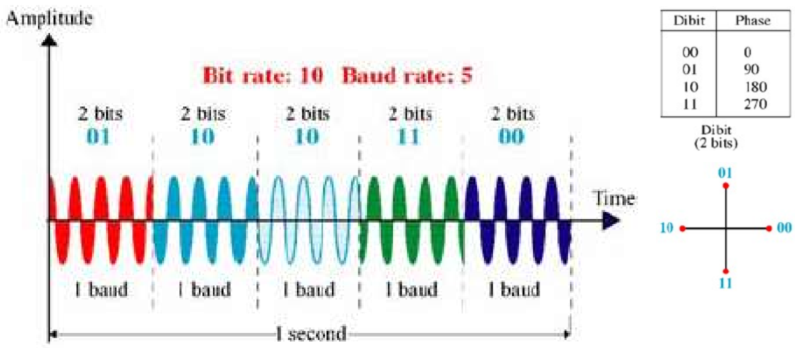


PSK – Phase Shift Keying

- Phase of carrier signal changes
- In the example 0° ve 180° are phases of two signals. faz farklı iki sinyal kullanılır. Therefore it is called Binary PSK
- PSK needs only one carrier frequency, but FSK needs how many states are there.



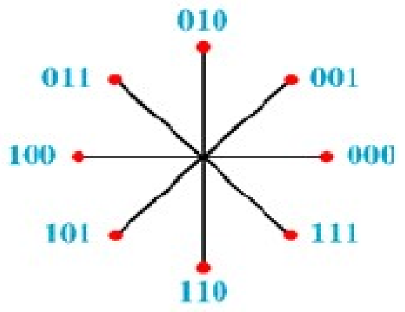
4 - PSK



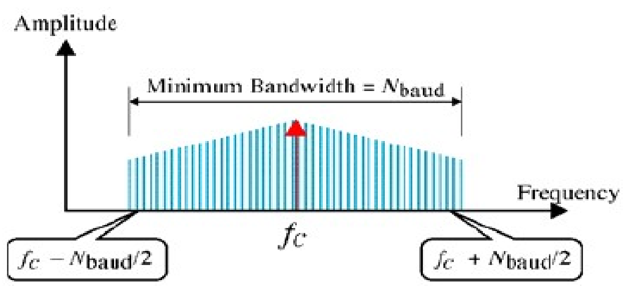
8 – PSK Structure

Tribit	Phase
000	0
001	45
010	90
011	135
100	180
101	225
110	270
111	315

Tribits
(3 bits)



PSK Bandwidth



- Q : Bandwitdth for a 8-PSK signal is 4000 Hz. What are the Baudrate and Bitrate values?
- A : For PSK signal, baudrate = BW = 4000 Hz

  bitrate = 3 * baudrate

  bitrate = 4000 * 3 = 12000 bps

Consellation Diagram

- Use to show amplitude and phase values of signal.
- Use for ASK, PSK ve QAM. Each dot shows the phase and amplitude state.

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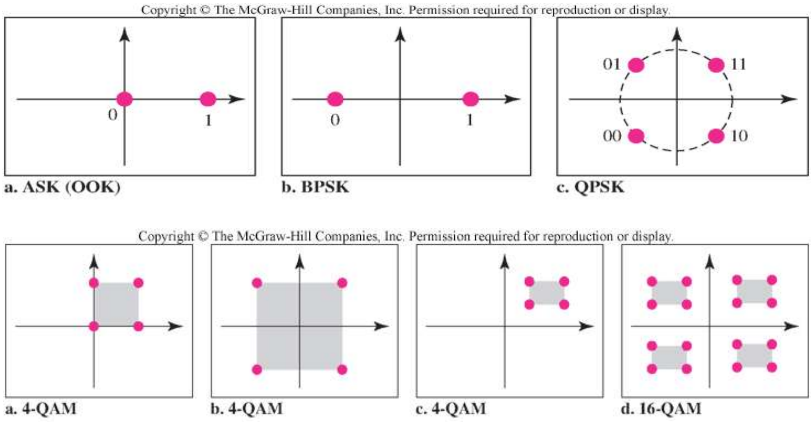
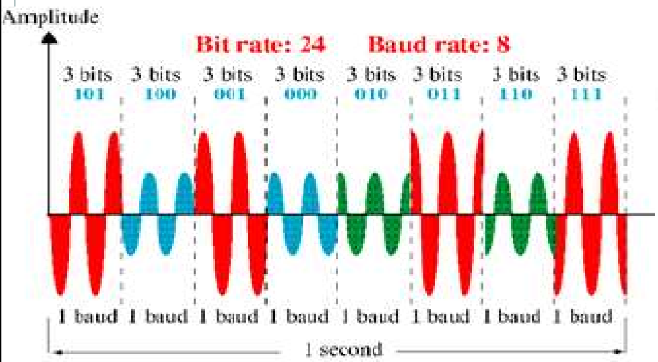


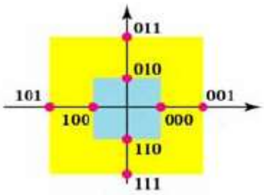
Quadrature Amplitude Modulation

- QAM used on asymmetric digital subscriber line (ADSL) and some wireless
- combination of ASK and PSK
- logical extension of QPSK
- send two different signals simultaneously on same carrier frequency
  - use two copies of carrier, one shifted 90°
  - each carrier is ASK modulated
  - two independent signals over same medium
  - demodulate and combine for original binary output

8 – QAM Signal

1 signal → 3 bits



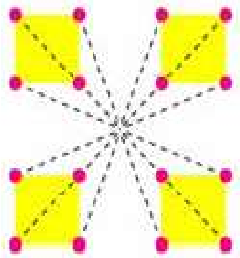


8-QAM
2 amplitudes, 4 phases

2 x 4 = 8 combinations
8 → 2^3

16 - QAM

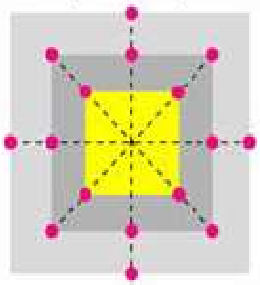
3 amplitudes, 12 phases



16-QAM

3 x 12 = 36 combinations
36 → 2^4 (16)

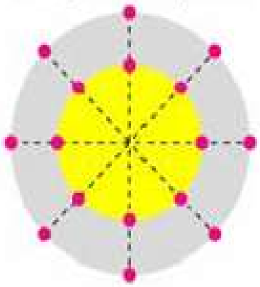
4 amplitudes, 8 phases



16-QAM

4 x 8 = 32 combinations
32 → 2^4 (16)

2 amplitudes, 8 phases

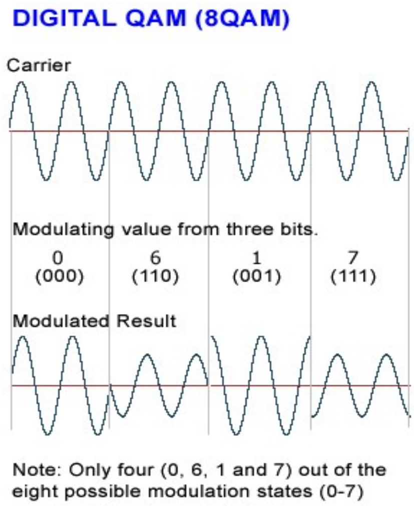


16-QAM

2 x 8 = 16 combinations
16 → 2^4 (16)

8-QAM

- In this 8QAM example, three bits of input generate eight different modulation states (0-7) using four phase angles on 90 degree boundaries and two amplitudes: one at 50% modulation; the other at 100% (4 phases X 2 amplitudes = 8 modulation states). QAM examples with more modulation states become extremely difficult to visualize



QAM Variants

- two level ASK
  - each of two streams in one of two states
  - four state system
  - essentially QPSK
- four level ASK
  - combined stream in one of 16 states
- have 64 and 256 state systems
- improved data rate for given bandwidth
  - but increased potential error rate

Baudrate and Bitrate Comparison

Modulation	Units	Bits/Baud	Baudrate	Bitrate
ASK, FSK, 2-FSK	Bit	1	N	N
4-PSK, 4-QAM	Dibit	2	N	2N
8-PSK, 8-QAM	Tribit	3	N	3N
16-QAM	Quadbit	4	N	4N
32-QAM	Pentabit	5	N	5N
64-QAM	Hexabit	6	N	6N
128-QAM	Septabit	7	N	7N
256-QAM	Octabit	8	N	8N